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AUTOMATED ESTIMATION OF MEASUREMENT UNCERTAINTY

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Abstract – Only complete expression of measurement result make possible correct and reliable decision making. Complete measurement result is the range of values determined with measured value, measurement uncertainty and measurement unit. Estimation of measurement uncertainty can be complex and time consuming for some digital instruments alone, and especially for results of indirect measurements. Using software it is possible to integrate digital instruments (with communication interface) and PC in an automated measuring system. Present automated measuring systems have features of automated measurements, storage of data, and report generation. To adopt these systems for a new demand of complete measurement result presentation, the additional steps are necessary: design of measurement model, measurement uncertainty analysis, design of algorithm for uncertainty estimation, and finally, automation of uncertainty calculation and presentation of complete measurement result. The process of complete measurement automation is illustrated on testing of power losses of power transformers with power analyzer (PA).

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

1. INTRODUCTION

Complete expression of measurement result slowly but firmly steps down the metrology pyramid. At first, complete expression of measurement result has been practiced in top-level metrology, than in accredited calibration laboratories, and now the new standard [1] demands complete expression of results in testing laboratories also. With certainty it can be predicted that the next step will be demand of complete expression of measurement results in ISO series 9000 [2] for registered testing laboratories in industry – and than the complete expression of measurement results will become generally accepted way of expressing results of measurements.

With the force of market digital instruments replaced analog-measuring instruments. At this transition, as a rule, all potentiality of digital instruments are not exploited, and especially not of digital instruments with communication interface. Using software it is possible to integrate this kind of measuring instruments with PC in an automated measuring system.

The existing PC-automated measuring systems usually guide operator step by step through measurements and tests, control 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 [3-6].

After detailed analysis of measurement uncertainty and design of adequate algorithm, one is capable to automate estimation of uncertainty of measurement results also.

Evaluation of uncertainty is based on mathematical models of measurement process and corresponding algorithms. With LabVIEW (graphical programming language) it is possible to develop applications for complex measuring processes [3-6]. Testing laboratory equipped with application for automated measurement and uncertainty calculation will satisfy market demand and in the same time the capacity will be increased and price of tests reduced.

The process of complete measurement automation is illustrated on testing of power no-load losses of power transformers carried out with power analyzer (PA).

2. AUTOMATION OF MEASUREMENT

During the conventional test of no-load losses of three-phase transformer three mean rectified voltages (m.r.), three root mean square voltages (r.m.s.), three r.m.s. currents, and three active powers at rated voltage (or at more voltages) are simultaneously measured and recorded. No-load losses and currents are calculated on the basis of instrument transformers nominal ratios, instrument readings and constants (automatically if PA is used). Besides, according to [7], measured no-load losses are corrected for sinusoidal voltage. Calculated data are then manually transcribed in test report form.

Similar processes are those for tree-phase transformer load losses, no-load current harmonics and zero impedance measurements [7]. Probability of errors and mistakes is high.

New digital instruments, called power analysers, integrate functions of voltmeters, ammeters, wattmeters, and more.

With LabVIEW we have made the program "Automated Measurements with Power Analyser" (AMPA) for measurements with PC-controlled PA trough GPIB communication bus. AMPA is a program for automated measurements of tree-phase transformer load losses, no-load losses, no-load current harmonics and zero impedance – all in accordance with [7]. Program guides the user trough measurement process, allows him to configure the PA, to run measurements via an intuitive Windows interface and to process data automatically, stores the data and generates customized test reports.

3. MEASUREMENT UNCERTAINTY ANALYSIS

If no-load losses of power transformer, P, are measured with instrument transformers and power analyzer, the estimation of uncertainty should be based on model of measurement with separate voltage and current channels:

$$P = (k_{\mathrm{U}} \cdot k_{\mathrm{U,PA}}) \cdot (k_{\mathrm{I}} \cdot k_{\mathrm{I,PA}}) \cdot \alpha_{\mathrm{PA}} \,, \tag{1}$$

where k_U is nominal ratio of voltage transformer, $k_{U,PA}$ is constant of PA's voltage channel, k_I is nominal ratio of current transformer, $k_{I,PA}$ is constant of PA's current channel, and α_{PA} is reading on PA's display. The standard measurement uncertainty of measured losses will be:

$$u(P)_{\%} = \sqrt{7{,}25 \cdot [u(U)_{\%}]^2 + [u(I)_{\%}]^2 + [u_{\mathrm{F}}(P)_{\%}]^2 + [u_{\delta}(P)_{\%}]^2} \tag{2}$$

in which $u(U)_{\%}$ is voltage uncertainty expressed in percent:

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

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

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

$$G_{\mathrm{PA}}(U)_{\%} = G(U)_{\%} + \frac{U_{\mathrm{R}}}{U_{\mathrm{p}}} G(U_{\mathrm{R}})_{\%} \,, \tag{4}$$

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.

Factor 7,25=(1+e^2). The term e^2 is necessary because of the interaction between the voltage setting uncertainty with the power measurement uncertainty:

$$P = k \cdot U^{e} \quad \Rightarrow \quad u_{\mathrm{V}}(P)_{\%} = e \cdot u(U)_{\%} \,. \tag{5}$$

Similarly the component of loss uncertainty because of frequency setting uncertainty $u_F(P)_{\%}$ is necessary to account for the interaction between the frequency and power measurement:

$$u_{\mathrm{F}}(P)_{\%} = g \frac{G(F)_{\%}}{\sqrt{3}} \,, \tag{6}$$

where $G(F)_{\%}$ is limit of setting error of frequency F, and g is exponent of power dependence with frequency.

Current uncertainty $u(I)_{\%}$ is analog to (3):

$$u(I)_{\%} = \frac{1}{\sqrt{3}} \sqrt{[G_{\mathrm{CT\%}}]^2 + [G_{\mathrm{CTE\%}}]^2 + [G_{\mathrm{CTM\%}}]^2 + [G_{\mathrm{PA}}(I)_{\%}]^2} \tag{7}$$

$G_{CT\%}$ is limit of current errors of current transformer, $G_{CTE\%}$ is limit of current errors of standard current transformer, and $G_{CTM\%}$ 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:

$$G_{\mathrm{PA}}(I)_{\%} = G(I)_{\%} + \frac{I_{\mathrm{R}}}{I_{\mathrm{p}}} G(I_{\mathrm{R}})_{\%} + G(R)_{\%} \,, \tag{8}$$

where $G(R)_{\%}$ is error limit of the shunt. For estimation of current error limit the manufacturer recommends that $I_p = \sqrt{2} \cdot I$ is used. But magnetizing current is distorted and in most cases the uncertainty will be underestimated. For more realistic uncertainty estimation one should record the peak current also.

The component of loss uncertainty caused by uncertainty of phase angle error δ' (in angular minutes) of current and voltage channels is:

$$u_{\delta}(P)_{\%} = 0{,}0291 \cdot \tan\varphi \cdot u\left(\frac{\delta'}{\mathrm{min}}\right)\% \,, \tag{9}$$

where φ is the phase angle between voltage and current.

The loss uncertainty caused by uncertainty of phase angle error δ' of current and voltage channels is calculated differently if correction is made or not, and how it is made.

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

$$u_{\delta}(P_{\mathrm{kor}})_{\%} = 0{,}0291 \cdot \tan\varphi \cdot u_{\mathrm{kor}}\left(\frac{\delta'}{\mathrm{min}}\right)\% \,, \tag{10}$$

and

$$u_{\mathrm{kor}}\left(\frac{\delta'}{\mathrm{min}}\right) = \frac{\sqrt{[G'_{\mathrm{CTE}}]^2 + [G'_{\mathrm{CTM}}]^2 + [G'_{\mathrm{VTE}}]^2 + [G'_{\mathrm{VTM}}]^2 + [G'_{\mathrm{PA}}]^2}}{\sqrt{3}} \tag{11}$$

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 current and voltage transformers, component of power loss uncertainty can be estimated as:

$$u_{\bar{\delta}}(P_{\mathrm{kor}})_{\%} = 0{,}0291 \cdot \tan\varphi \cdot u_{\mathrm{kor}}\left(\frac{\bar{\delta}'}{\min}\right)\% , \qquad (12)$$

and

$$u_{\mathrm{kor}}\left(\frac{\bar{\delta}'}{\min}\right) = \sqrt{s_{\delta\mathrm{CT}}^2 + s_{\delta\mathrm{VT}}^2 + \left[u_{\mathrm{kor}}\left(\frac{\delta'}{\min}\right)\right]^2 + \left[\frac{G'_{\mathrm{PA}}}{\sqrt{3}}\right]^2} , \qquad (13)$$

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 instrument transformers.

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

$$u_{\delta}(P_{\mathrm{m}})_{\%} = 0{,}0291 \cdot \tan\varphi \cdot u\left(\frac{\delta'_{\Delta}}{\min}\right)\% , \qquad (14)$$

where

$$u\left(\frac{\delta'_{\Delta}}{\min}\right) = \frac{\max\left[(\delta'_{\mathrm{CTmax}} - \delta'_{\mathrm{VTmin}}),(\delta'_{\mathrm{CTmin}} - \delta'_{\mathrm{VTmax}})\right]}{\sqrt{3}} . \qquad (15)$$

If voltage is not sinusoidal, according to [7] correction should be made for sinusoidal voltage:

$$P_{\mathrm{SIN}} = P(1+d) = P\left(2 - \frac{U_{\mathrm{r.m.s}}}{1{,}1107 \cdot U_{\mathrm{m.r.}}}\right), \qquad (16)$$

because d is defined as:

$$d = 1 - \frac{U_{\mathrm{r.m.s}}}{1{,}1107 \cdot U_{\mathrm{m.r.}}} . \qquad (17)$$

Because r.m.s. and m.r. voltages are measured and calculated both with the same PA channel, and on the basis of the same digitalized voltage samples, the correlation is 1 (uncertainty of digital signal processor can be neglected). So

$$u(P_{\mathrm{SIN}}) = u(P) , \qquad (18)$$

and

$$u(P_{\mathrm{SIN}})_{\%} = \frac{u(P)}{P_{\mathrm{SIN}}} 100\% . \qquad (19)$$

Measurement uncertainty of no-load losses of three phase power transformer is estimated as:

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

and expressed in percent as:

$$u(P_{3\mathrm{f}})_{\%} = \frac{\sqrt{[P_{1\mathrm{SIN}} \cdot u(P_1)_{\%}]^2 + [P_{2\mathrm{SIN}} \cdot u(P_2)_{\%}]^2 + [P_{3\mathrm{SIN}} \cdot u(P_3)_{\%}]^2}}{P_{1\mathrm{SIN}} + P_{2\mathrm{SIN}} + P_{3\mathrm{SIN}}} \qquad (21)$$

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

$$M = \{M(1 \pm u_{\%})\} \cdot [M], \qquad (22)$$

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.

4. 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 measurements users should develop theirs own application for automatic calculation of measurement uncertainty on the basis of measurement process models and uncertainty analysis. If one intend to develop a new automated measuring system, it is better to include calculation of uncertainty and presentation of complete measurement result from the start. LabVIEW simplify development of automated measurements, but the present level of it's development is still not easy enough for testing personnel.

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