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AUTOMATED MEASUREMENT UNCERTAINTY ESTIMATION – A NEW PARADIGM OF MEASURING INSTRUMENTS AND SYSTEMS

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Abstract – Only complete expression of measurement result (measurement uncertainty included) makes possible correct interpretation of measurement results and reliable decision-making. Estimation of measurement uncertainty is complex and time consuming for some stand-alone digital instruments, and especially for indirect measurements results. It is possible to integrate calculation of measurement uncertainty into digital instrument containing processor. For direct and indirect measurements it is advantageous to develop appropriate software application for integration of digital instrument(s) and personal computer into an automated measuring system with the capability to display complete measurement result. The idea is illustrated on measurement of load-losses of power transformers using power analyzer. Software application for instrument transformers errors correction and reduction of measurement uncertainty is also briefly described.

Keywords: automated uncertainty calculation, transformer loss measurement, LabVIEW.

1. INTRODUCTION

Complete measurement result is the range of values determined with measured value (the best estimate), measurement uncertainty, and measurement unit [1, 2]. At first, complete expression of measurement result has been practiced in top-level metrology, than in accredited calibration laboratories, and recently issued standard ISO/IEC 17025 [3] demands complete expression of results in testing laboratories also. It can be predicted that the next step will be demand of complete expression of measurement results in ISO series of standards 9000 [4] for registered testing laboratories in industry – and than the complete expression of measurement results will become generally accepted.

The most significant component of total measurement uncertainty in direct measurements is type B uncertainty, derived from instrument specifications. Customers of modern digital instruments expect and demand from manufacturers that modern instruments display complete measurement result (measurement uncertainty derived from instrument specifications including). Than, if other sources of error cannot be neglected, the total uncertainty can be calculated easier.

In indirect measurements it is advantageous to develop software application for integration of digital instrument(s) and personal computer (PC) in an automated measuring system. The existing PC-automated measuring systems usually guide operator step by step through measurements or tests, control instrument(s) and monitor measurements, display measurement results graphically and numerically, simplify the analysis and storage of data, and drastically reduce time for customized test report generation [5-8].

After measurement uncertainty analysis and design of adequate algorithm have been done, it is possible to automate estimation of measurement results uncertainty also. Evaluation of uncertainty is based on mathematical model of measurement process and corresponding algorithm.

For testing engineers it is easier to develop applications for complex measuring processes using graphical programming languages (for example LabVIEW), than text-based programming languages.

2. DIRECT MEASUREMENTS

The major component of measurement uncertainty is caused by measurement bias. Corresponding uncertainty can be calculated from manufacturers specifications. Modern digital instruments have microprocessors. Consequently, manufacturers can add firmware for uncertainty calculation easily.

For example, the error limit of power analyzer's current channel, according to manufacturer manual [9] is given as:

$$G_{\mathrm{PA}}(I)_{\%} = G(I)_{\%} + \frac{I_{\mathrm{R}}}{I_{\mathrm{p}}} G(I_{\mathrm{R}})_{\%} + G(R)_{\%}\,, \qquad (1)$$

where automatically selected range is determined with the peak of measured current $I_{\mathrm{p}} \leq I_{\mathrm{R}}$, regardless on measured root mean square (r.m.s.) current I. I_{R} is the full scale peak current of the range, $G(I)_{\%}$ is specified error limit of reading (I), $G(I_{\mathrm{R}})_{\%}$ is specified error limit in percent of full scale peak current of selected range, and $G(R)_{\%}$ is error limit of the built in shunt.

Assuming uniform errors distribution, standard uncertainty is calculated as:

$$u_{\mathrm{PA}}(I)_{\%}=\frac{G_{\mathrm{PA}}(I)_{\%}}{\sqrt{3}}\,. \tag{2}$$

The standard uncertainty can be estimated more accurately, if errors distribution of batch of instruments is known.

3. INDIRECT MEASUREMENTS

For indirect measurements the application for automatic calculation of measurement uncertainty should be developed on the basis of measurement process model and uncertainty analysis. Two examples will be presented.

3.1. Load-loss measurement of power transformers

Estimation of uncertainty of measurement of load-losses is based on the expression for active power:

$$P=U\cdot I\cdot\cos\varphi\,. \tag{3}$$

Total differential of function P is:

$$\mathrm{d}P=\sum_i\left(\frac{\partial P}{\partial x_i}\right)\mathrm{d}x_i=(I\cos\varphi)\mathrm{d}U+(U\cos\varphi)\mathrm{d}I-(UI\sin\varphi)\mathrm{d}\varphi \tag{4}$$

Dependence of relative changes of quantities is derived dividing equation (4) by equation (3).

In order to emphasize the possibility of applying the equation to correct the losses when measured by means of instrument transformers we express the changes by means of differentials:

$$\frac{\Delta P}{P}=\frac{\Delta U}{U}+\frac{\Delta I}{I}-\Delta\varphi\cdot\tan\varphi\,, \tag{5}$$

for $\Delta\varphi = \delta_U - \delta_I$. The δ_U is angle error of voltage transformer, and δ_I is angle error of current transformer, expressed in radians.

Absolute (standard) measurement uncertainty is estimated on the basis of (3) and according to [1] by means of equation:

$$u(P)=\sqrt{[(I\cos\varphi)u(U)]^2+[(U\cos\varphi)u(I)]^2+[(UI\sin\varphi)u(\varphi)]^2} \tag{6}$$

and relative (standard) measurement uncertainty expressed in percent is:

$$u(P)_{\%}=\sqrt{[u(U)_{\%}]^2+[u(I)_{\%}]^2+[\tan\varphi\cdot u(\varphi)\cdot 100\%]^2}\,. \tag{7}$$

But, load-losses are declared for certain current, and the current is measured and adjusted with uncertainty. Estimation of uncertainty of measured losses should be done regarding the fact that due to error of measuring current losses are actually measured at wrongly adjusted current. Load-losses depend on current exponentially (with exponent 2), so the component of uncertainty of load losses caused by uncertainty of adjusting current is:

$$u_{\mathrm{I}}(P_{\mathrm{m}})_{\%}=2\cdot u(I)_{\%}\,, \tag{8}$$

where $u(I)_{\%}$ is uncertainty of current measurement.

The final expression for uncertainty of load-losses for associated current is:

$$u(P_{\mathrm{m}})_{\%}=\sqrt{[u(U)_{\%}]^2+5\cdot[u(I)_{\%}]^2+[u_{\delta}(P)_{\%}]^2}\,. \tag{9}$$

Uncertainty of measurement of voltage $u(U)_{\%}$ is estimated on the basis of voltage (amplitude) error limit of voltage transformer and voltage error limit of PA:

$$u(U)_{\%}=\frac{1}{\sqrt{3}}\sqrt{[G_{\mathrm{VT}\%}]^2+[G_{\mathrm{VTE}\%}]^2+[G_{\mathrm{VTM}\%}]^2+[G_{\mathrm{PA}}(U)_{\%}]^2} \tag{10}$$

$G_{\mathrm{VT}\%}$ is limit of voltage errors of voltage transformer, $G_{\mathrm{VTE}\%}$ is limit of voltage errors of standard voltage transformer, and $G_{\mathrm{VTM}\%}$ is limit of voltage errors of measuring bridge at calibration of voltage transformer.

$G_{\mathrm{PA}}(U)_{\%}$ is limit of voltage errors of PA's voltage channel. In manufacturer specifications [9] this limit is given as follows:

$$G_{\mathrm{PA}}(U)_{\%}=G(U)_{\%}+\frac{U_{\mathrm{R}}}{U_{\mathrm{p}}}G(U_{\mathrm{R}})_{\%}\,, \tag{11}$$

where automatically selected range is determined with the peak of measured voltage $U_p \leq U_R$, regardless on measured voltages U (r.m.s. = root mean square, or m.r. = mean rectified). $G(U_R)_{\%}$ is error limit in percent of full scale peak voltage of selected range, and $G(U)_{\%}$ is error limit of reading.

Current uncertainty $u(I)_{\%}$ is analogously to (10):

$$u(I)_{\%}=\frac{1}{\sqrt{3}}\sqrt{[G_{\mathrm{CT}\%}]^2+[G_{\mathrm{CTE}\%}]^2+[G_{\mathrm{CTM}\%}]^2+[G_{\mathrm{PA}}(I)_{\%}]^2}\,. \tag{12}$$

$G_{\mathrm{CT}\%}$ is limit of current errors of current transformer, $G_{\mathrm{CTE}\%}$ is limit of current errors of standard current transformer, and $G_{\mathrm{CTM}\%}$ is limit of current errors of measuring bridge at calibration of current transformer.

For the PA's current channel the error limit is given as in (1).

The component of loss uncertainty caused by uncertainty of phase angle error δ' (in angular minutes) of current and voltage channels (the third term in (7) or (9)) is:

$$u_{\delta}(P)_{\%}=0{,}0291\cdot\tan\varphi\cdot u(\delta')\,\%\,, \tag{13}$$

where φ is the phase angle between voltage and current phasors.

The loss uncertainty caused by uncertainty of phase angle errors $u(\delta')$ of current and voltage channels is calculated differently if correction is made or not, and in which way it is made.

If correction of measured losses is made for each pair of voltage and current transformer on the basis of their calibration curves, the component of power loss uncertainty can be estimated as:

$$u_{\delta}(P_{\mathrm{cor}})_{\%} = 0{,}0291 \cdot \tan\varphi \cdot u_{\mathrm{cor}}(\delta')\,\% , \qquad (14)$$

and

$$u_{\mathrm{cor}}(\delta') = \frac{\sqrt{[G'_{\mathrm{CTE}}]^2 + [G'_{\mathrm{CTM}}]^2 + [G'_{\mathrm{VTE}}]^2 + [G'_{\mathrm{VTM}}]^2 + [G'_{\mathrm{PA}}]^2}}{\sqrt{3}} , \qquad (15)$$

where G'_{CTE}, G'_{CTM}, G'_{VTE}; G'_{VTM}, and G'_{PA} are limits of phase angle errors (in angle minutes) of current standard, current bridge, voltage standard, voltage bridge, and power analyzer, respectively.

If measured losses are corrected on the basis of average difference of phase angle errors of used current and voltage transformers, component of power loss uncertainty can be estimated as:

$$u_{\bar{\delta}}(P_{\mathrm{cor}})_{\%} = 0{,}0291 \cdot \tan\varphi \cdot u_{\mathrm{cor}}\left(\bar{\delta}'\right)\% , \qquad (16)$$

and

$$u_{\mathrm{cor}}\left(\bar{\delta}'\right) = \sqrt{s_{\delta\mathrm{CT}}^2 + s_{\delta\mathrm{VT}}^2 + [u_{\mathrm{cor}}(\delta')]^2} , \qquad (17)$$

where $s_{\delta\mathrm{CT}}$ is standard deviation of phase angle errors of current transformers, and $s_{\delta\mathrm{VT}}$ is standard deviation of phase angle errors of voltage transformers at all ranges of used types of voltage and current transformers.

And finally, if measured losses are not corrected, component of power loss uncertainty can be estimated as:

$$u_{\delta}(P_{\mathrm{m}})_{\%} = 0{,}0291 \cdot \tan\varphi \cdot u(\delta'_{\Delta})\,\% , \qquad (18)$$

where uncertainty because of difference of angle error of voltage transformer and angle error of current transformer is:

$$u(\delta'_{\Delta}) = \frac{\max[(\delta'_{\mathrm{CTmax}} - \delta'_{\mathrm{VTmin}}), (\delta'_{\mathrm{CTmin}} - \delta'_{\mathrm{VTmax}})]}{\sqrt{3}} , \qquad (19)$$

because limits of phase angle errors of power analyzer's pair of current and voltage channels can be neglected.

Uncertainty of measured load-losses of a three-phase transformer is estimated on the basis of the sum of load-losses for all three phases, so that:

$$u(P_{3\mathrm{f}}) = \sqrt{[u(P_1)]^2 + [u(P_2)]^2 + [u(P_3)]^2} , \qquad (20)$$

and the measurement uncertainty expressed in percent:

$$u(P_{3\mathrm{f}})_{\%} = \frac{\sqrt{[P_1 \cdot u(P_1)_{\%}]^2 + [P_2 \cdot u(P_2)_{\%}]^2 + [P_3 \cdot u(P_3)_{\%}]^2}}{P_1 + P_2 + P_3} \qquad (21)$$

Load-losses are defined for standardized referential average winding temperature ϑ_{ref} (according to [10] 75 °C, and according to [11] 85 °C). As load-losses are measured at quite lower winding temperatures and at usually lower currents, they have to be recalculated.

The procedure is as follows (the same for one-phase and three-phase transformers):

1. Active winding resistances (R_1 i R_2) are measured at associated temperature ϑ_{R}, by means of the U-I method,
2. Load losses P_{m} are measured at current I_{m} and winding temperature ϑ_{R},
3. Measured losses are recalculated into losses at rated current I_{r}:

$$P_{\mathrm{LL}} = P_{\mathrm{m}}\left(\frac{I_{\mathrm{r}}}{I_{\mathrm{m}}}\right)^2 . \qquad (22)$$

4. I^2R losses are calculated at temperature ϑ_{R}:

$$P_{\mathrm{R}} = \left(I_{1\mathrm{r}}^2 R_1 + I_{2\mathrm{r}}^2 R_2\right). \qquad (23)$$

For three-phase transformers, the following equation is applied:

$$P_{\mathrm{R}} = 1{,}5\left(I_{1\mathrm{r}}^2 \overline{R_1} + I_{2\mathrm{r}}^2 \overline{R_2}\right), \qquad (24)$$

where $\overline{R_1}$ and $\overline{R_2}$ are average values of resistances of the first and the second windings between their phase connections (terminals).

5. Additional losses are calculated at temperature ϑ_{R} as:

$$P_{\mathrm{ad}} = P_{\mathrm{LL}} - P_{\mathrm{R}} . \qquad (25)$$

6. Finally, the load-losses at rated current are calculated for standardized referential (average) winding temperature ϑ_{ref} as:

$$P_{\mathrm{LL;ref}} = P_{\mathrm{R}}\frac{235 + \vartheta_{\mathrm{ref}}}{235 + \vartheta_{\mathrm{R}}} + P_{\mathrm{ad}}\frac{235 + \vartheta_{\mathrm{R}}}{235 + \vartheta_{\mathrm{ref}}} = P_{\mathrm{R}}\beta + P_{\mathrm{ad}}\frac{1}{\beta} = P_{\mathrm{R}}\left(\beta - \frac{1}{\beta}\right) + P_{\mathrm{m}}\left(\frac{I_{\mathrm{r}}}{I_{\mathrm{m}}}\right)^2\frac{1}{\beta} . \qquad (26)$$

On the basis of this equation, uncertainty of load-losses at standardized temperature is estimated as:

$$u(P_{\mathrm{LL;ref}}) = \sqrt{\left[\left(\beta - \frac{1}{\beta}\right)u(P_{\mathrm{R}})\right]^2 + \left\{\left[\left(1 + \frac{1}{\beta^2}\right)P_{\mathrm{R}} - \frac{1}{\beta^2}P_{\mathrm{m}}\left(\frac{I_{\mathrm{r}}}{I_{\mathrm{m}}}\right)^2\right]u(\beta)\right\}^2 + \left[\frac{1}{\beta}\left(\frac{I_{\mathrm{r}}}{I_{\mathrm{m}}}\right)^2 u(P_{\mathrm{m}})\right]^2 + \left[\frac{2}{\beta}\frac{P_{\mathrm{m}}}{I_{\mathrm{m}}}\left(\frac{I_{\mathrm{r}}}{I_{\mathrm{m}}}\right)^2 u(I_{\mathrm{m}})\right]^2} . \qquad (27)$$

Absolute uncertainty $u(P_R)$ is estimated on the basis of (23) as:

$$u(P_R) = \sqrt{\left[I_{1r}^2 u_T(R_1)\right]^2 + \left[I_{2r}^2 u_T(R_2)\right]^2}\ , \qquad (28)$$

or for three-phase transformers on the basis of (24) as:

$$u(P_R) = \sqrt{\left[1{,}5 I_{1r}^2 u_T(\overline{R_1})\right]^2 + \left[1{,}5 I_{2r}^2 u_T(\overline{R_2})\right]^2}\ , \qquad (29)$$

where $u_T(R)$ is total uncertainty of winding resistance with associated temperature. With realistic assumption that uncertainty of measurement of winding resistance is the same for all three phases, $u_T(\overline{R}) = \frac{u_T(R)}{\sqrt{3}}$.

Winding active resistance is measured by means of the U-I method, i.e. with two digital voltmeters and a measurement shunt:

$$R = \frac{U}{I} = \frac{U R_S}{U_S}\ , \qquad (30)$$

where U is dc voltage on winding which resistance is measured, R_S is resistance of shunt, and U_S is dc voltage on shunt.

Measurement uncertainty of the winding resistance R, expressed in percent, equals:

$$u_m(R)_{\%} = \sqrt{\left[u(U)_{\%}\right]^2 + \left[u(U_S)_{\%}\right]^2 + \left[u(R_S)_{\%}\right]^2}\ , \qquad (31)$$

and expressed in resistance measurement units:

$$u_m(R) = \frac{u_m(R)_{\%}}{100\%} \cdot R\ . \qquad (32)$$

Voltages are measured with digital multimeters, and measurement uncertainty is estimated on the basis of manufacturer specification ±(a% of reading + b% of full scale) as:

$$u(U)_{\%} = \frac{1}{\sqrt{3}}\left[a\% + b\% \cdot \frac{\alpha_{max}}{\alpha}\right], \qquad (33)$$

where α_{max} is the maximum reading on selected range **(**F.S.**)**, and α is reading value.

Winding resistance depends on temperature. Therefore, measured winding resistance should be associated with corresponding temperature. With the assumption that average winding temperature in oil-immersed power transformers equals average oil temperature, measured resistance is associated to average oil temperature, which is determined as arithmetic mean of oil temperatures in upper layer ϑ_t and in exit from cooler ϑ_b.

Uncertainty of determination of to-resistance associated temperature consists of uncertainty of determination of average oil temperature and the uncertainty of the very association – because winding and oil temperatures may not be the same.

As average oil temperature is:

$$\vartheta_m = \frac{\vartheta_t + \vartheta_b}{2}\ , \qquad (34)$$

the measurement uncertainty is estimated by the equation:

$$u(\vartheta_m) = \sqrt{\left[\frac{\partial \vartheta_m}{\partial \vartheta_t} u(\vartheta_t)\right]^2 + \left[\frac{\partial \vartheta_m}{\partial \vartheta_b} u(\vartheta_b)\right]^2} = \frac{1}{\sqrt{2}} u(\vartheta)\ . \qquad (35)$$

Oil measurement uncertainty $u(\vartheta)$, is estimated as:

$$u(\vartheta) = \frac{1}{\sqrt{3}} \sqrt{G_{TP}^2 + G_{DTM}^2}\ , \qquad (36)$$

where G_{TP} is errors limit of thermocouple, and G_{DTM} errors limit of digital thermometer.

The uncertainty of oil temperature associated to winding resistance, due to the possible difference between winding and oil temperatures, u_Δ, is estimated to be approximately 0,50 °C.

Therefore, total uncertainty of temperature associated to-winding resistance, $u(\vartheta_R)$, (in "cold condition") is:

$$u(\vartheta_R) = \sqrt{\left[u(\vartheta_m)\right]^2 + \left[u_\Delta\right]^2}\ . \qquad (37)$$

The uncertainty of associated temperature causes uncertainty of the resistance because, at specifying resistance value with associated temperature, the temperature is considered as referential (i.e. absolutely accurate). Therefore, uncertainty of measurement of temperature has to be transformed into the component of resistance uncertainty. This we do by the known dependence of resistance on temperature [12]:

$$\frac{R_\vartheta}{R_{\vartheta o}} = \frac{T + \vartheta}{T + \vartheta_o}\ , \qquad (38)$$

where as per [12], for copper T=235 K, and for aluminum T=225 K.

Resistance $R_{\vartheta R}$, with associated temperature ϑ_R is:

$$R_{\vartheta R} = \frac{R_{\vartheta o}}{T + \vartheta_o}\left(T + \vartheta_R\right), \qquad (39)$$

and the uncertainty of resistance with associated temperature ϑ_R is:

$$u(R_{\vartheta R}) = \frac{R_{\vartheta o}}{T + \vartheta_o} \cdot u(\vartheta_R) = \frac{R_{\vartheta R}}{T + \vartheta_R} \cdot u(\vartheta_R)\ , \qquad (40)$$

and

$$u(R_{\vartheta\mathrm{R}})_{\%} = \frac{u(\vartheta_{\mathrm{R}})}{T + \vartheta_{\mathrm{R}}} \cdot 100\ \%\,. \qquad (41)$$

Total uncertainty of winding resistance with associated temperature is:

$$u_{\mathrm{T}}(R) = \sqrt{[u_{\mathrm{m}}(R)]^2 + [u(R_{\vartheta\mathrm{R}})]^2}\,. \qquad (42)$$

At the end, since

$$\beta = \frac{235 + \vartheta_{\mathrm{ref}}}{235 + \vartheta_{\mathrm{R}}}\,, \qquad (43)$$

it follows

$$u(\beta) = \frac{235 + \vartheta_{\mathrm{ref}}}{(235 + \vartheta_{\mathrm{R}})^2}\, u(\vartheta_{\mathrm{R}})\,. \qquad (44)$$

With this all terms for (27) are calculated.

3.2. Software correction of instrument transformers errors

Relative systematic error in loss measurement by means of instrument transformers is calculated using (5), and the relative measurement uncertainty on the basis of (9).

The most significant component of total error and uncertainty of load-loss measurement is the third term in (9). This term (13) depend of measurement and data processing.

An analysis is given for four cases (Table I):

A) when correction is not made and uncertainty is estimated from limits of error of instrument transformers,

B) when correction is not made and uncertainty is estimated from calibrated limits of error of used set of instrument transformers,

C) when correction is made on the basis of average difference of (calibrated) phase angle errors of used set of instrument transformers,

D) when correction is made for each pair of voltage and current transformer on the basis of their calibration curves.

For each case the load-losses are measured by means of instrument transformers accuracy class 0,1 in the span of 0,4 to 1,2 rated current of current transformers, and of 0,4 to 1,2 rated voltage of voltage transformers at power factor 0,01 and 0,03 respectively (a, and b in the Table).

TABLE I. Errors and uncertainties of measured load-losses caused by angle errors of the set of instrument transformers of accuracy class 0,1 as the function of measurement and data processing.

Process	Errors in %	Uncertainties in %
Aa	37,8	21,8
Ab	12,6	7,3
Ba	19,2	11,6
Bb	6,4	3,9
Ca	6,1	5,5
Cb	2,0	1,8
Da	**0,0**	**3,3**
Db	**0,0**	**1,1**

4. COMPLETE MEASUREMENT RESULT

After the uncertainty is calculated for all measured quantities, the complete measurement result will be expressed as:

$$M = \{M(1 \pm u_{\%})\} \cdot [M]\,, \qquad (45)$$

where $\{M\}$ is numerical value of the best estimate of the measurand, $\{u_{\%}\}$ is numerical value of standard uncertainty expressed in percent of the measurand, and $[M]$ is measurement unit.

5. CONCLUSIONS

Expressing complete measurement results will be soon the usual way of measurement results presentation. Estimation of measurement uncertainty is complex and time consuming. Customers of modern digital instruments expect and demand from manufacturers that instruments display complete measurement result (measurement uncertainty including). For indirect measurement the application for automatic calculation of measurement uncertainty on the basis of measurement process model and uncertainty analysis should be developed. If one is developing a new automated measuring system, it is recommended to include calculation of uncertainty and presentation of complete measurement result from the start. LabVIEW simplifies development of automated measurements, but it is not easy enough for testing engineers yet.

Testing laboratory equipped with application for automated measurement and uncertainty calculation will satisfy market demand and in the same time test capacity will be increased and price of tests reduced.

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