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MEASURING ACCURACY OF ELECTRIC ENERGY IN HV POWER NETWORKS

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***Summary*: The article presents the effect of secondary circuits of inductive current and voltage transformers on measuring accuracy in HV power networks. The basic parameters of instrument transformers were defined, such as errors or rated output. The impedance effect of the leads connecting secondary terminals with measuring instruments and the impact of burden power on the energy measuring error were analyzed. The calculation samples illustrate the procedure when assessing energy (power) measuring error. The algorithm may be applied, with positive results, by the operating personnel of measuring circuits with instrument transformers.**

Keywords:
Electric energy measuring
Instrument transformers
Measuring accuracy

1. INTRODUCTION

Instrument transformers are the electrical apparatus indispensable for measuring energy or electric power both in HV power networks and when testing e.g. power transformers. Their metrological characteristics, currently specified by the relatively high accuracy class (of e.g. 0,1 or higher), are often unsatisfactory, because in real operating measurement conditions, errors caused by the instrument transformers exceed significantly the limit values set by the relevant standards [1, 2]. This fact, often unnoticed by its users is only investigated, when the measurement of energy (power) performed on the transformers of the same rating in the same place but of a different type, show significant differences. Apart from the errors caused by the instrument transformers, power or energy measurement errors are heavily dependent on the frequently ignored factors such as: the leads connecting their secondary terminals (S1-S2 for current transformers, and – the a-n or a-b for voltage transformers) with measuring devices (the current circuits of watt-hour meters or measuring instruments), as well as the power factor of loads of the power network or the tested objects (i.e. the transformers). Furthermore it cannot be underestimated that the burden power factor of instrument transformers is different from the rated output (most often 0,8) and the burden power value is lower than 25% of their rated output.

The following article reviews inductive measuring current and voltage transformers. It investigates the influence of the power factor of network total load whose energy or power are measured, the resistance of the leads in secondary circuits of instrument transformers and the effect of the actual burden of the instrument transformers on the change of necessary accuracy of energy or power measurement based on the catalogue data or the error characteristics provided by the producer. The overall objective of the analysis is to systematize the error assessment criteria of the introduced instrument transformers which cause errors in energy or power measuring circuits, both in laboratory research and in the network operation, with a special regard to high tension systems (110 kV and higher).

2. THE BASIC METROLOGICAL DEFINITIONS

In order to clarify further arguments, the most important definitions, useful from the users' perspective, were given and systematised, pertinent to metrological properties of instrument transformers. Moreover the errors' limit values ascribed to the specific accuracy class of current and voltage transformers were presented.

2.1. Current transformer (CT)

From the secondary side a current transformer may be treated as a current source. Its metrological characteristics are marked by the current error Δi and the phase displacement (angle error) δi corresponding to the specific effective value expressed as the percentage of the primary current I_p and the burden power S.

The *current (ratio) error* defines the relative difference, expressed in percentage, of the effective values of the primary current I_p and the secondary I_s. It is given by:

$$\Delta i = \frac{K_{In} I_s - I_p}{I_p} 100\% = \frac{\frac{I_{pn}}{I_{sn}} I_s - I_p}{I_p} 100\% = \frac{I_s - I_p^{'}}{I_p^{'}} 100\% \quad (1)$$

The abovementioned formula is valid for the current error value of the CT in which the turns correction was not applied ($w_p : w_s = I_{sn} : I_{pn}$).

Phase displacement (*angle error*) δi defines a secondary current phase shift, expressed in minutes or centiradians, in relation to the primary current, that is $\delta i = \arg\{\underline{I}_s\} - \arg\{\underline{I}_p\}$. This means that the phase displacement is said to be positive, when the secondary current $\underline{I}_s$ leads the primary current $\underline{I}_p$ in the phase.

The burden power S defines the apparent power, expressed in volt-amperes, which is referred to the secondary circuit of the CT by current circuits of measuring instruments or relays with the burden impedance Z_B. It is defined for the secondary rated current I_{sn}, i.e, it is described by the formula: $S = Z_B I_{sn}^2$. In the case when it corresponds to the rated conditions, i.e. when it relates to fixing requirements as for accuracy, [1] we call it a *rated output* (S_n). According to the standards, the errors of CT are calculated at the burden power of 100% and 25% of rated output (that is for Z_{Bn} and $0{,}25Z_{Bn}$, where $Z_{Bn} = S_n : I_{sn}^2$). The admissible values of errors of the CT, when performing measurements in specified conditions, are connected with the accuracy class, which is the conventional categorization of a transformer. Its values are listed in Table 1. The abovementioned conditions are as follows: the range from 5% to 120% of the rated current and the burden of between 25 % and 100 % of the rated output with the inductive power factor 0,8.

2.2. Voltage transformer (VT)

From the secondary side a voltage transformer may be treated as a voltage source. Its metrological characteristics are determined by the voltage (ratio) error Δu and the phase displacement (angle error) δu corresponding to the specified percentage effective value of the primary voltage U_p and the burden power S.

The *voltage (ratio) error* defines the expressed as a percentage of the relative difference of effective values of primary U_p and secondary voltage U_s. It is given by:

$$\Delta u = \frac{K_{Un} U_s - U_p}{U_p} 100\% = \frac{\frac{U_{pn}}{U_{sn}} U_s - U_p}{U_p} 100\% = = \frac{U_s - U_p^{'}}{U_p^{'}} 100\% \qquad (2)$$

The abovementioned formula is valid for the voltage error value of the VT in which the turns correction was not applied ($w_p / w_s = U_{pn} / U_{sn}$).

The *phase displacement* (*angle error*) δu defines a secondary voltage phase shift, expressed in minutes or centiradians, in relation to the primary voltage, i.e. $\delta u = \arg\{\underline{U}_s\} - \arg\{\underline{U}_p\}$. This means that the phase displacement is positive, when the secondary voltage $\underline{U}_s$ leads the primary voltage $\underline{U}_p$ in the phase.

The *burden power S* defines the apparent power, expressed in volt-amperes, which is referred to the secondary circuit of the VT by voltage circuits of measuring instruments or relays with the burden impedance Z_B. It is defined for the secondary rated voltage U_{sn}, that is, it is described by the formula: $S = U_{sn}^2 / Z_B$. In the case when it corresponds to the rated burden, i.e. when it relates to fixing requirements as for accuracy, [2] it is called *rated output* (S_n). According to the standards, the errors of the VT are calculated at the burden power of 100% and at 25% of rated output (that is for Z_{Bn} and $4Z_{Bn}$, where $Z_{Bn} = U_{sn}^2 : S_n$). The permissible errors of the VT when performing measurements in specified conditions are connected with the accuracy class, which is the conventional categorization of a transformer. Its values are listed in Table 2. The abovementioned conditions are as follows: the range from 5% to 120% of the rated voltage and the burden of between 25 % and 100 % of the rated output with the inductive power factor 0,8.

3. EFFECT OF INSTRUMENT TRANSFORMERS ON THE ACCURACY OF ELECTRIC ENERGY (POWER) MEASUREMENT

The analysis of instrument transformers error influence on the error occurrence in electric energy (power) measurement was based on the basic single-phase indirect circuit, presented in Fig.1a. Using the vectorial presentation of currents and voltages in Fig. 1b it is possible to introduce the relationship defining the percentage value of the measure-

Table 1. Phase displacement and current error limit values for the measuring CT [1]

Accuracy class	Percentage current (ratio) error at percentage of rated current shown below ±				Phase displacement at percentage of rated current shown below ±							
					Minutes				Centiradians			
	5	20	100	120	5	20	100	120	5	20	100	120
0.05*)	0.15	0.075	0.05	0.05	10	5	3	3	0.30	0.15	0.10	0.10
0.1	0.4	0.2	0.1	0.1	15	8	5	5	0.45	0.24	0.15	0.15
0.2	0.75	0.35	0.2	0.2	30	15	10	10	0.9	0.45	0.30	0.30
0.5	1.5	0.75	0.5	0.5	90	45	30	30	2.7	1.35	0.9	0.9
1	3.0	1.5	1.0	1.0	180	90	60	60	5.4	2.7	1.8	1.8

*) For the accuracy class of 0.05 and more precise current transformers (i.e. of accuracy class 0.02 or 0.01) the accepted error limit values are set by the relevant standard regulations contained in the national weights and measures office newsletters or else are the result of an agreement between the manufacturer and the user.

ment error of active energy (power) $E_p(P)$, caused by the instrument transformers, in the following form (the derivation of the formula in appendix A):

$$\delta E_{p\%} = \frac{E_p^{'} - E_p}{E_p} 100\% = \Delta u + \Delta i + \frac{\pi}{108}(\delta i - \delta u) tg\,\varphi \quad (3)$$

where:

Δu, Δi — the voltage and current error of the VT and CT respectively,

δu, δi — the phase displacement expressed in minutes of the VT and CT respectively,

φ — the phase angle of the measured power networks load.

In the case of the reactive energy (power) E_q *(Q)* in view of additional phase displacement of $\pi/2$, the relation (3) is the following:

$$\delta E_{q\%} = \frac{E_q^{'} - E_q}{E_q} 100\% = \Delta u + \Delta i + \frac{\pi}{108}(\delta u - \delta i)\ \mathrm{ctg}\varphi \quad (4)$$

where the notations used are identical as in the formula (3).

What results from the dependence (3) and (4), is that the value of the phase displacements difference of the VT and CT has a significant effect on the error of energy (power) measurement. A particularly critical situation occurs when the active energy (power) of the loads with a low power factor value is measured, or the measurement of reactive energy (power) of the loads with the *cosφ* value approaching the value 1.

In practice of the tests on power transformers, the measurement of power losses in the no-load circuit and in the measuring short-circuit state is accompanied by very low values of the power factor. In the measuring short-circuit state of a tested transformer, the value cosφ can approach 0.02 (tgφ = 50) or smaller value. In this case the percentage error due to the difference of the phase displacement ($\delta i - \delta u$) = 10 minutes, is enormous: + 14.5 %!

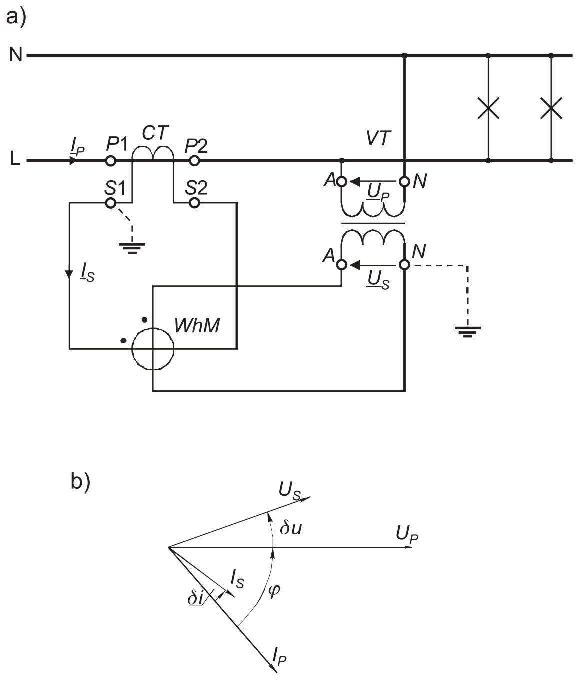

Fig.1. A circuit for measuring of active energy with instrument transformers: a) the scheme of connections, b) the phasor diagram.

Similarly, in the case of reactive electrical energy measurement in the power network, in which the power factor after the compensation of the inductive reactive power with the capacitors, is e.g. 0.94 (ctgφ = 2.8), the percentage error due to difference of the phase displacement ($\delta i - \delta u$) = 10minutes the value of (–0.8) %. In comparison with the ratio errors of the instrument transformers of e.g. the accuracy class 0.2 (see Tables 1 and 2), it is a relatively large additional error.

Apparently, despite using the instrument transformers with high accuracy classes, e.g. 0.1 or even 0.05, the measuring errors of energy (power) caused by the unfavourable characteristics of the phase displacement of instrument transformers ($\delta i \times \delta u < 0$) may reach unacceptably large values.

Table 2. Phase displacement and current error limit values for the measuring VT [2]

Accuracy class	Percentage voltage (ratio) error ±	Phase displacement ±	
		Minutes	Centiradians
0.05*)	0.05	3	0.10
0.1	0.1	5	0.15
0.2	0,2	10	0.3
0.5	0.5	20	0.6
1.0	1.0	40	1.2
3.0	3.0	not defined	not defined

*) For the accuracy class of 0.05 and more precise voltage transformers (i.e. of the accuracy class 0.02 or 0.01) the accepted error limit values are set by the relevant standard regulations contained in the national weights and measures office newsletters or else are the result of an agreement between the manufacturer and the purchaser.

4. DEPENDENCE OF ADDITIONAL ERRORS FROM LEADS AND BURDEN IMPEDANCE

Apart from the metrological characteristics of the instrument transformers themselves, the energy measurement accuracy, especially in the highest voltage aerial substations, where the distance between the instrument transformers and measuring instruments can reach even a few hundred metres, is determined by the leads connecting their secondary terminals with current or voltage circuits of the watt-hour or var-hour meters. Although, according to the relevant regulations, cross-sections of these conductors are sufficiently large, and their connections with watt-hour meters (Fig. 2) make it possible to ignore return leads[1], their resistance does influence the accuracy of current and voltage transformation. Apparently, despite fulfilling the formal requirements concerning high class instrument transformers (e.g. of class 0.2 or 0.1), the energy measurement errors caused by ignoring the leads resistance, often reach unacceptably large values.

Another metrological issue to be considered, which is connected with the presence of the instrument transformers in electric energy (power) measuring setup, is the actual burden of the instrument transformers. In many measuring circuits the burden of instrument transformers does not adhere to the relevant standards [1,2] of the requirements discussed in clause 2. It is not contained between 100% and 25% of the rated output with the power factor $\cos\varphi = 0.8$ind. Thus, the users of instrument transformers, basing on the characteristics of errors specification provided by the manufacturer, should have the possibility of verifying, whether, in the condition of actual burden the errors of instrument transformers exceed the permissible limits determined by the accuracy class, causing as a result, an uncontrolled increase of energy (power) measurement error of the loads of power network.

The following investigation supports the necessity for consideration of the resistance of conductors in secondary circuits of the instrument transformers. It resulted in analytical relationships enabling the calculation of the degree of additional errors change caused by the resistance of leads. The way of estimating the error change of the instrument transformers was presented, with a different from given for the specified accuracy class burden impedance. The overall objective of this analysis is to indicate the users of the instrument transformers the way to assess the risk of the impermissible increase of electrical energy measuring error occurrences due to the lack of conformity to the impedance parameters of secondary circuits of instrument transformers.

4.1. Current transformers

A. Effect of leads in secondary circuit

The analysis of the influence of conductors on the secondary side of the CT on the transformation accuracy of the current was conducted basing on the circuit introduced in Fig. 3a, the corresponding equivalent circuit (Fig. 3b) and the phasor diagram (Fig. 3c). The real relation between the length of currents phasors $\mathbf{I}_s$ and $\mathbf{I'}_p$ and the length of the exciting current phasor $\mathbf{I'}_\mu$ causes that the phasors $\mathbf{I}_s$ and $\mathbf{I'}_p$ are practically parallel. The errors Δi and δi of the CT correspond to the relative measures of the phasor $\mathbf{I'}_\mu$ projections on the appropriate axes of the coordinate arrangement (segments $\overline{0A}$ and $\overline{0B}$ on Fig. 3c). The relations describing the percentage value of current error without turns correction and phase displacement expressed in minutes, is given as:

$$\Delta i = -\frac{I'_\mu \sin\gamma}{I'_p}100\% \approx -\frac{I'_\mu \sin\gamma}{I_s}100\% \tag{5}$$

$$\delta i = \frac{I'_\mu \cos\gamma}{I'_p}\frac{10800}{\pi}\min \approx \frac{I'_\mu \cos\gamma}{I_s}\frac{10800}{\pi}\min \tag{6}$$

where:
$\gamma = \alpha + \beta$ (α, β - the angles given in Fig. 3c),
I'_μ – non-load current referred to the secondary winding of the CT.

When applying the relations (5) and (6), it is possible to determine the values of the angle γ and the relative value of no-load current I'_μ / I_s of the CT for the corresponding data obtained from the measuring reports of actual errors of the instrument transformer:

$$\gamma = -\mathrm{arctg}\left(\frac{108\Delta i}{\pi\delta i}\right) \tag{7}$$

$$\frac{I'_\mu}{I_s} = \frac{\pi\delta i}{10800\cos\gamma} = \frac{-\Delta i}{100\sin\gamma} \tag{8}$$

where:
$1[\Delta i] = 1\%$,
$1[\delta i] = 1$ min.

The resistance R_L corresponding to leads in secondary circuit of the CT **increases the resistive burden of instrument transformer** (the augmentation of the load for "current source") by the value $P_{add} = R_L I^2_{sn}$ (see subclause 2.1). The increase of secondary circuit power is accompanied by the augmentation of no-load current I'_μ. Thus, in order to estimate the influence of leads ($R_L \neq 0$) it is necessary to first of all determine the coefficient k of the no-load current increase. Its value, on the assumption that a relatively small change of secondary current does not cause the change of the value of the parameters R'_{Fe} and X'_μ[2], may be determined on the basis of the following relationship:

[1] When connecting each of three CT's with two conductors (a cable $6\times S_{Cu}$) is applied, the leads of a bigger cross-section must be selected. For example for the same rated output it must be approximately doubled.

[2] The assumed condition that the given parameters are constant is fulfilled quite well in the case of the resistance parameter R_{Fe}, as it can be proven that with the square dependence of the loss in the iron of the VT core on B_m there is a linear relationship of the current $I_{\mu a}$ to the voltage U_μ. Accepting the linear character of the parameter X_μ leads in turn, to over-determining of the passive component $I_{\mu r}$ of the exciting current for a VT, which, having considered the error calculation, makes it the worse, thus the "safe" case.

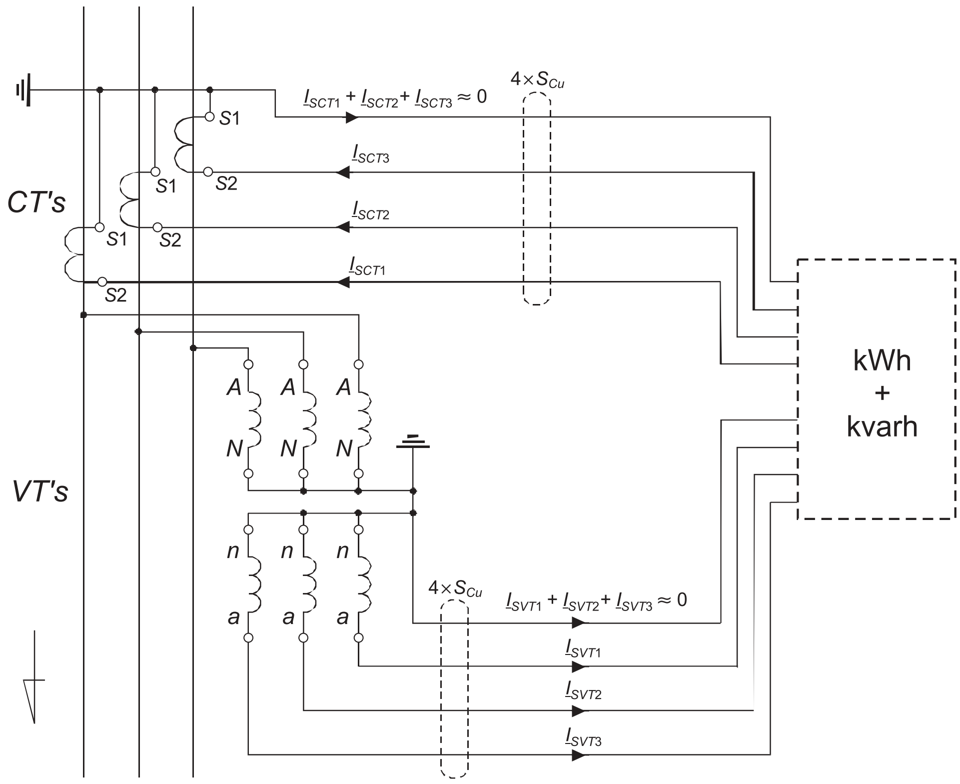

Fig. 2. A circuit for measuring of active and reactive energy in a HV substation area

$$k = \frac{I_\mu^{'*}}{I_\mu^{'}} \approx \frac{U_\mu^{'*}}{U_\mu^{'}} = \sqrt{\frac{\left(R+R_L\right)^2 + X^2}{R^2 + X^2}} \tag{9}$$

where:
$R = R_s + R_B$
$X = X_s + X_B$.

The resistance R_L of leads causes the change of the phase angle of the secondary circuit by the angle $\Delta\beta$ whose negative value may be calculated from the equation (see Fig. 3c).

$$\cos\left(\Delta\beta\right) = \frac{U_\mu^{'2} + U_\mu^{'*2} - R_L^2 I_s^2}{2U_\mu^{'} U_\mu^{'*}} = \frac{k^2+1}{2k} - \frac{1}{2k}\frac{R_L^2}{R^2+X^2} \tag{10}$$

where:
$\Delta\beta < 0$
k — the coefficient of no-load current increase given by the equation (9) ($k = f(R_L)$);
R, X — the notations as in formula (9).

The increments of the current error and phase displacement caused by the resistance of leads can be described by the relations (they correspond to the segments *AA*' and *BB*' in Fig. 3c):

$$\Delta\left(\Delta i\right) = \left(-\frac{I_\mu^{'*}\sin(\gamma+\Delta\beta)}{I_s} + \frac{I_\mu^{'}\sin\gamma}{I_s}\right)100\% = \frac{I_\mu^{'}}{I_s}\left[-k\sin\left(\gamma+\Delta\beta\right) + \sin\gamma\right]100\% \tag{11}$$

$$\Delta\left(\delta i\right) = \left(\frac{I_\mu^{'*}\cos(\gamma+\Delta\beta)}{I_s} - \frac{I_\mu^{'}\cos\gamma}{I_s}\right)\left(\frac{10800}{\pi}\right)' = \frac{I_\mu^{'}}{I_s}\left[k\cos\left(\gamma+\Delta\beta\right) - \cos\gamma\right]\left(\frac{10800}{\pi}\right)' \tag{12}$$

It is possible to prove, that the error value increases described with the relations (11) and (12) are proportional to the resistance of conductors R_L. What follows from the equivalent circuit shown in Fig. 3b and from the phasor diagram in Fig. 3c is that the equation of no-load current is described by:

$$\underline{I}_\mu^{'} = jI_s\left[\left(\frac{R+R_L}{R_{Fe}^{'}} + \frac{X}{X_\mu^{'}}\right) + j\left(\frac{X}{R_{Fe}^{'}} - \frac{R+R_L}{X_\mu^{'}}\right)\right] \tag{13}$$

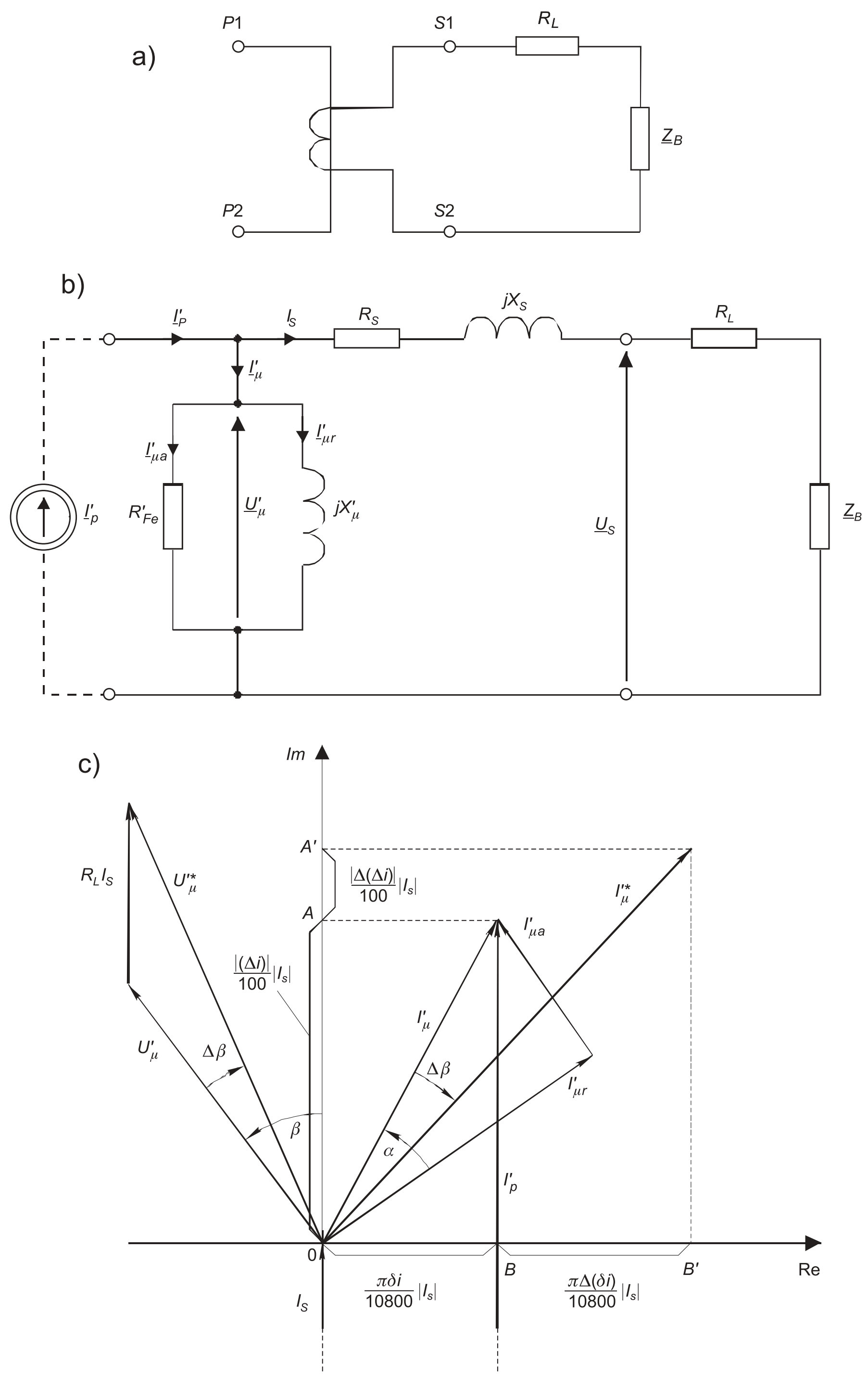

Fig. 3. A current transformer loaded with the impedance Z_B connected to the secondary terminals by means of the leads having resistance R_L: a) the scheme of connections, b) the equivalent circuit, c) the phasor diagram

where:
R, X — the notations as in the equation (9).

The current error and phase displacement of a CT, assuming that $I_s \approx I'_p$, can be determined on the basis of the following relations (Fig. 3c):

$$\Delta i = -\frac{Im\{\underline{I}'_\mu\}}{I_s}100\% = -\left(\frac{R+R_L}{R'_{Fe}} + \frac{X}{X'_\mu}\right)100\% \quad (14)$$

$$\delta i = \frac{Re\{\underline{I}'_\mu\}}{I_s}\frac{10800}{\pi}min = \left(\frac{R+R_L}{X'_\mu} - \frac{X}{R'_{Fe}}\right)\left(\frac{10800}{\pi}\right)' \quad (15)$$

The changes of current error and phase displacement caused by the resistance of leads R_L are thus:

$$\Delta(\Delta i) = \Delta i(R_L) - \Delta i(R_L = 0) = -\frac{R_L}{R'_{Fe}}100\% \quad (16)$$

$$\Delta(\delta i) = \delta i(R_L) - \delta i(R_L = 0) = \frac{R_L}{X'_\mu}\left(\frac{10800}{\pi}\right)' \quad (17)$$

What follows from the relations (16) and (17), is that both $\Delta(\Delta i)$ and $\Delta(\delta i)$ are in direct proportion to R_L.

Errors of the CT, having considered the resistance R_L, can be calculated by applying the following relations

$$(\Delta i)^* = \Delta i + \Delta(\Delta i) \quad (18)$$

$$(\delta i)^* = \delta i + \Delta(\delta i) \quad (19)$$

In order to emphasise the importance of the abovementioned problem a calculation sample was given.

Example 1

The measuring CT's with the following ratings are considered: the accuracy class 0.2, the rated output S_n = 15 VA, $\cos\beta = 0.8$. The CT's are connected by means of a four-vein copper conductor of the 4×6 mm^2 cross-section to a three-phase measuring device ($3 \times R_B$, $3 \times X_B$) of the power of each phase of S_B = 10 VA ($\cos\beta = 0.9$). The measuring device is situated in the distance of d = 300m from the instrument transformers. The errors change of the CT's should be calculated with regard to leads resistance and on the assumption that the errors without turns correction for I_s = 5A, at S_B = 10 VA and $\cos\beta = 0.9$ are: $\Delta i = -0.18\%$, $\delta i = +3.5'$. Moreover, the secondary winding resistance of the CT is known to be equal $R_s = 0.2\Omega$. The leakage reactance of secondary winding is $Xs \approx 0$. The calculations were done according to the following algorithm:

— R_B and X_B

$$R_B = (S_B / I^2_{sn})\ \cos\beta = (10 / 5^2) \cdot 0.9 = 0.36\Omega$$

$$X_B = (S_B / I^2_{sn})\ \sin\beta = (10 / 5^2) \cdot 0.436 = 0.17\Omega$$

— R_L (without the resistance of the return conductor — see Fig. 2):

$$R_L = d / (\gamma_{Cu}\, S_{Cu}) = 300 : (57 \cdot 6) = 0.88\ \Omega$$

— γ and I'_μ / I_s according to the relations (7) and (8):

$$\gamma = 60.5° \qquad I'_\mu / I_s = 2.07 \cdot 10^{-3}$$

— k according to (9):

$$k = 2.48$$

— $\Delta\beta$ according to (10):

$$\cos(\Delta\beta) = 0.986 \quad \Rightarrow \quad \Delta\beta = -9.6°$$

— the additional errors $\Delta(\Delta i)$ and $\Delta(\delta i)$ calculated from the relations (11) and (12) are:

$$\Delta(\Delta i) = -0.218\ \% \qquad \Delta(\delta i) = +7.6'$$

— the resultant errors, with additional errors ($R_L \neq 0$) taken into account are:

$$(\Delta i)^* = -0.18\% - 0.218\% \approx \mathbf{-0.40\%}$$

$$(\delta i)^* = +3.5' + 7.6' = \mathbf{+11.1'}$$

If in the abovementioned example it was assumed, that the length of leads is 400 m ($R_L = 1.17\Omega$), while the other data remain unaltered, the result of the calculations would be the following:

$$\Delta(\Delta i) = -0.218\% \cdot \frac{1.17}{0.88} = -0.29\%$$

and

$$\Delta(\delta i) = +7{,}6\,\text{min} \cdot \frac{1.17}{0.88} = +10.1'$$

as well as:

$$(\Delta i)^* = -0.18\% - 0.29\% \approx \mathbf{-0.47\%}$$

$$(\delta i)^* = +3.5' + 10.1' = \mathbf{+13.6'}$$

Note: The percentage change of measuring errors of active and reactive energy at $\cos\varphi = 0.94$, due only to error change of the CT's determined by leads, may be calculated in the following way for the former case of the aforementioned example:

$$\Delta(\delta E_{p\%}) = \Delta(\Delta i) + \frac{\pi}{108}\Delta(\delta i)\,\mathrm{tg}\varphi =$$
$$= -0.218\% + \frac{\pi}{108} \cdot 7.6 \cdot \mathrm{tg}19.9° \cong -0.14\%$$

$$\Delta(\delta E_{q\%}) = \Delta(\Delta i) - \frac{\pi}{108}\Delta(\delta i)\,\mathrm{ctg}\varphi =$$
$$= -0.218\% - \frac{\pi}{108} \cdot 7.6 \cdot \mathrm{ctg}19.9° \cong -0.83\%$$

For the leads of the length d = 400m the changes of measuring errors of active and reactive energy respectively, would amount to:

$$\Delta(\delta E_{p\%}) \cong -0.11\% \qquad \Delta(\delta E_{q\%}) \cong -1.03\%$$

As follows from the given computation examples, ignoring the influence of "appropriately" selected leads on the errors of the instrument transformers, and thus on the measuring errors of active and reactive energy, may lead to the undermining of the need to install the instrument transformers of the higher than 0.2 accuracy class in the 110 kV or higher voltage substations.

B. Effect of the burden

Basing on the results of the analysis in subclause 4.1.A, having ignored the leads resistance ($R_L \approx 0$), the change of current error and phase displacement of CT was determined after its burden had been changed, from the one within the limits of the standard [1] (i.e. $Z_B \in \leq 0.25 Z_{Bn}, Z_{Bn} \geq$ and $\cos\beta = 0.8$ ind, where $Z_{Bn} = S_n / I_{sn}^2$) to the burden of the impedance Z^*_B and the power factor $\cos\beta^*$. In real measuring setup, as a result of "overpowering" of the rated output of the CT's, and the power factor of connected to secondary terminals measuring devices approaching the value 1, the following relations occur most frequently:

$$Z_B^* < 0.25 Z_{Bn} \quad \text{and} \quad \cos\beta^* > 0.8 \tag{20}$$

With the assumptions made, the formula (9) determining the **no-load current change** coefficient is given by:

$$k = \frac{I_\mu^{'*}}{I_\mu^{'}} \approx \frac{U_\mu^{'*}}{U_\mu^{'}} = \sqrt{\frac{(R_s + Z_B^* \cos\beta^*)^2 + (X_s + Z_B^* \sin\beta^*)^2}{(R_s + 0.8 Z_B)^2 + (X_s + 0.6 Z_B)^2}} \tag{21}$$

For the change of the phase angle β of the secondary circuit of a CT an approximate calculation can be made following from the relation

$$\Delta\beta \approx \beta^* - \beta \tag{22}$$

By applying the relations (7), (8), (11), (12), (18) and (19) it is possible to calculate the changes of errors occurring due to, different from the standard, burden impedances of a CT.

In order to illustrate the way in which the abovementioned method can be applied, the calculation sample is presented below, in which the most critical case is discussed, i.e. when the burden fulfils the condition of power rating but is practically resistive.

Example 2

The measuring CT's with the following ratings are considered: the accuracy class 0.2, the rated output S_n = 15 VA, $\cos\beta = 0.8$. The CT's are connected with the measuring device of the apparent power of each phase of S_B = 15 VA ($\cos\beta^* = 1$). The CT's errors ought to be calculated under these conditions, being aware of the fact that for I_s = 5 A the current error without turns correction at S_B = 15 VA and $\cos\beta = 0.8$ is $\Delta i = -0.18\%$, and the phase displacement $\delta i = +3.5'$. Moreover, it is clear that the secondary winding resistance of the CT is $R_s = 0.2\ \Omega$. The leakage reactance of the secondary winding can be assumed to be equal zero ($Xs \approx 0$). The calculations were done according to following algorithm:

— Z_B and Z^*_B

$$Z_B = Z^*_B = (S_B / I^2_{sn}) = (15/5^2) = 0.60\ \Omega$$

— γ and I'_μ / I_s according to the relations (7) and (8):

$$\gamma = 60.5° \qquad I'_\mu / I_s = 2.07 \cdot 10^{-3}$$

— k according to (21):

$$k = 1.04$$

— $\Delta\beta$ according to (22):

$$\Delta\beta = \beta^* - \beta = \text{arctg } 0 - \text{arctg } 0.8 = -38.7°$$

— increments of errors $\Delta(\Delta i)$ and $\Delta(\delta i)$ in relation to normal conditions, calculated with the formulae (11) and (12) are:

$$\Delta(\Delta i) = +0.10\ \% \qquad \Delta(\delta i) = +3.4'$$

— errors for the burden 15 VA, $\cos\beta^* = 1$

$$(\Delta i)^* = -0.18\% + 0.10\% \approx \mathbf{-0.08\%}$$

$$(\delta i)^* = +3.5' + 3.4' = \mathbf{+6.9'}$$

4.2. Voltage transformers

A. Effect of leads in secondary circuit

The analysis of the influence of leads in the secondary circuit on the precision of voltage transformation by the VT was carried out basing on the circuit presented in Fig. 4a, and the corresponding equivalent circuit (Fig. 4b) as well as on the phasor diagram (Fig. 4c). The real relation of the length of voltages phasors $\boldsymbol{U_s}$ and $\boldsymbol{U_p'}$ to the length of $\boldsymbol{\Delta U}$, which represents the voltage decrease on the series elements of the equivalent circuit (R'_p, X'_p, R_s, X_s) causes that the phasors $\boldsymbol{U_s}$ and $\boldsymbol{U'_p}$ are practically parallel.

The additional resistance R_L represented in the secondary circuit of VT **increases their series resistance** (internal resistance of voltage "source") by the value R_L. In this case the resistance R_L influences the change in the metrological characteristics of "VT—the leads arrangement". This does not occur by the increase of the burden power S, and thus the no-load current I'_μ but as a result of the increase of the voltage drop ΔU on the series impedance of the VT. Therefore, the VT's errors dependent on no-load current: Δu_0 and δu_0, called *non-load errors*, remain constant at S = const. What is essential then is the components of the resultant errors which depend on the burden of the VT. These errors are called *loads errors*. They equal zero when the current in the secondary circuit does not flow, i.e. when $Z_B \to \infty$. They will be further marked as Δu_B i δu_B. In Fig. 4c there are the corresponding relative measures of the phasor $\boldsymbol{\Delta U}$ projections on the axes of the coordinate system (segments *A'B'* and *A"B"* in Fig. 4c).

Load errors of the VT can be calculated from the following relations (Fig. 4c):

$$\Delta u_B = -\frac{S}{U_s^2}\left(R\cos\beta + X\sin\beta\right)100\% = -\frac{R\cos\beta + X\sin\beta}{Z_B}100\% \tag{23}$$

$$\delta u_B = \frac{S}{U_s^2}\left(R\sin\beta - X\cos\beta\right)\left(\frac{10800}{\pi}\right)' =$$

$$= \frac{R\sin\beta - X\cos\beta}{Z_B}\left(\frac{10800}{\pi}\right)' \qquad (24)$$

where:
$R = R'_p + R_s$
$X = X'_p + X_s$
S — the apparent burden power of the VT.

Additional load errors caused by the resistance R_L of leads can be calculated by applying the relations below (They correspond to the segments $\overline{0A'}$ and $\overline{0B'}$ in Fig. 4c):

$$\Delta(\Delta u_B) = -\frac{S}{U_s^2} R_L \cos\beta \cdot 100\% \qquad (25)$$

$$\Delta(\delta u_B) = \frac{S}{U_s^2} R_L \sin\beta\left(\frac{10800}{\pi}\right)' \qquad (26)$$

Errors of the VT, after considering the additional errors resulting from the resistance R_L, can be calculated with the following formulae:

$$\left(\Delta u\right)^* = \Delta u + \Delta(\Delta u_B) \qquad (27)$$

$$\left(\delta u\right)^* = \delta u + \Delta(\delta u_B) \qquad (28)$$

In order to estimate, in practical terms, the VT errors changes caused by the different from zero resistance of the leads connecting their secondary terminals to measuring apparatus, the calculation sample was provided illustrating the analysis above.

Example 3

The measuring VT's with the following ratings are considered: the accuracy class 0,2, the rated output S_n = 15 VA, cos β = 0.8 and the secondary voltage U_{sn} = (100 : $\sqrt{3}$) V. The VT's are connected by means of a four-vein copper conductor of the 4×4 mm^2 cross-section to a three-phase measuring device (3×R_B, 3×X_B) of the power of each phase of S_B = 10 VA (cos β = 0.9). The measuring device is situated in the distance of d = 300m from the instrument transformers. The errors change ought to be calculated with regard to the additional errors occurring as a result of the effective resistance of leads and on the assumption that the errors without turns correction for U_s = (100 : $\sqrt{3}$) V, at S_B = 10 VA and cos β = 0.9 are: Δu = –0.15% and δu = + 2,5'. The calculations were made according to following algorithm:

— R_L (without the resistance of the return conductor— see Fig. 4) is:

$$R_L = \text{d} : (\gamma_{Cu} S_{Cu}) = 300 : (57 \cdot 4) = 1{,}32\Omega$$

— $\Delta(\Delta u_B)$ and $\Delta(\delta u_B)$ according to (25) and (26):

$$\Delta(\Delta u_B) = -\frac{10}{\left(100/\sqrt{3}\right)^2} \cdot 1.32 \cdot 0.9 \cdot 100\% = -0.36\%$$

$$\Delta(\delta u_B) = \frac{10}{\left(100/\sqrt{3}\right)^2} \cdot 1.32 \cdot \sqrt{1-0.9^2}\left(\frac{10800}{\pi}\right)' = +5.9'$$

— the errors with regard to additional errors ($R_L \neq 0$) are:

$$(\Delta u)^* = -0.15\% - 0.36\% \approx \mathbf{-0.51\%}$$

$$(\delta u)^* = +2.5' + 5.9' = \mathbf{+8.4'}$$

If it were assumed in the abovementioned example that the length of leads 400 m was (R = 1.76Ω), whereas the other data remained invariable, the result of calculations would be the following:

$$\Delta(\Delta u_B) = -\frac{10}{\left(100/\sqrt{3}\right)^2} \cdot 1.76 \cdot 0.9 \cdot 100\% = -0.48\%$$

$$\Delta(\delta u_B) = \frac{10}{\left(100/\sqrt{3}\right)^2} \cdot 1.76 \cdot \sqrt{1-0.9^2}\left(\frac{10800}{\pi}\right)' = +7.9'$$

and $$(\Delta u)^* = -0.15\% - 0.48\% \approx \mathbf{-0.63\%}$$

$$(\delta u)^* = +2.5' + 7.9' = \mathbf{+10.4'}$$

Note: The percentage change of measuring errors of active and reactive energy at cos φ = 0.94, caused only by the change of errors of the CT's dependent on leads, can be calculated for the first case of the abovementioned example in the following manner:

$$\Delta(\delta E_{p\%}) = \Delta(\Delta u_B) - \frac{\pi}{108}\Delta(\delta u_B)\,\text{tg}\varphi =$$

$$= -0.36\% - \frac{\pi}{108} \cdot 5.9 \cdot \text{tg}\,19.9^\circ \cong -0.42\%$$

$$\Delta(\delta E_{q\%}) = \Delta(\Delta u_B) + \frac{\pi}{108}\Delta(\delta u_B)\,\text{ctg}\varphi =$$

$$= -0.36\% + \frac{\pi}{108} \cdot 5.9 \cdot \text{ctg}\,19.9^\circ \cong +0.11\%$$

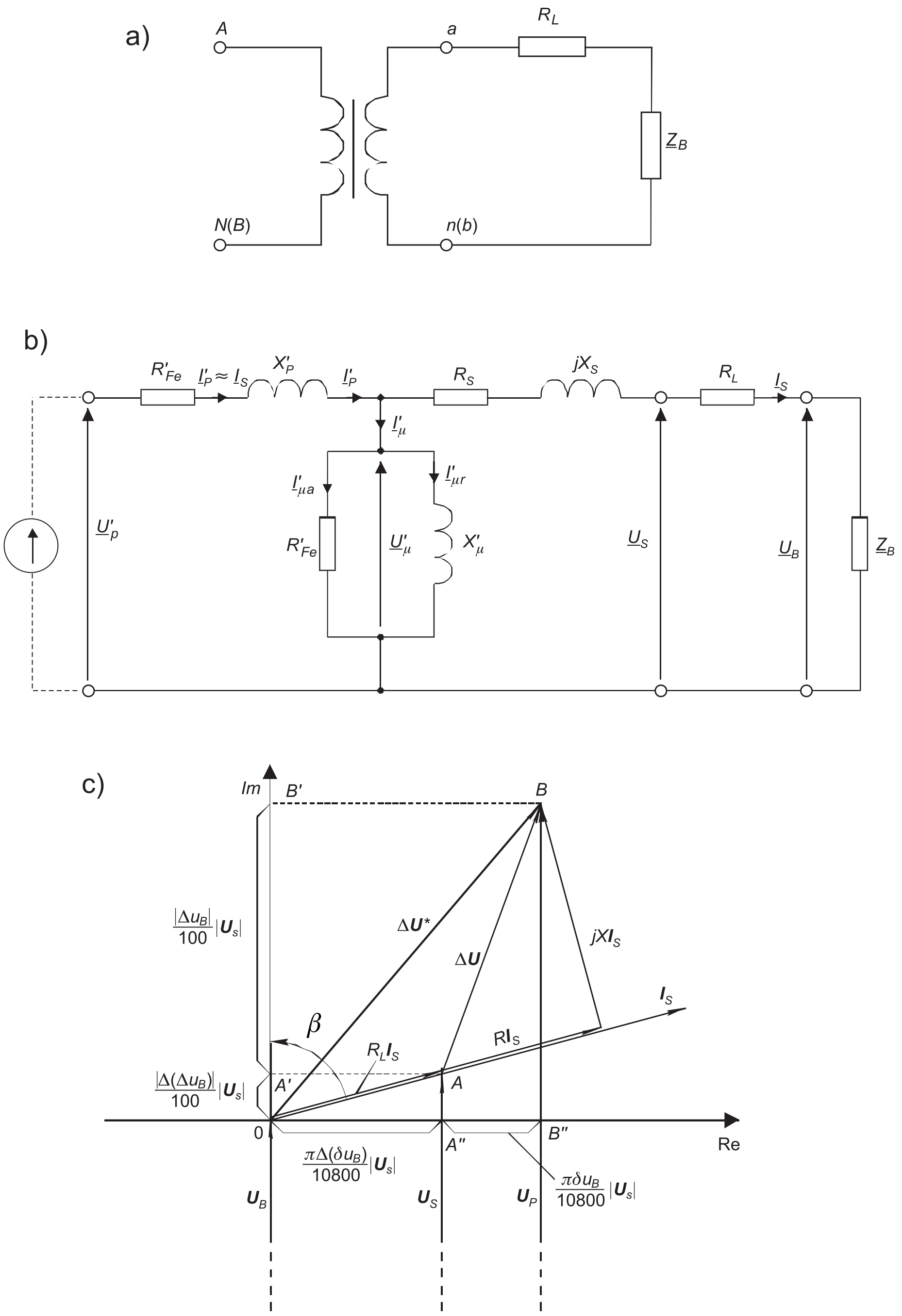

Fig. 4. A single-phase inductive voltage transformer loaded with the impedance Z_B connected to the secondary terminals by means of the leads having resistance RL: a) the scheme of connections, b) the equivalent circuit, c) the phasor diagram

For the leads of the length $l = 400$m, the increments of measuring errors of active and reactive energy respectively, would amount to

$$\Delta(\delta E_{p\%}) \cong -0.56\% \qquad \Delta(\delta E_{q\%}) \cong +0.15\%$$

B. Effect of the burden

On the basis of the results of the analysis in subclause 4.2.A having ignored the leads resistances ($R_L \approx 0 \Rightarrow \left|\overline{0A} = 0\right|$, i.e. point $A \rightarrow$ point 0 in Fig. 4c), it was possible to determine the error dependence as a function of burden, using the relations (23) and (24). Though, in order to apply this, it is necessary to know the parameters is R and X dependent on the resistance and the leakage reactance of windings ($R = R'_p + R_s$; $X = X'_p + X_s$). The values of these parameters can be calculated on the basis of VT errors measured by its manufacturer in accordance with the relevant standard [2] discussed in clause 2, for 100% and 25% of the rated output S_n. These errors are the sum of errors of the non-load state Δu_0 and δu_0 (dependent on the voltage U_s) and the load errors Δu_B and δu_B given by the equations (23) and (24):

$$\begin{cases} \Delta u(100) = \Delta u_0 + \Delta u_k - \dfrac{S_n}{U_s^2}(R\cos\beta + X\sin\beta)\ \cdot 100\% \\ \Delta u(25) = \Delta u_0 + \Delta u_k - \dfrac{S_n}{4U_s^2}(R\cos\beta + X\sin\beta)\ \cdot 100\% \end{cases} \tag{29}$$

$$\begin{cases} \delta u(100) = \delta u_0 + \dfrac{S_n}{U_s^2}(R\sin\beta - X\cos\beta)\left(\dfrac{10800}{\pi}\right)' \\ \delta u(25) = \delta u_0 + \dfrac{S_n}{4U_s^2}(R\sin\beta - X\cos\beta)\left(\dfrac{10800}{\pi}\right)' \end{cases} \tag{30}$$

where:

Δu_k — the additional value of voltage error resulting from the turns correction.

Subtracting the equations (29) and (30) the following system of equations gives:

$$\begin{cases} R\cos\beta + X\sin\beta = \dfrac{U_s^2}{75\,S_n}\left[\Delta u(25) - \Delta u(100)\right] \\ R\sin\beta - X\cos\beta = \dfrac{\pi U_s^2}{8100\,S_n}\left[\delta u(100) - \delta u(25)\right] \end{cases} \tag{31}$$

After solving the system of equations (31) the values obtained were R and X, from which the load-errors given by the equations (23) and (24) were derived, for rated and real operating conditions. Subsequently, the values of non-load errors independent from the burden, including the voltage error with turns correction should be derived from the equations (29) and (30), for the given voltage U_s:

$$\Delta u_0 + \Delta u_k = \Delta u\,(100) + \frac{S}{U_s^2}\left(R\cos\beta + X\sin\beta\right)\cdot 100\% =$$

$$= \Delta u(25) + \frac{S}{4\ U_s^2}\left(R\cos\beta + X\sin\beta\right)\cdot 100\% \tag{32}$$

$$\delta u_0 = \delta u(100) - \frac{S_n}{U_s^2}(R\sin\beta - X\cos\beta)\left(\frac{10800}{\pi}\right)' =$$

$$= \delta u(25) - \frac{S_n}{4U_s^2}(R\sin\beta - X\cos\beta)\left(\frac{10800}{\pi}\right)' \tag{33}$$

On this basis, applying the relations (23) and (24), it is possible to find the load-errors $(\Delta u_B)^*$ and $(\delta u_B)^*$ of the VT loaded with the power S^*, with the power factor $\cos\beta^*$, outside the limits defined by the standard [2], then, to calculate its voltage error and phase displacement:

$$\begin{cases} (\Delta u)^* = \Delta u_0 + \Delta u_k + (\Delta u_B)^* \\ (\delta u)^* = \delta u_0 + (\delta u_B)^* \end{cases} \tag{34}$$

A calculation sample was provided to illustrate the abovementioned analysis.

Example 4

The measuring VT with the following ratings is considered: the accuracy class 0.5, the rated output S_n = 30 VA, $\cos\beta$ = 0.8 and the secondary voltage U_{sn} = (100 : $\sqrt{3}$) V. The errors of the VT loaded with the power S^* = 5VA at $\cos\beta^*$ = 1 should be calculated for $U_s = U_{sn}$, knowing that its errors measured for U_s = (100 : $\sqrt{3}$) V, at $S = S_n$ = 30 VA and $\cos\beta$ = 0.8 are equal: Δu (100) = –0.35%, δu(100) = +12', where for $S = 0.25S_n$ = 7.5 VA – Δu(25) = +0.22% and δu(100) = +3.5'. The calculations were made according to the following algorithm:

— R and X according to (31) are:

$$\begin{cases} 0.8R + 0.6X = 0.844 \\ 0.6R - 0.8X = 0.366 \end{cases} \Rightarrow \quad R \cong 0.90\Omega; \quad X \cong 0.21\ \Omega$$

— $\Delta u_0 + \Delta u_k$ and δu_0 according to (32) and (33) are:

$$\Delta u_0 + \Delta u_k = -0.35\% + \frac{30}{(100/\sqrt{3})^2}\cdot$$

$$\cdot\left(0.90\cdot 0.8 + 0.21\cdot 0.6\right)\cdot 100\% \approx +0.41\%$$

$$\delta u_0 = 12 - \frac{30}{(100/\sqrt{3})^2}(0.9\cdot 0.6 - 0.21\cdot 0.8)\left(\frac{10800}{\pi}\right)' = +0.5'$$

— $(\Delta u_B)^*$ and $(\delta u_B)^*$ according to (23) and (24) are:

$$(\Delta u_B)^* = -\frac{5}{(100/\sqrt{3})^2}\left(0.9\cdot 1 + 0.21\cdot 0\right)100\% = -0.135\%$$

$$(\delta u_B)^* = \frac{5}{(100/\sqrt{3})^2}\left(0.9\cdot 0 - 0.21\cdot 1\right)\left(\frac{10800}{\pi}\right)' = -1.1'$$

— $(\Delta u)^*$ and $(\delta u)^*$ according to (34)

$$(\Delta u)^* = +0.41\% + (-0.135\%) = +0.275\%$$

and $$(\delta u)^* = +0.5 + (-1.1') = -0.6'$$

5. CONCLUSIONS

Even if the analysis presented in the article has spelled out to the reader the problem of the effect of inductive instrument transformers on measuring accuracy of electrical energy (power) to a limited extent, the author will acknowledge that the declared objective has been accomplished. The problems itself is seemingly simple, especially that there is a preconception among the experts who claim that by applying the instrument transformers of a sufficiently high class (0,2 or 0,1), the high accuracy of electrical energy (power) measurement is ensured. However, numerous expert evaluations and reports carried out by the author during his years of work at Technical University of Lodz (Poland), reviewed the real measuring circuits of electrical energy in substations of high voltage (110 kV and 220 kV) as well as the circuits for the power transformers in Poland. Moreover, computational examples presented in the article clearly demonstrate that underestimating the impact of leads, or the inappropriate burden values for the ratings of the instrument transformers can lead to serious and thus unacceptable measuring errors.

In the setup of electrical energy (power) measurement with the instrument transformers special attention should be paid to the following:

- The interdependence of phase displacements of instrument transformers, with the worst case – as in the relations (24) and (25) occurring, when these errors have different signs ($\delta i \cdot \delta u < 0$). What follows from the technological and constructional characteristics of HV inductive instrument transformers, is that ordinary phase displacements of CT's are positive, while for VT's – negative.
- The assessment of the instrument transformers errors in real operating conditions, taking into account the resistance of conductors, is most often carried out without considering the return conductor (Fig. 2) or the burden, due to the input circuits of the measuring devices.

In order to analyse the abovementioned issues correctly one should have at their disposal the instrument transformers errors characteristics in accordance with the standards [1, 2]. The characteristics should be provided by the manufacturer. The calculation the errors caused by instrument transformers in setup for measurement of electrical energies (power) makes it possible to:

- Select appropriately the instrument transformers to be installed in HV substations areas, or to be used in testing laboratories for the verification of e.g. transformers, which ensures the minimization of errors resulting from different values of phase displacements of CT's and VT's. The author of this article finds it is recommendable to arrange with the producer when ordering instrument transformers that, in specific conditions $\delta i \approx \delta u$.
- Make such a choice (correction) of the actual burden of already installed instrument transformers, so that with the requirements of relevant standards [1,2] fulfilled, it would be possible to minimise the measuring errors of energy (power).

APPENDIX A

Applying the notations as in Fig.1, the relation describing the active energy taken by the loads of a single-phase line of the power factor $\cos\varphi$ is given by:

$$E_p = U_p I_p \cos\varphi \cdot \Delta t \qquad (1A)$$

The active energy of the power networks load measured by watt-hour meter *WhM* (Fig. 1) corresponds to the formula which includes the phase displacement of instrument transformers (Fig. 1b):

$$E_p^{'} = K_{Un} K_{In} U_s I_s \cos\left(\varphi + \delta u - \delta i\right)\Delta t \qquad (2A)$$

where:

K_{Un}, K_{In} — the transformation ratio of VT and CT respectively,

δu, δi — phase displacement of a VT and a CT respectively.

Having considered the relations (1) and (2), the results of which are:

$$K_{Un} U_s = U_p \left(1 + \frac{\Delta u}{100}\right) \qquad (3A)$$

$$K_{In} I_s = I_p \left(1 + \frac{\Delta i}{100}\right) \qquad (4A)$$

the equation (2A) is given by:

$$E_p^{'} = U_p I_p \left(1 + \frac{\Delta u}{100}\right)\left(1 + \frac{\Delta i}{100}\right)\cos(\varphi + \delta u - \delta i) \qquad (5A)$$

Taking into account the relatively small values of current and voltage errors (see tables 1 and 2), it is possible to assume, that:

$$\frac{\Delta u}{100}\,\frac{\Delta i}{100} \approx 0$$

The relationship (5A) could be written as:

$$E_p^{'} \approx U_p I_p \left(1 + \frac{\Delta u}{100} + \frac{\Delta i}{100}\right)\cos(\varphi + \delta u - \delta i) \qquad (6A)$$

The percentage measuring error of active energy is described by the equation:

$$\delta E_{p\%} = \frac{E_p^{'} - E_p}{E_p}\,100\% =$$

$$= \left[\frac{\left(1 + \frac{\Delta u}{100} + \frac{\Delta i}{100}\right)\cos(\varphi + \delta u - \delta i)}{\cos\varphi} - 1\right] 100\% \qquad (7A)$$

from which the following formula results:

$$\delta E_{p\%} = (100 + \Delta u + \Delta i)\left[\cos(\delta u - \delta i) - \mathrm{tg}\varphi\,\sin(\delta u - \delta i)\right] - 100 \qquad (8A)$$

Having considered the phase displacement of instrument transformers reaching the maximum value of approximately several dozens of minutes, it was possible to come up with the following simplification:

$$\cos(\delta u - \delta i) \approx 1 \text{ and } \sin(\delta u - \delta i) \approx \frac{\pi}{10800}(\delta u - \delta i)$$

In the face of this, with a minor error, following the transformations the formula (8A) is possible to be given by the following simplified form:

$$\delta E_{p\%} \approx \Delta u + \Delta i + \frac{\pi}{108}(\delta i - \delta u)\, tg\varphi \qquad (9A)$$

where:
Δu and Δi are expressed in percent, while δu and δi – in minutes.

When measuring reactive energy, the formula (9A) has to be transformed with regard to the fact that φ should to be replaced with the angle ($\varphi - \pi/2$). In this case the following formula will be obtained

$$\delta E_{q\%} \approx \Delta u + \Delta i + \frac{\pi}{108}(\delta u - \delta i)\, \mathrm{ctg}\varphi \qquad (10A)$$

APPENDIX B: List of symbols

E_p, E_q — active, reactive energy to be measured (Wh, varh)
I'_μ — no-load current of a CT referred to the secondary winding
I'_p — primary current of a CT referred to the secondary winding
I_p, I_s — primary, secondary current of a CT
k — coefficient of increase of the no-load current of a CT caused by the resistance R_L
K_{In}, K_{Un} — nominal transformation ratio of a CT/VT
R, X — total resistance, reactance of the secondary circuit of a CT/VT
R_B, X_B — resistance, reactance of the burden of a CT/VT
R'_{Fe}, X'_μ — loss resistance, shunt reactance of the equivalent circuit of a CT/VT, referred to the secondary winding
R_L — total resistance of leads in the secondary circuit of a CT/VT
R_s, X_s — resistance, reactance of the secondary winding of a CT/VT
S — apparent burden power of a CT/VT (VA)
S_n — rated output of a CT/VT (VA)
U'_p — primary voltage of VT referred to the secondary winding
U_p, U_s — primary, secondary voltage of a VT
β — phase angle of the burden of a CT/VT
δi, δu — phase displacement (angle error) of a CT, VT (minutes)
$\delta E_{p\%}$ — percentage value of the measurement error of active energy
$\delta E_{q\%}$ — percentage value of the measurement error of reactive energy
φ — phase angle of a measured power network
Δi, Δu — current, voltage error of a CT, VT (%)
Δu_0, δu_0 — non-load voltage error, non-load phase displacement (angle error) of a VT (%, minutes)
Δu_B, δu_B — load voltage error, load phase displacement (angle error) of a VT (%, minutes)
Δu_k — additional voltage error of a VT resulting from the turn correction (±%)

The underlined values I, U and Z mean complex quantities of a current, voltage and impedance respectively.

REFERENCES

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2. IEC 60044-2:1997, Instrument transformers – Part 2: Inductive voltage transformers.

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Wieslaw Jalmuzny graduated from the Electrical Engineering Department at the Technical University of Lodz (Poland) in 1972. In 1980 he obtained a doctoral degree in the composite error measurement of current transformers in the overcurrent state. He has been working at the Technical University of Lodz ever since. He has conducted research on instrument transformers, innovating and creating software used for their design and for a few years he has been exploring electromagnetic compatibility. Wieslaw Jalmuzny, PhD has cooperated with the industry designing new instrument transformers (recently a combined transformer) also of the highest accuracy class as well as the measuring setup with instrument transformers. He is the author of the expert reports and opinions concerning the energy measurement error in high voltage power stations and the energy loss in power transformers manufactured in Poland.

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