A METHOD FOR FIELD VERIFICATION OF THE PRECISION CLASS OF INDUCTIVE VOLTAGE TRANSFORMERS

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Abstract

It is shown here that the precision class of an IVT – Inductive Voltage Transformer – can be verified in the field, using the results obtained in the usual tests of no-load loss and current, short circuit and winding ohmic resistantes, performed with common meters. A graphic diagram – the Möllinger & Gewecke diagram – is employed together with the results of an accuracy test previously carried out in order to determine the exact value of the winding turns relation and of the primary winding dispersion reactance. These values are used to calculate phase and magnitude errors, that must obey standards and must lie between definite limits, defined by the precision class of the instrument. Some commercial IVT's were tested in order to check the validation of the procedure. The errors were compared with the ones obtained with the Shering-Alberti method (CA bridge and comparison with standard IVT).

1. General

The Inductive Voltage Transformer - IVT presents divergences in the voltages and currents of the primary and secondary windings not only in the magnitude but also in the phases, errors that change with the load conditions. The current formulae (see 2) require the values of the primary dispersion reactance calculated separately and also of the exact winding turns relation. The dificulty of this knowledge probably explains the scarce use of the analytical method in the verification of an IVT's precision class, laboratories prefer comparative methods, which employ expensive standard AC bridges.

The objective of this work is to show the possibility of verifying, in the field, the accuracy of an IVT, from the commercial type, throughout short circuit and no-load tests, performed with usual instruments. It is avoided, this way, the transportation to a laboratory for the accuracy verification, a process that, in general, is expensive and troublesome. A graphical method, known as the Möllinger & Gewecke[1,2] (M&G) diagram allows the determination of the separate primary winding reactance, and also of the compensation adopted in the winding turns relation. With these values it is possible to calculate the errors and to verify the precicion class of the transformer.

Today many electromechanical measurement devices are being replaced by new digital ones, more modern and accurate. The former devices represent a sensible burden connected to the secondary, and the IVT is compensated for values of 12.5 to 400 VA, in order to adequate to the Standards. Changing the meter by a newer digital device, on the other hand, characterize a condition of almost open circuit (aprox 2 VA), causing an "overvoltage" corresponding to the previous compensation of the IVT, which could work in sistematic error, favouring the electric energy supplier.

As this study was developed specifically for Inductive Voltage Transformers, it is valid only for transformers with rated primary voltages up to 34.5 kV (phase-phase) and up to 34.5/V3 (phase-neutral)[2].

2. Errors in IVT's

According to the standards, the precision classes of IVT's define limits to the errors of magnitude and of phase, and a ratio correction factor. The classes are: 0.3, 0.6 and 1.2, which correspond to maximum errors of 0.3%, 0.6% and 1.2% of the rated secondary vontage. An IVT is considered to be in good condition when the point determined by the magnitude error (ε_p) or by the ratio correction factor (FCR_p) and by the phase angle (γ) is inside an exactitude paralelogram. They are tested first with open secondary terminals (no-load), and then with standard loads conected to the secondary, in different voltage contitions, p.ex., 90%, 100% e 110% of the rated voltage. The precision class is indicated[2] followed by the greatest rated load. For example, an IVT with precision class 0,6P75, shall be understood as presenting maximum error of 0,6%, for loads varying from zero to the rated one, 75 VA.

The magnitude error is ε_p, defined by :

$$\varepsilon_p\,\% = [(K_p.U_2 - |U_1|)/|U_1|].100\,\% \qquad (1)$$

where $K_p = U_{1N} / U_{2N}$ is the relation of the rated voltages, and U_1 and U_2 are actual winding voltages. Since it is always possible to measure U_2 with a callibrated instrument, it can be considered as the real value or exact value of the secondary voltage. So, defining the actual voltages relation as $K_r = U_1/U_2$, it is possible to write

$$\varepsilon_p\,\% = [(K_p / K_r) - 1]\,.100\,\% \qquad (2)$$

Also, defining the relation correction factor as $FCR_p = K_r/K_p$,one can obtain

$$\varepsilon_p\,\% = 100 - FCR_p\,\% \qquad (3)$$

Equations: The equivalent "T" model is used in order to calculate the magnitude and phase errors. The transformer phasor diagram, referenced to the primary side is shown in figure 1, where

I_1 and I_2 are the primary and secondary currents;
$I_o = I_p + j\,I_\mu$ = no load (excitation) current;
K_e = winding turns ratio = N_1 / N_2
r_1 and r_2 are the winding ohmic resistances;
x_1 and x_2 are the winding dispersion reactances.

The angle between the voltages $-K_eU_2$ and

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U_1 is γ, positive if $-K_eU_2$ is leading. The magnitude error ε_p is positive in the case that the actual secondary voltage U_2 is greater than its corresponding rated value U_{2N} ,when the voltage in the primary is the rated one, or, the magnitude error is positive if the nominal turns ratio is greater than the real one.

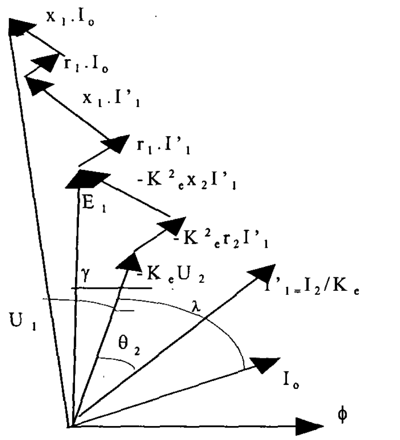

Figure 1 – Phasor Diagram referenced to the Primary Side of the Transformer

Defining

$R_p = r_1 + K_e^{\,2}.r_2$ and $X_p = x_1 + K_e^{\,2}.x_2$ (4)

the primary voltage can be written as

$U_1 = - K_e.U_2 + (R_p + j\,X_p\,).I'_1 + (r_1 + jx_1).I_o$ (5)

λ is the angle between the no-load current and the voltage $-U_2$, $\cos\theta_2$ is the power factor of the load. The projections of U_1 in the line of K_eU_2 are:

$U_1\cos\gamma = K_eU_2 + I'_1(R_p\cos\theta_2 + X_p\text{sen}\,\theta_2) + I_o\,(r_1\cos\lambda + x_1\,\text{sen}\lambda)$ (6)

$U_1\text{sen}\,\gamma = I'_1(R_p\text{sen}\,\theta_2 - X_p\cos\theta_2) + I_o\,(r_1\,\text{sen}\,\lambda - x_1\cos\lambda)$ (7)

And from equation (5),

$U_1 / U_2 = K_r = K_e +$
$[I'_1\,(R_p\cos\theta_2+X_p\text{sen}\,\theta_2) + I_o(r_1\cos\lambda+ x_1\text{sen}\,\lambda)]/U_2$ (8)

$\cos\phi$ is the core power factor, $\phi=\cos^{-1}(I_p / I_o)$,
γ is small, so $\cos\gamma\sim1$, and λ is near ϕ, and

$I_o\cos\lambda = I_o\cos\phi = I_p$; $I_o\text{sen}\lambda = I_o\text{sen}\phi = I_\mu$ (9)

From equation (8) the actual relation K_r is

$K_r = K_e + [I'_1(R_p\cos\theta_2+ X_p\text{sen}\,\theta_2)+(r_1\,I_p + x_1\,I_\mu)]/ U_2$ (10)

dividing (7) by (6), taking the approximation $\lambda\sim\tan\lambda$, for a small λ, and neglecting all the voltages in the denominator comparing to K_eU_2 , the phase error γ is:

$\gamma = [I'_1\,(R_p\text{sen}\theta_2 - X_p\cos\theta_2\,)+ (r_1\,I_\mu - x_1\,I_p)] / K_eU_2$ (11)

The phase and magnitude errors are caused by two voltage drops: the first one is due to the no-load current that flows only in the primary winding; and the second one is due to the load current that flows in both windings, depending on the load power factor.

3. Möllinger & Gewecke Diagram

The Möllinger & Gewecke diagram allows two applications: either from the IVT errors- obtained from an accuracy test - the values of the primary dispersion reactance and of the compensation can be calculated, or, from the results of short circuit and open circuit tests, the magnitude and phase errors can be determined for any load. In per unit values:

$U_1/U_2= K_e\,[1+ (R_s+jX_s)I_2\,/U_2 + (r_1+jx_1)I_o/K_e.U_2\,]$ (12)

where

$R_s= r_1 / K_e^{\,2} + r_2$ and $X_s = x_1 / K_e^{\,2} + x_2$ (13)

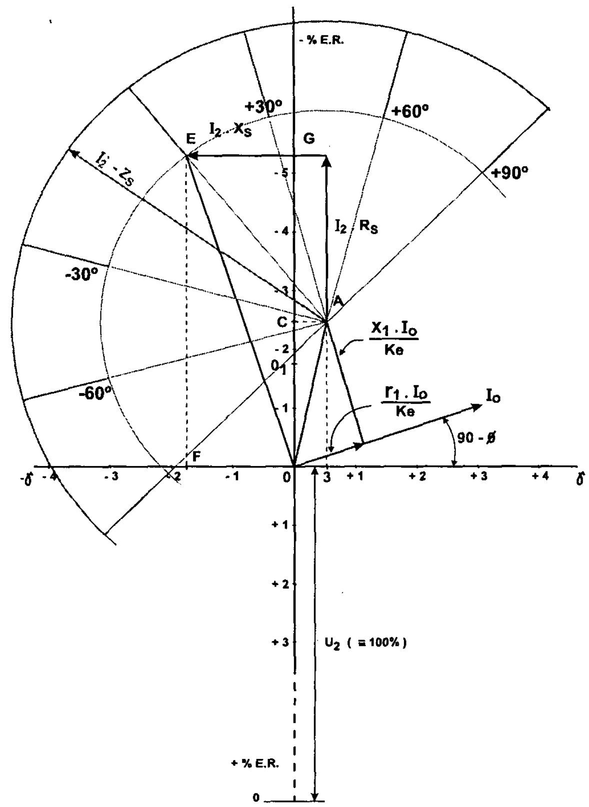

DIAGRAMA DE MÖLLINGER & GEWECKE

Figure 2

R_s, X_s ,r_1 and an estimation of the part of X_s that corresponds to x_1, make possible the drawing of the two axis as shown in figure 2. The horizontal one has the direction of the common flux and the vertical one has the direction of the induced voltage in the secondary. As the voltage drops due to the winding resistances and dispersion reactances are small, this direction can be admitted as the direction of the voltage U_2 at the terminals of the secondary. The values of I_μ ,I_p e I_o and $\cos\phi$ are accessed by the tests of magnetising current and no-load losses. It is possible to draw the phasor of I_o in a direction of the angle (90 - ϕ) from the direction of the flux phasor and, at this line, to mark $r_1\,.\,I_o / K_e$. Perpendicularly to the magnetising current direction it is marked x_1I_o / K_e which defines the point "A". U_2 is supposed constant and these two quantities are in per unit of U_2. The relation error is in the vertical axis, and in the horizontal one, the phase error. From A the per unit relation error is OC and the phase error is OB, in the no-load loss condition. Since the magnetic flux do not depends on the load current, OA continues to represent the voltage drop due to the magnetising current even when load is applied to the transformer.

For a resistive load the secondary current causes the voltage drop AD which is paralell to the voltages axis, equal to I_2R_s. From this point DE is marked representing I_2X_s completing the voltage drop due to the load. The errors of the IVT are OF – phase error, and OG – relation error. The segment AE represents I_2Z_s . The semicircle with this radius and the center A is the geometric place of point E to all values of this load power factors. Another load requires another semicicle, centered in A and with radius I'_2Z_s, where I'_2 is the new load current. It is assumed that there is no compensation, or $K_e = K_p$. If it is not the case, there is a correction in the number of windings, the relation error measurement must be taken from the second origin O_1 - figure 2,

$$OO_1 = (K_p/K_e - 1).100\ [\%] \quad (14)$$

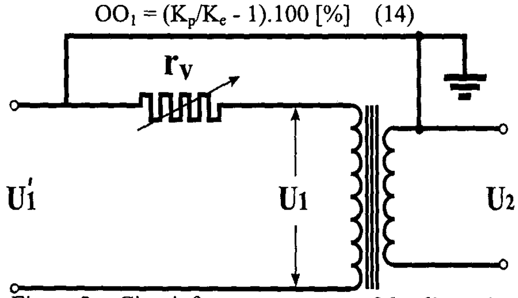

Figure 3 - Circuit for measurement of the dispersion

It is possible to apply the diagram reversely: from the results of an accuracy test to determine the the magnitude of x_1. A series variable resistor (r_v) is connected to the IVT primary, figure 3. When r_v=0 and the secondary is open, for rated primary voltage, the phase and relation errors are measured against a standard transformer, for example. These values determine the point "A_1", figure 4.

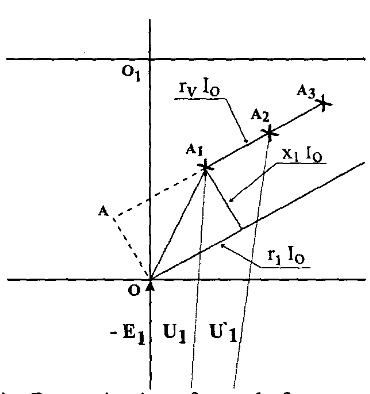

Figure 4 – Determination of x_1 and of compensation

The value of the resistor is modified and the magnetising current is maintained constant by small variations of the applied voltage. To each value of the resistor, the relation and phase errors are measured and plotted, figure 4. The segments AA_n lengths are proportional to the total primary circuit resistance, AA_1 is proporcional to r_1, AA_2 to (r_1+r_v) which allows to mark the point A. "r_v" can be varied from zero to two or three times the value of the resistance of the primary winding. Once this point is established, a perpendicular is traced from this point to "O" in the vertical axis, defining both the regulation and the primary dispersion reactance x_1.

4.Methodology

An accuracy test is previously carried out in order to determine the exact value of the winding turns relation and of the primary winding dispersion reactance. The test can be performed in the laboratory by a comparison with a standard voltage transformer, for example, and the Schering-Alberti bridge. The errors are measured with a known resistor, connected in series to the primary winding. Transf1, a program written in "C", uses as data the relation and phase errors with no-load and with the series resistor; K_e; the magnetisation current; the rated secondary voltage; the resistances of the primary winding and of the variable resistor. The output is the value of the compensation in the number of windings and the separate values of the dispersion reactances values.

IVT's field tests: The resistances of the primary and of the secondary windings are measured with the precision of common meters, generally in the range of 1%. Normally, the primary winding presents a relatively high and easily measurable resistance; for the secondary the value is in the range of miliohms, and the Kelvin bridge is used. In sequence the magnetisation and short circuit tests are performed[3]. For program Transf2 the input data are the nominal relation of the windings; the magnetisation current; the winding resistances; the rated voltages; the results of the short circuit test; the results of the magnetization and no-load losses; VA load value and power factor. The output are the phase and relation errors to no-load and load conditions.

5. Test Results

Four different voltage transformers, with plate characteristics presented in table 1, were tested in the Serviço Técnico de Metrologia Elétrica of IEE/USP. The transformers were tested in order to determine the model parameters, no-load test made by the low voltage winding, short circuit test by the high voltage winding, the results are in table 2. The results of the accuracy tests are in table 3, and also the results obtained by the program transf1, which calculates the regulation and the primary winding dispersion reactance. The results of the accuracy tests carried out by the comparative method against a standard voltage transformer of the class 0,005% using AC bridge (Schering-Alberti method) are presented in table 4. The equipment employed was the AC bridge

TETTEX type 2711/22 for comparison with the standard IVT, and the algebraic method[3], in order to determine the correction factor for relation and phase angle of the load. The voltage at the secondary was kept in 100% of the rated value.

Transformer number	Insulation	Rated Primary Voltage (kV)	Rated Second Voltage (V)	Frequency (Hz)	Thermal Rated kVA	Accuracy Class
1	epoxi	14.400	120	60	1400	0,3WXYZ-1,2ZZZ
2	epoxi	4.600	115	60	500	0,3P25
3	epoxi	1.200	200	60	400	0,2P12,5
4	air	600	100	60	400	0,2P12,5

Table 1 – Plate Characteristics of the IVT's

Transfr. Number	Winding Resistances		No-load tests - secondary			Short circuit tests - primary	
	Prim.(Ω)	Sec(mΩ)	Voltage (V)	Curr.(mA)	Power(W)	Voltage (V)	Curr.(mA)
1	1200	96,37	120	357,5	19,52	120, ,75	27,9
2	417,5	0,343	115	462,4	25,4	152	108,8
3	28,4	611	200	167,5	15,7	21,84	33
4	19,6	0,409	100	44,05	3,11	22,62	597

Table 2 – No-load and short circuit tests

Transfr. Number	Accuracy test., without r_v		Accuracy test., with r_v			Calculated values	
	error ε %	γ[min/centirad]	error ε %	γ[min/centirad]	r_v (Ω)	regulation(%)	x_1 (Ω)
1	0,23	0,6 /0,0175	0,21	2,5 /0,0727	3500	0,27	400
2	0,28	1,4 /0,0407	0,23	4,4 / 0,128	417,5	0,41	348
3	0,07	0,86 /0,025	0,04	2,86 /0,083	30	0,1562	27,9
4	-0,89	0,6 /0,0175	-0,90	0,99/,0288	20	-0,887	7,77

Table 3 – Results of the accuracy tests and model

Transfr Number	No-load ε(%)/γ(min)			12,5 VA ε(%)/γ(min)			25 VA ε(%)/γ(min)		
	AC bridge	proposed	diference	AC bridge	proposed	diference	AC bridge	proposed	diference
1	0,23/0,6	0,23/0,2	0,0/0,4	0,21/1,1	0,21/0,7	0,0/0,4	0,18/0,4	0,18/0,0	0,0/0,4
2	0,28/1,4	0,25/1,2	0,03/0,4	0,22/2,9	0,19/2,9	0,03/0,0	0,13/1,1	0,09/1,2	0,04/0,1
3	,07/0,86	0,08/1,2	,01/0,34	0,03/2,1	0,04/2,6	0,01/0,5			
4	-,89/0,6	-,90/0,4	0,01/0,2	-,95/4,3	-,97/4,2	0,02/0,1			

Table 4 – Comparison between errors obtained by AC bridge and by the proposed method

Table 4 presents a comparison between the errors of the four IVT's tested caculated by the proposed method and the values obtained with the AC bridge (Schering-Alberti method). The difference is less than 0,05 % for the ratio error and less than 0,5 minute for the phase error. These values, 0,05% for the ratio error and 0,5 minute for the phase error, are the margin errors commonly employed in standard bridges for calibration of IVT's.

Since for the accuracy class 0,3%, which is the value for energy measurements for billing purposes, the ratio error can vary ± 0,3% and the phase error can be within ± 15 minutes, it is possible to conclude that the present method is adequate to check calibrations of inductive voltage transformers.

6. Conclusions

The errors in an inductive voltage transformer are caused by the voltage drops due to the magnetisation and load currents. As the diagram M&G is once built, using the errors obtained in an accuracy test, the following up of its accuracy characterisitics during the operational life can be carried out only based on simple tests of short circuit impedance, magnetisation current, no-load losses and the measurements of the ohmic resistances of the windings. The methodology shown here is also useful either when the calibration instruments with the necessary precisions are not available, and the condition of an IVT is to be checked, or else when there are two different results for the same instrument obtained by different sources.

7. References

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