How measurement system solves accuracy loss measurement tradeoff

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Abstract

International standards and quality policy of manufacturers have increased the needs of measurements for transformers and reactors. Many measurements have been raised from type tests to routine test, making a measurement system with improved data management mandatory. Measurement equipment manufacturers have to design systems that take advantage of most of the technology improvement, from measurement electronic to IT system. Not only the measurement is important, but also the complete chain, data management, reporting and accuracy assessment of the measurement have to be automatically computed for the end user.

Traditional Loss Measurement approaches

Loss measurement classically is facing the controversial requirements of measuring iron losses vs. measuring copper losses. Measuring of iron losses implies high voltage (for example the nominal voltage of the transformer) in an open circuit and low current values. Measuring of copper losses in a short circuited cycle implies high current (for example the nominal current of the transformer) and low voltage.

The traditional approaches of loss measuring have been dealing with these controversial test requirements by separate test infrastructures. This means for the test engineers the process of testing was including a high demand of cabling time for providing the correct setup for each kind of test, using the right kind of measuring equipment for each single test for providing the best possible measuring accuracy.

The increasing production capacities of modern transformer plants and the increasing customer's demand on routine tests putting a lot of pressure on the test labs. More

Transformers have to be tested and more distinct tests have to be accomplished at shorter available time resources.

Out of this reasons new approaches for transformer testing have to be found. Integrated systems offer drastically decreased testing times and therefore reduced testing costs beside to major other advantages in the workflow of the state of the art test labs.

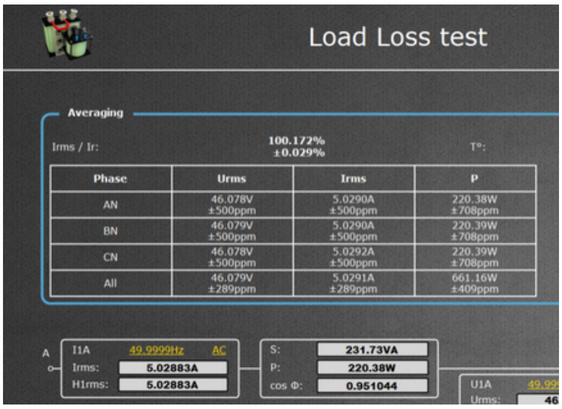
Advantages of integrated systems

Digital processing of measurement values, as already mentioned, offers a variety of possibilities to the measurement process itself. Synchronic and automatic reading and processing of data eliminates reading errors what caused uncertainties and errors with old measurement instruments.

Digital processing techniques are highly important for the digital sampling of measurements. The importance of harmonics contents of the measured signal has to be determined. Electromagnetic noise what can be found in industrial equipment has to be filtered.

The most important advantage by digital techniques is the possibility of automatic compensation of measurement devices. Only in case of highly accurate and highly stable standard transformers are used for measurement of voltage and current an automatic compensation of amplitude and frequency can be done easy and reliable. The requirements and technical abilities of the standard transformers will be highlighted later in this article.

The overall accuracy of measurements has to be assessed constantly. The responsible person constantly has to collect the accuracy data of different measuring systems and devices. Plus to this we have to consider the relationship of different uncertainties and the relations of this on the overall measurement results. Integrated measuring systems drastically reduce the work and the related uncertainty that constant assessment brings with. With integrated systems complete accuracy data is available constantly; this includes each part of the whole system. An integrated measurement system has to point out directly, at each measurement, the values of measurement uncertainty of the related measurement.



State of the art IT management is another big argument for fully integrated systems. Both the manufacturer of the system as well as the user of the system easily takes advantages of building up databases of test routines and test objects on a daily base. While the user of the system can build up test object databases and databases of different test routines, the manufacturer of the system is able to do long term statistical calculation for verifying the accuracy data; this has also its main importance for calibration and calibration intervals.

Calibration and verification

Any measurement system is only accurate during its calibration period, any system has to be recalibrated or verified periodically. The structure of the measuring system is having tremendous influences on the calibration periods. In fact calibration periods always are defined by the quality management system of the specific user of the system but in general national authorities are giving at least informal indications for different types of devices. Normally passive (inductive) components as standard transformers are used to have longer calibration periods (for example 8 years or even longer). This helps the customer in terms of economic test bay management while the devices cause less calibration cost and less lab downtime.

Electronic system parts have to be calibrated more often, informal indications speak of yearly or bi-yearly basis. Manufacturers of integrated test systems have to foresee this calibration work. The parts for calibration should be size and weight reduced. Also the process has to be considered. In case of availability of spares during the calibration period downtimes can be reduced to zero. The usage of front-end devices ensures the ability of a simple change for calibration purposes.

For best measurement quality it is preferable to use automatic self verification measurement devices. A self verification will be performed prior to each measurement process and this is building confidence in measurement results as well as good traceability of all measurements.

It is obvious to mention that all parts of integrated measurement systems have to be calibrated related to the common standards as well as the entire complete system. Traceability to national standards for voltage, current or power is a must.

This rigid way dealing with calibration and verification is the only effective way only with this rigorous trading about calibration or verification can provide a high level of accuracy in the loss measurements. A measurement system foreseen for flexible calibration is the only way to avoid some tradeoff between the calibration period of the system and the production throughput. If calibration process is not a bottleneck for testing resources, calibration will not be delayed for production throughput reasons.

Accuracy of loss measurements

The evaluation of the accuracy of power measurements for the losses has been described in the standards since a long time, and is still of the first importance.

The basic calculation of the power measurement is given in [1] and is composed of the different measurement uncertainties of each measured quantity.

As described in the standards, the accuracy of measurement is of first importance for the voltage and current, but the most important factor for power measurement is the phase angle or power factor measurement.

The measured power losses are expressed as

[1] $$P = U \times I \times \cos\varphi$$

For the composite relative error the formula gives:

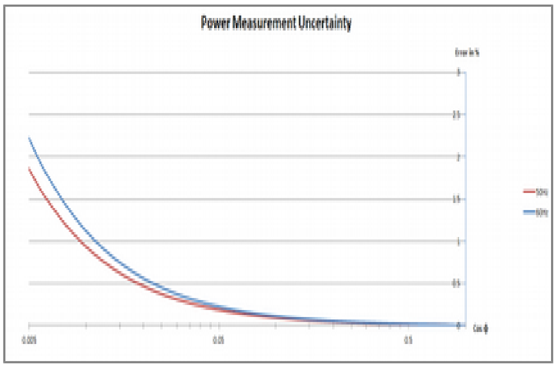
$$\frac{\partial P}{P} = \frac{\partial U}{U} + \frac{\partial I}{I} - \frac{\sin\varphi}{\cos\varphi} \times \partial\varphi$$

Modified, this equation shows that when the phase angle is small due to the inductive nature of the equipment under test, the power measurement error, which varies with the inverse of the power factor, will increase.

If somebody first analyses the first terms of current and ratio, another term comes into account as the loss measurement usually deals with high voltages or high currents. This term is the ratio of the divider used during the measurements. Reducing the uncertainty of voltage and current measurements is mandatory. But, as explained in the standards;the ratio of the measurement transformer can be compensated in the calculations of power to improve their accuracy. In order to compensate these ratios, the ratio deviation must be known exactly with the best accuracy and last but not least, must be very stable, not depending from temperature or humidity or electromagnetic noise for example.

The phase angle between current and voltage or the power factor must be measured accurately to reduce the uncertainty of the power.

The Phase or power factor measurement errors are impacting the active power measurement very fast, applying the equations from [1] directly leads to curves like the Figure below.



The typical curve of the Figure was obtained by assuming current and voltage at ±200ppm and a phase error of maximum 0.4 min.

The different error sources for the phase are coming from the measurement transformers and eventually, the front end electronic and the digitizing system synchronization.

As described before in this article, the phase error coming from the measurement transformers and the front end electronic can be compensated by the measurement system if they are well calibrated and stable over environment conditions and time.

In a digital power meter, the synchronization of the sampling system must be of the first importance to securethe lowest jitter between the samples. The latest digital signal processing techniques have to be used to provide the best determination of the phase shift between current and phase.

In practice, the phase errors are very difficult to quantify from the theory. Some verification setups have to be measured over long periods of time and the phase error can be determined experimentally using statistical methods. In this case, the same current or voltage will be observed using identical measurement devices and an important amount of results will be acquired. Analyzing these results and their dispersion will increase the confidence in the determination of the phase error.

These experimental results then need to be calibrated with equipmentthat are themselves calibrated to the national normal (like PTB for example).

Parameters that degrade the accuracy

Effect of electromagnetic noise

The most actual point of interest for the losses measurement is the matter of electromagnetically noise. Many laboratories are using electronic power supplies for their tests in order to get flexible power conditions like higher frequencies.

These electronic power supplies are switching power supplies and are emitting a wide spectrum of electromagnetically noise. This noise has already been studied in many articles mainly for partial discharge measurements.

The electromagnetically noise at high frequencies can be coupled on the measurement devices themselves or on the connecting cables. A modular system with front-end and digitizing as near as possible from the measurement transformers reduces the coupling of noise.

Electronic power sources generally use capacitor banks in order to stabilize the control system or provide a tank of reactive power. The control system and the capacitor bank can generate higher harmonics content in the power circulating in the device under test.

The standards do not require yet a frequency analysis, but the increasing content in harmonics gives important information about the measurement conditions.

Effect of range switching

An important aspect to reduce the measurement uncertainty is the stability of the measurement setup. Changes in the measurement setup directly impact the uncertainty of the measurements.

Measurement devices including range switching with relays influences the impedance in the measurement circuits and then brings an additional uncertainty to the measurements. Even the best measurement front end will be inaccurate if the setup is changed during the measurements.

Important but forgotten points to accuracy

As soon as a measurement discussion starts, it ends quickly to accuracy assessment. During these discussions, the metrological point of view is immediately on the scene, but some points are often forgotten, even if they can affect dramatically the accuracy of any measurement, and in the worst case make the measurement unusable.

Effect of the system user

The use of digital measurement devices has reduced the uncertainties due to the user against the old measurement devices with arrows. The “reading” errors have been eliminated.

There is still an error that can come from the user and that affect the measurement. The user can still make mistakes during the test, especially if the user is not experienced or trained to these types of measurements.

The use of the latest man machine interfaces with touch screen or other displays guides the user during the tests in order to avoid any failure during the measurements. The use of intuitive graphics is of first importance to terminate through the requirements of the standards, without forgetting any measurement or action.

Integration of automatic power source control can also avoid testing at bad current or voltage levels. Issuing an automatic report from secured test result database is also a security that different test results will not be mixed at the end.

Effect of equipment quality

As seen above, the measurement equipment directly impacts the measurement uncertainty of the power, not only with the initial accuracy, but mainly from their stability.

In case of usage of inductive parts the end user is gaining a variety of advantages over the life cycle of any measuring system. In compares to electronic or capacitive dividers inductive parts are stable over decades and under outer influences. This is shown in the unofficial meaning of major meteorological authorities, for example in Germany. Where inductive measuring instruments are scheduled for recalibration each 16 years only there is the broad meaning of calibration for capacitive parts every single year or at least all 2 years.

Inductive standard transformers offer the highest level of accuracy in voltage/current measurement and also in phase angle. Really state of the art standard transformers should offer accuracies between +/-0,005 and +/- 0,01% and a phase angle uncertainty of not more than 0,5-1,0min depending on the height of the rated voltage/current.

Obviously accuracy is only one parameter what has to be achieved for stable and exact measuring, the other point is stability. Stability in fact has two meanings, you can distinguish between environmental stability and range as well as time stability. Both aspects of stability are perfectly covered by inductive standard transformers.

Environmental stability means that the measuring output has to be on the same level for same measurements even if outer conditions as temperature, humidity of air or altitude strongly varying. To be brought on a practical example this means the measuring device has to show hardly same measuring results weather it is operated in Mumbai where humidity is very high or operated in Arizona / USA where humidity is low and temperatures are extremely high, or if it is operated in Quito / Ecuador what is hardly 3.000m above sea level. Inductivity always calculates on same physical values and formulas. Theoretically there are compensation factors for all these values but in case of inductive devices these factors easily can be neglected, there are no empirical values for this.

Time stability is guaranteed at inductive standard transformers because of the construction/design parameters. The lifetime of inductive standard transformers is calculated in decades it is proven technology with no variations over time. Range stability means the development of the measuring uncertainty over a wide measuring range. High quality standard transformers are defined by accuracy. It is easy to reach a very high measuring accuracy at the rated voltage/current. The critical point and question in the daily work in the test lab is the range where the stability is guaranteed. High quality standard transformers are offering a failure of less than 0,1% over a wide measuring range (i.e. between 20 and 120% of rated). Even below 20% of rated for example at a minimum of 1% of rated the failure should be constant. In this case the failure will be more than 0,1% but stability conditions should be the same in all other categories.

If these conditions are completely reaches, and only in this case it is possible that the measurement system compensates the transducers ratio and phase displacement. In this case the end user receives a tremendous advantage. Stability and perfect accuracy of a measuring system over a wide range of measuring values. In a practical point of view this means flexibility in the test lab.

Effect of temperature measurement

Maybe one of the most neglected parts of the loss measurement, maybe because it is not directly related to the power loss measurement, is the temperature measurement. Every standard gives a method to correct the measured losses, depending on the materials composing the transformer or the reactor. Where every expert will discuss about some tens of a percent in the loss measurement accuracy, the same expert will take an approximated measurement of the temperature to correct the loss according to the standards.

The following example shows how important are the accuracy of temperature measurement in the final results of the loss measurements.

Considering the Load Losses in W as defined in the standards, the temperature correction applied to these losses is calculated using the following formula:

$$P_{LL} = P_j(I_r, T) \times \frac{T_k + T_r}{T_k + T} + P_a(I_r, T) \times \frac{T_k + T}{T_k + T_r}$$

Where

$P_j(I_r, T)$: Ohmic losses at I_r and T.
$P_a(I_r, T)$: Additional losses at I_r and T.
T_k: Temperature coefficient of EUT windings.
T_r: Assigned temperature, in °C.
T: Temperature measurement, in °C.
I_r: EUT assigned current, in A.
P_{LL}: Load losses, in W.

Taking a small academic example to calculate the consequences of a bad temperature measurement uncertainty gives the following:

With:

T_r = 75 °C, Assigned temperature, in °C.

I_r = 10A, EUT assigned current, in A.

T_k = 235 (Copper), Temperature coefficient of EUT windings.

R_{Tr} = 0.715Ω ± 0ppm EUT windings resistance at Tr

Measurements		Calculations	
P	T R_T	P_{LL} (W)	
90W ± 291ppm	70°C ± 0°C	0.727Ω ± 0ppm	88.55W ± 435ppm
	70°C ± 0.3°C	0.727Ω ± 984ppm	88.55W ± 926ppm
	70°C ± 1°C	0.727Ω ± 3279ppm	88.55W ± 2757ppm
	70°C ± 5°C	0.727Ω ± 16390ppm	88.55W ± 13620ppm

This example has shown the importance of the temperature measurement in the computed results. It becomes obvious from these results that a measurement system must include an accurate measurement of the temperature, synchronized with the power measurement. This ensures that during the averaging time of the loss measurements, the measurements are always corrected with the right temperature.

Conclusion

This Article shows that modern measurement centers are complex systems. The task of measuring transformers is not an easy one and brings various tradeoffs and with it. Modern measurement centers are able to minimize the tradeoffs and the total uncertainty of the measurement process. Therefore some abilities should be guaranteed, the architecture of the measurement system can help minimizing tradeoffs and uncertainties. The Architecture of a combination of electronics and automation in combination with well proven inductive measuring devices brings advantages of two worlds together. The end user has to focus on easy handling, security and accuracy. All these points are important and are having a big influence on the process and therefore on the productivity of a lab.