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Automated Measurement System of High Accuracy for Shunt Reactors

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Summary **— System for automated transformer tests (ATT) enables different measurements on power transformers, from simple to the most complex, with a high degree of automation. ATT system is now expanded with modules for measurements on shunt reactors. The measurements related to shunt reactors that are covered with the system are: measurement of losses, impedance measurement, linearity test, zero impedance measurement, winding resistance measurement, temperature rise test and measurement of mutual reactance. Besides the measurement, ATT enables data analysis and report generation, all in accordance with [1,2]. Measurement of shunt reactor losses with satisfactory accuracy is a big challenge due to power factors of the reactors as low as 0,001. A system for loss measurements with high accuracy, consisting of measuring bridge, current comparator and standard capacitor is integrated into ATT. In the paper, a comparison in terms of loss measurement accuracy on shunt reactor is given for two measurement systems – a newly integrated system for shunt reactors and standard system used for transformer measurements.**

Keywords **— Shunt reactors, automated tests, high accuracy, measurement uncertainty**

I. Introduction

Shunt reactors [3,4] are components of electrical energy system used to compensate for capacitive power generated by long overhead lines or extended cable networks. Conceptually, shunt reactors are similar to transformers, but with only one (single-phase or three-phase) winding.

Significant changes need to be made in the transformer test field to meet the requirement of shunt reactor testing – changes in test equipment, measurement system and ATT software. Although the equipment beyond measuring components is not subject of this paper, a short description of test circuit is given. The measurement system used for transformer loss measurements consists of instrument transformers and power analyzer. When choosing the components of measurement system, special attention was paid to obtain loss measurements with satisfactory accuracy, even in the case of low power factor. Measurement of shunt reactor losses represents great challenge because the power factor in these cases can be as low as 0,001. Since satisfactory accuracy can't be reached with conventional instrument transformers, a new special high accuracy system has been purchased, consisting of three sets of instruments. Each set consists of HV measuring bridge with standard capacitor and current comparator. Although the primary purpose of HV measuring bridge is measurement of capacitance and tanδ, here they are used as a part of loss measurement system. In the paper, an explanation is given why standard transformer measurement system is less appropriate for shunt reactor loss measurements. Examples of uncertainty calculations are given for different measurement systems and different power factors.

II. Measurement Accuracy and Selection of the Measurement System

It is in the interest of both the test engineer and the customer to achieve measurement result of the highest quality, i.e., a measurement result with the lowest measurement uncertainty possible. A higher quality measurement result reduces risk of accepting the product which exceeds the guaranteed values, which means reduced risk for the customer, but also reduces the risk of rejecting the product which satisfies guaranteed values, which is in the interest of the manufacturer. A higher quality measurement may also enable a more quality design of the product which leads to saving in material and finally to a less expensive product [5]. These statements hold even if the decision of accepting/rejecting the product rely only on best estimate of measurement result, without considering measurement uncertainty [6]. On the other hand, more accurate measurement equipment is more expensive, as well as its maintenance and calibration [7]. What is a satisfactory measurement uncertainty can be defined by the standard or the decision is made between the transformer manufacturer and the customer.

IEC/TS 60076-19:2013 [8] gives the procedure for the estimation of uncertainties in the measurement of the losses of power transformers and reactors. Mathematical model for the measurement of losses can be expressed as:

$$P_L = k_{CN}\frac{1}{1+\frac{\varepsilon_C}{100}}\cdot k_{VN}\frac{1}{1+\frac{\varepsilon_V}{100}}\cdot\frac{P_W}{1-(\Delta_{\varphi V}-\Delta_{\varphi C})tan\varphi} \quad (1)$$

where k_{CN} and k_{VN} denote rated ratios of current and voltage transformer respectively, ε_C and ε_V are corresponding ratio errors, P_W is the reading of power analyzer and $\Delta_{\varphi V}$ and $\Delta_{\varphi C}$ denote angle errors of instrument transformers. Since the aim of this paper is to make comparison of measured losses, without concerning contributions specific to load losses and no-load losses, a mathematical model given in equation (1) is slightly different from those given in technical specifications [6] for load losses

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and no-load losses.

Based on mathematical model (1) expression for measurement uncertainty of losses can be written as:

$$u_{\%P} = \sqrt{u_{\%C}^2 + u_{\%V}^2 + u_{\%PW}^2 + u_{\%FD}^2} \quad (2)$$

where $u_{\%C}$ is the uncertainty of current transformer ratio, $u_{\%V}$ is uncertainty of voltage transformer ratio, $u_{\%PW}$ is uncertainty of power indicated by the analyzer and $u_{\%FD}$ denotes measurement uncertainty that affects the phase displacement correction F_{D}.

In the next, a parallel comparison in terms of loss measurement uncertainty is made for two measurement systems – transformer loss measurement system and system with single-phase measuring bridge.

A. Accuracy of Transformer Loss Measurement System

Transformer loss measurement system (TLMS) of high accuracy consists of three main components, each of them contributing to loss measurement uncertainty:

- power analyzer,
- voltage transformer
- current transformer

Uncertainty component for power analyzer $u_{\%PW(AS)}$ is estimated based on limits of errors. Limits of error for power analyzers, provided by different manufacturers, differ a lot. General expression for power analyzers can be always expressed in the form:

$$G_{PA}(P)_{\%} = G_{PA}(V)_{\%} + G_{PA}(I)_{\%} + G_{PA}(cos\varphi)_{\%} \quad (3)$$

where $G_{PA}(P)_{\%}$ is limit of error for active power, $G_{PA}(V)_{\%}$ is limit of error for voltage channel, $G_{PA}(I)_{\%}$ is limit of error for current channel and $G_{PA}(cos\varphi)_{\%}$ is limit of error due to angle error. Uncertainty of power measured with power analyzer (PA), $u_{\%PW}$, is:

$$u_{\%PW(PA)} = \frac{G_{PA}(P)_{\%}}{\sqrt{3}} \quad (4)$$

Uncertainty components due to ratio errors of voltage transformer ($u_{\%V}$) and current transformer ($u_{\%C}$) are:

$$u_{\%V} = \frac{G_{\%V}}{\sqrt{3}} \quad (5)$$

$$u_{\%C} = \frac{G_{\%C}}{\sqrt{3}} \quad (6)$$

where error of limits for voltage transformer $G_{\%V}$ and current transformer $G_{\%C}$ are given in technical specification of instrument transformers.

The uncertainty u_{FD} that affect the phase displacement correction F_D for practical application can be estimated by the following simplified relation [6]:

$$u_{\%FD} \approx u_{\Delta\varphi} \cdot tan\varphi \cdot 100\,\% \quad (7)$$

where $u_{\Delta\varphi}$ represents the combined uncertainty of the instrument transformer phase displacement that may be determined by:

$$u_{\Delta\varphi} = \sqrt{\left[\frac{G_{\Delta\varphi V}}{\sqrt{3}}\right]^2 + \left[\frac{G_{\Delta\varphi C}}{\sqrt{3}}\right]^2} \quad (8)$$

where the limits of angle error for voltage transformer $G_{\Delta\varphi V}$ and current transformer $G_{\Delta\varphi C}$ are given in technical specification of instrument transformers.

B. Accuracy of System with Measuring Bridge

System with single-phase measuring bridge (MBS) for loss measurement consists of:

- measuring bridge
- standard capacitor
- current comparator

Measuring bridge and standard capacitor are in manufacturer's specifications treated as one unit, with given limits of errors for voltage $G_{MB}\,(V)_{\%}$, for current $G_{MB}\,(I)_{\%}$ and for power factor $G_{MB}\,(cos\varphi)_{\%}$. Based on this specification, uncertainty of power measurement with measuring bridge and standard capacitor is calculated as:

$$u_{\%PW(MB)} = \frac{1}{\sqrt{3}} \cdot \sqrt{G_{MB}(V)_{\%}{}^2 + G_{MB}(I)_{\%}{}^2 + G_{MB}(cos\varphi)_{\%}{}^2} \quad (9)$$

Current comparator contributes to overall uncertainty of losses measurement with amplitude $G_{\%C}$ and angle $G_{\Delta\varphi C}$ limits of error which should be inserted in equations (6) and (8) respectively.

C. Analysis of Measurement Uncertainty for Losses

Measurement of shunt reactor losses with satisfactory accuracy is a big challenge due to low power factors. Dominant contributors to measurement uncertainty of losses in case of Transformer loss measurement system used are angle errors $G_{\Delta\varphi V}$ and $G_{\Delta\varphi C}$ of instrument transformers, considered by component $u_{FD\%}$ in equation (2), and the uncertainty of power measured with power analyzer $u_{\%PW(AS)}$. With neglecting the amplitude errors of instrument transformers, measurement uncertainty of losses can be expressed as:

$$U(P)_{\%} \approx \sqrt{u_{\%PW}^2 + u_{\%FD}^2} \quad (10)$$

If power analyzer LEM-NORMA D6133TE [9] is used in TLMS limit of error can be expressed as:

$$\mathrm{G}(P)_{\%} = G(V)_{\%} + G(I)_{\%} + 0{,}00358 \cdot tan\varphi\,\% \quad (11)$$

And for low power factor uncertainty component can be approximated as:

$$u_{\%PW(PA)} = \frac{G_{PA}(P)_{\%}}{\sqrt{3}} \approx \frac{0{,}00358 \cdot \tan\varphi\,\%}{\sqrt{3}} \quad (12)$$

Finally, expanded measurement uncertainty of TLMS is:

$$U(P)_{\mathrm{TLMS}\%} \approx \frac{2 \cdot 10^{-4} \cdot \tan\varphi}{\sqrt{3}} \cdot \sqrt{\left[G_{\Delta\varphi V}\right]^2 + \left[G_{\Delta\varphi C}\right]^2 + [35{,}8]}\ \% \quad (13)$$

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When measuring power losses with MBS, dominant influence is measurement uncertainty of measuring bridge ($u_{\%PW(MB)}$), while amplitude and angle error of current comparator can be neglected. Therefore, expanded measurement uncertainty (k=2) for losses in case of MBS can be calculated as:

$$U(P)_{\mathrm{MBS}\%} \approx \frac{2}{\sqrt{3}}\left(\sqrt{0{,}2^2+0{,}1^2+0{,}5^2+\frac{1\cdot 10^{-3}}{\cos\varphi}+\left(\frac{1\cdot 10^{-3}}{\cos\varphi}\right)^2}\right)\% \quad (14)$$

Comparison of power loss uncertainties for two systems (TLMS, MBS) in dependency of power factor (PF) is given in Fig 1. It can be clearly seen that the expanded uncertainties for power factor of 0,01 are practically the same, but as power factor goes down to 0,001, MBS assures substantially more accurate measurement. Uncertainties given in Fig 1 are for each phase separately. In case of three-phase power loss measurement, with approximately the same losses measured in each phase, expanded uncertainty of total losses would be $\sqrt{3}$ times smaller.

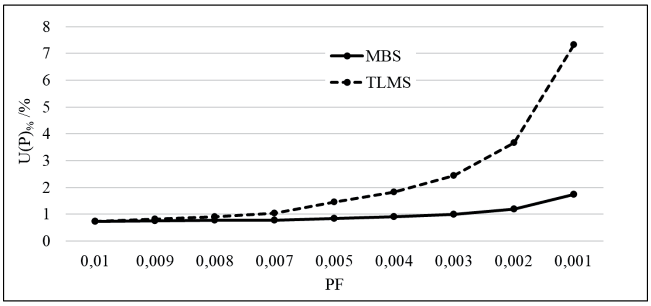

Fig. 1. Comparison of power loss measurement uncertainty (single-phase) for two measurement systems: TLMS and MBS

III. Automated Measurement System for Shunt Reactors

Software for Automated Transformer Test (ATT) enables different tests on power transformers, from simple to the most complex, with a high degree of automation. ATT leads test engineers through measurements, checks functionality of the measurement system, automatically measures different values (currents, voltages, losses, temperatures), perform analysis, saves data to the files, and generate test reports.

ATT enables communication with measuring equipment. Besides standard equipment for measurement of transformer losses (power analyzers, current transformers, voltage transformers), ATT supports communication with digital thermometers, voltmeters, and other types of instruments for special purposes. Expansion of ATT software with modules for shunt reactors also implied integration of system with measuring bridge, to assure shunt reactor loss measurements with satisfactory accuracy in case of very low power factor.

A. Communication and measurement principles

Measurement bridge in combination with current comparator and standard capacitor enables single-phase measurement. Although it is possible cover three phase shunt reactors with single-phase measurement, such measurements would be less accurate and highly time demanding, also with modifications in measurement procedure. KPT test bay requirement on fast, simultaneous and accurate measurements for both single-phase and three-phase shunt reactors resulted in integration of three measuring bridge into one system.

Basic communication principle is given in Fig 2. Each measuring bridge communicates with corresponding software over ethernet card. Since only one special purpose software can be installed on personal computer (PC), three PCs are required for a three-phase measurement system. ATT as a client software communicates with measuring bridges indirectly, by using interface of corresponding software. Task for ATT is to configure equipment for measurement, to collect and analyse data according standards [1] and to generate test report.

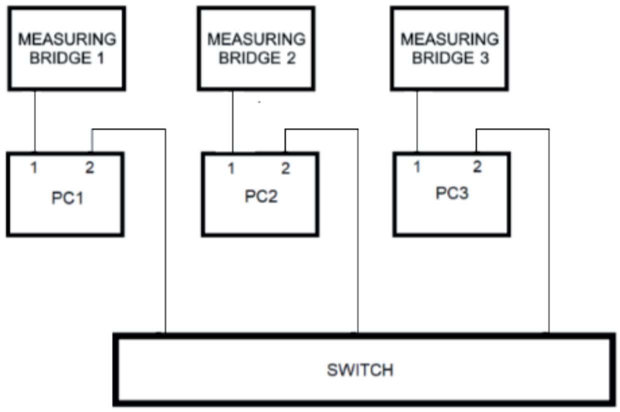

Fig. 2. Basic communication principles

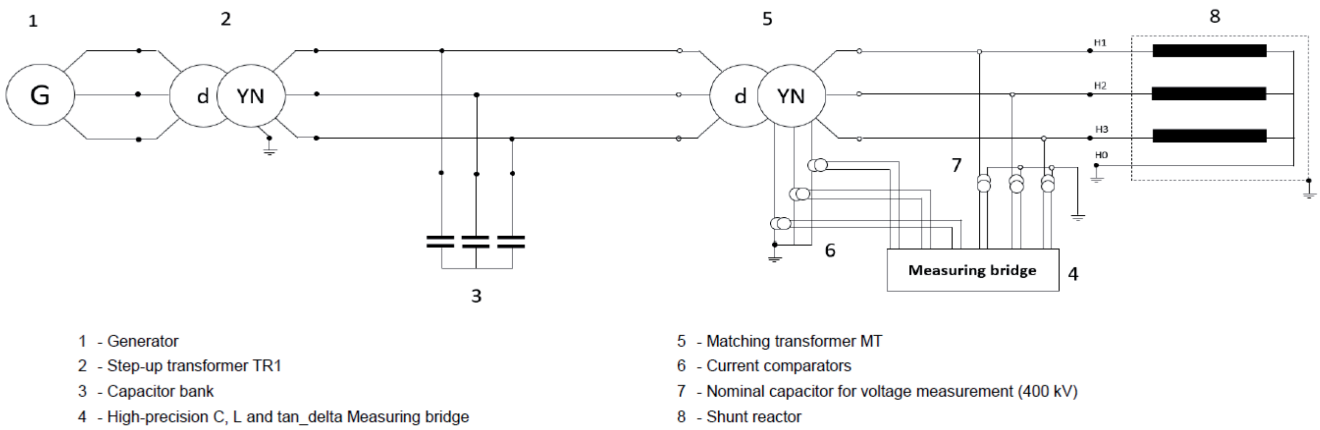

Fig. 3. Basic measurement principles

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The principal scheme for measurement of losses and impedance for shunt reactors is given in Fig. 3. Testing of shunt reactors puts high requirements on measuring equipment, since most of the test are performed at rated voltage, at maximum operating voltage or even at higher voltage level in case of induced voltage test. Compared to transformer tests, the AC source must be stronger. Requirements on high reactive power at high voltage levels are satisfied by use of specially designed matching transformer. As already explained, measuring bridge is used for highly accurate measurement of shunt reactor losses. Since the test currents of shunt reactors are substantially higher than the measuring bridge rated current, a current comparator is used in each phase to level down the test current. The test voltage is measured indirectly by measuring current flowing through the standard (nominal) capacitor. Capacitor bank put between the step-up transformer and matching transformer is used to compensate high amount of reactive power.

B. ATT FOR SHUNT REACTORS

Main window of ATT software for shunt reactors is given in Fig 4. It contains of 6 main parts:

- *Hardware test* – testing communication with instruments included in software
- *Reactors* –selection, power reactors or transformers
- *Reactor Data* – input data of power reactor on test
- *Measurement* – 9 different modules
- *Analysis* – 2 different modules
- *Print* – test report generation for all tests (test report for customer or draft report for research and development)

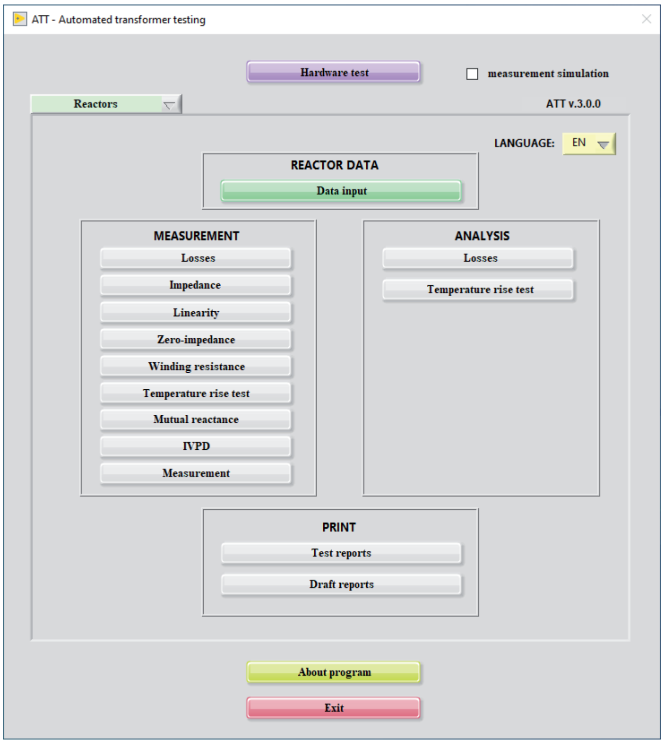

Fig. 4. ATT – main window

Fig. 5. Reactor Loss measurement

Based on standard requirements [1] new modules for automated measurement are developed: measurement of losses, impedance measurement, linearity test, zero impedance measurement, winding resistance measurement, temperature rise test, measurement of mutual reactance, IVPD module and control measurement. For complex measurements (losses, temperature rise test) ATT provides the possibility of subsequent data analysis.

The example for *Loss measurement* is given in Fig 5. After starting the measurement, measurements in real time from measuring bridge are displayed in ATT user interface. Test engineer decides about the moment of recording of the data. Immediately after recording, data are stored in files to be available for analysis, test reporting or as a source for research and development purposes.

IV. CONCLUSION

ATT software covers most of electrical type and routine tests for power transformers, except the dielectric tests. Now, the software is expanded with new modules for measurement on shunt reactors – loss measurement, impedance measurement, linearity test, zero-impedance measurement, winding resistance measurement, temperature rise test and measurement of mutual reactance all in accordance with [1]. HV measuring bridge and accompanying software are intended for single- phase measurements. Single-phase measurement on three-phase shunt reactors would require special procedures and would result in time consuming measurements. Instead of such solution, ATT successfully integrates three measuring bridges in one three-phase system, to assure fast, accurate and simultaneous measurements for both single-phase and three-phase shunt reactors.

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