Loss measurement accuracy as key factor for energy saving programs

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Abstract

Efficiency programs of most of the governments are focusing on reducing the energy losses in the distribution network, and for some of them even give metrics for these improvements. A big amount of these losses is coming from the distribution transformers and the manufacturers are encouraged to improve the efficiency of their designs. These improvements are often managed with the use of better materials and then increase the costs of the transformers. The needs for accurate loss measurements are therefore increased, if the manufacturers don't want to see their efforts under coming in the measurement uncertainties of a measurement system. Proving a small improvement in efficiency, even at high costs for the manufacturer will be difficult if the measurement system can't measure this improvement accurately. Accuracy of measurement systems and comparison of these accuracies are of the biggest importance, and have been a subject of discussion between experts since long time. The article will describe how a modern measurement system can be accurate, assess its accuracy for every measurement performed and set confidence over the time about the stability of its accuracy. In this approach, 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.

Analysis of current situation:

Transformer loss measurement is a well known field. All manufacturers of transformers have to do loss measurement tests for proving the technical data of their products especially in load losses and no load losses. It is stated in many studies and articles that the general losses of the transmission and distribution network is around 9% of total[1]. The losses generated by transformers are the second biggest part of the total distribution and network losses. It is stated that the losses caused by transformer load and no load losses have an approximate value of 300 TWh per annum, this is for compares approx. 2 times the annual consumption of Poland[2]. Efficiency programs worldwide are trying to force manufacturers in investments in R&D and production to reach lower losses. Speaking about losses we have to state that the efficiency values at transformers already are in a quite high range. Fig. 1 shows the efficiency values for liquid filled transformer tiers.

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[1] Scholand, Blackburn, Hopkinson, Sampat: SEAD Distribution Transformers Report Part 3 ; www.superefficient.org

[2] Fogelberg : Transformer Losses – European Commission Regulations and European Standards

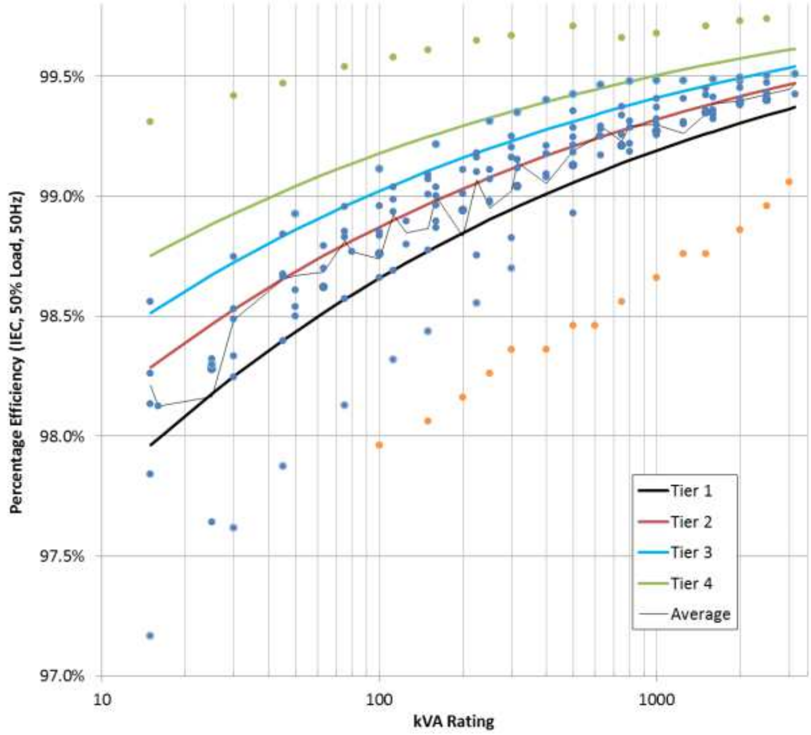

Figure 1 – Liquid filled Transformer tiers – efficiency values[3]

Figure 2 Shows a variety of international programs for energy efficiency and illustrates a trend for the future. Hardly all countries will propose programs like this to force transformer manufacturers to optimize the losses of their products.

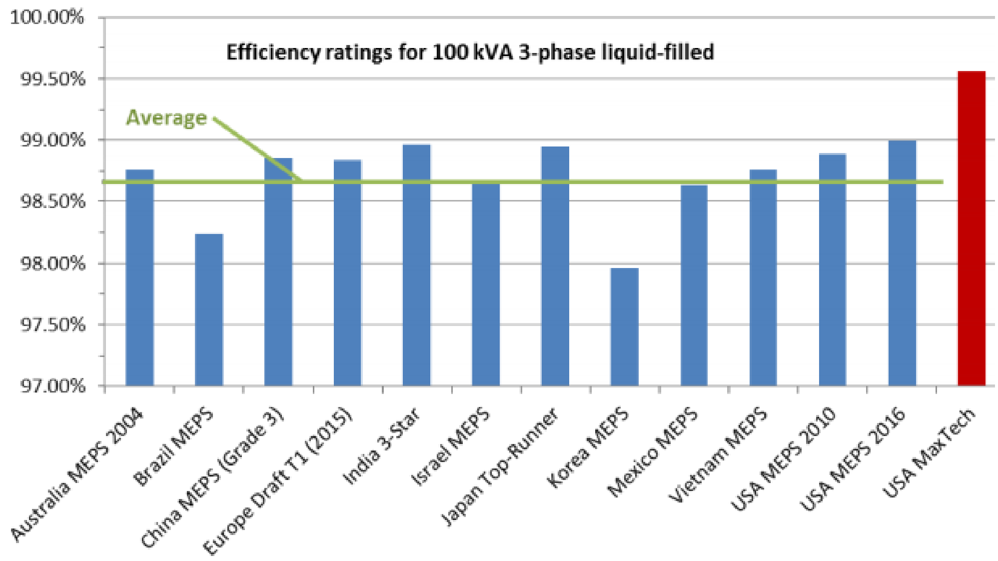

Figure 2 – Efficiency criteria at 50% load for 100kVA liquid filled transformers in different countries[4]

[3] Scholand, Blackburn, Hopkinson, Sampat: SEAD Distribution Transformers Report Part 3 ; www.superefficient.org

These overview data shows the importance of high efficient transformer materials and the necessity in optimizing each single part in the transformer. But just on the second sight it points out very clearly a major question for reaching these goals. What is with transformer testing and the measuring uncertainties involved in this testing process?

All efforts done by transformer manufacturers are for nuts if the expensive improvements are eaten by measurement uncertainties of the transformer testing equipment. Thinking this statement to an end it reduces in two main issues:

a. The measurement uncertainty has to be as small as possible
b. The measurement uncertainty has to be known. And to be known means not having the information on the general (theoretical) uncertainty of a test system, it means that the actual uncertainty at each measurement has to be known and stated in the test report.

In order to have an idea about the impact of the accuracy and uncertainty of the measurements on the efficiency measurement, we can consider the example given in [6] Chapter 3.2. In this example, applying a system accuracy of 0.1% on measurement losses (including uncertainties to illustrate clearly this example) will yield automatically to a 0.03% tolerance on the transformer efficiency itself. This easy calculation really illustrates the importance of the loss measurement system in this efficiency improvement process.

Measurement uncertainties in Loss measurement system

The measurement uncertainties have been studied and discussed for years since the first well known publication[5] of the National Bureau of Standards in the eighties. This publication had already stated the problematic of efficiency improvement and the needs of accurate loss measurements in order to assess correctly these improvements. Even if the problematic is not new, the IEC has only published its part IEC 60076-19 about the determination of uncertainties in loss measurement for transformers and reactors in 2013.

The NBS publication has pointed out in the eighties that a measurement uncertainty statement in such systems can only be made efficiently if the measurement chain is reduced to its minimum. Every part of the chain brings its uncertainties, and these uncertainties are combined as a sum for a worst case study, or as RSS (root square of the sum). Even with low mathematical background, it is obvious that low part count in the measurement chain may bring less uncertainty as a bigger amount of uncertainties factors.

System calibration and longtime stability

All calibration methods are based on a standard alignment of the measurement system to higher level standards in order to keep measurement traceability. The alignment on the standards provides a very good accuracy at the time of the calibration, but the question remains on the longtime stability of this calibration. Can a measurement system

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[4] Scholand, Blackburn, Hopkinson, Sampat: SEAD Distribution Transformers Report Part 3 ; www.superefficient.org

[5] NBS Technical Note 1204 – Calibration of Test Systems for measuring power losses of transformers – Oskars Petersons – S.P. Mehta

[6] Scholand, Blackburn, Hopkinson, Sampat: SEAD Distribution Transformers Report Part 2: Test Method Review ; www.superefficient.org

manufacturer prove that a system will be enough stable to stay in the specifications it has given? And with which measurement uncertainty can this assumption be assessed?

This long term stability implies some basic principles for a measurement system. All components of the system must show:

- a very high long term stability that is proven and accepted in the industry, such as passive inductive transducer for voltage and current which are known for being very accurate and stable and therefore require very long calibration intervals
- A well-known variation that has to be proven using statistical methods and that can be compensated during the measurements. This is mostly the case of electronic front-end in the measurement chains, that are subject to change with temperature or other environmental aspects

The loss measurement methods and its accuracy

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.

Analyzing 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.

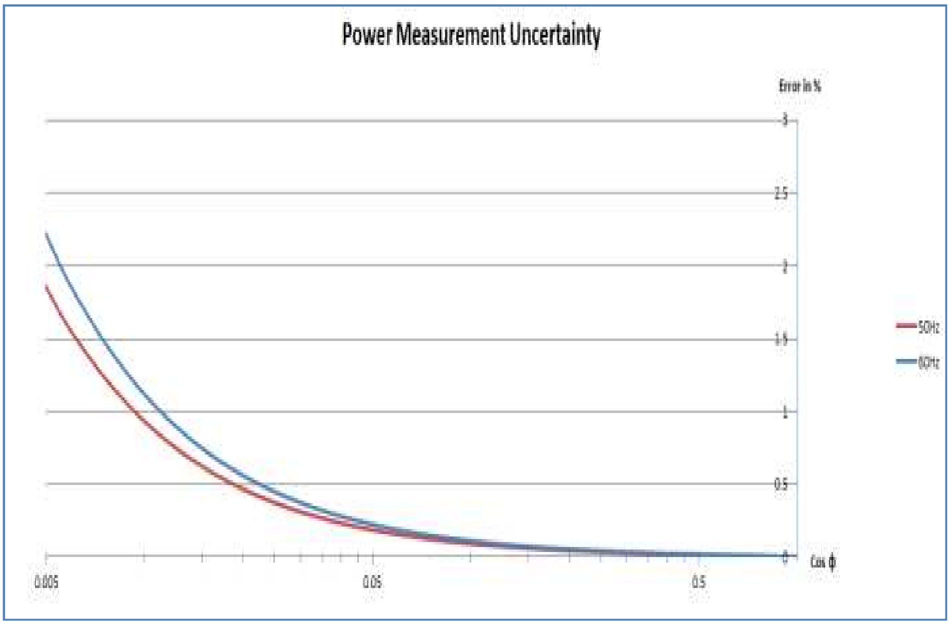

Figure 3 – Power measurement uncertainty in relation to the power factor

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

Parameters that degrade the accuracy

- **electromagnetic noise**

Because of its random nature, electromagnetical noise is for sure the most difficult source of error in the loss measurements. Many laboratories are using electronic power supplies for their tests in order to get flexible power conditions like higher frequencies, but motor used in the factories and their frequence converter can also be important sources of noise.

These electronic power supplies are switching power supplies and are emitting a wide spectrum of electromagnetical noise. This 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 instability like range switching**

An important aspect to reduce the measurement uncertainty is the stability of the measurement setup, and once the transducers are considered, the focus comes on the electronic front-end. Changes in the measurement setup directly impact the uncertainty of the measurements. The predictable behavior can be compensated such as the temperature variation, but the non-predictable components in the system have to be avoided.

For example, 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 its setup is changed during the measurements.

It is of the first importance that the electronic contains a system of self-verification to ensure that the measurements are still made with the best accuracy. The verification and the calibration must be made in a way that shows a very low uncertainty. Using for example electronic front-end clearly identified with a conventional voltage or current, can allow a quick verification at any time with power standard devices on the market. For example, if the front end for current measurement is working on a range 0-10A it can be calibrated or verified with a common power standard like Fluke 6105 for example, leading to combined measurement uncertainties of less than 50 ppm.

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. The measurement operator 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.

Figure 4 – State of the art man machine interface for measurement system

- **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.

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.

Including electronic in the transducers must be made very carefully, as the electronic can have direct drawbacks on the measurement quality. First, the power supply needed by the electronic can carry conducted electromagnetic noise from external sources, and second will bring its own uncertainties in the uncertainty of the equipment. Keeping the transducer simple is still the most efficient.

The measurement system can compensate the transducers ratio and phase displacement only if the long term stability is proven, it can otherwise even add some errors to the measurements.

Figure 5 – State of the art standard voltage transformer, 40kV rated

- **temperature measurement**

A very good example 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. Most of the laboratories 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

Figure 6 – effect of temperature uncertainty to measurement uncertainty

This example shows the importance of the temperature measurement in the computed results. It is 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.

Live accuracy assessment

After reviewing the characteristics that can bring or avoid uncertainties in the measurements, a statement must be made for every measurement. Every measurement engineer has faced the difficulties of calculating the accuracy of measurement and their uncertainty.

Arising thanks to modern data processing possibilities, it is of best practice for a measurement system to provide directly the accuracy of every measurement. These assessment are then stated through the calibration documents and traceable to the national standards.

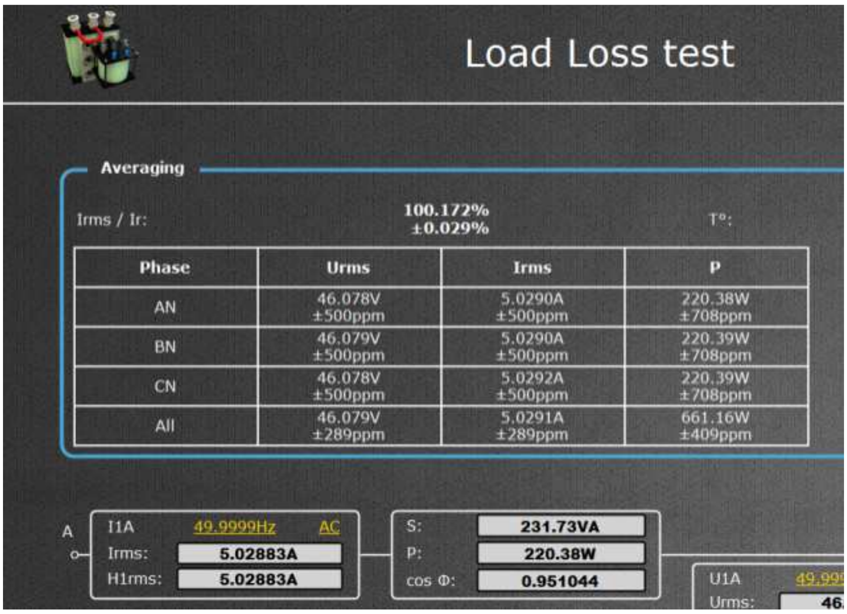

Figure 7 – live accuracy and printout of uncertainty in modern measurement system

Conclusion

This Article shows that modern measurement centers are complex systems. The task of measuring transformers is not easy and brings various tradeoffs. Modern measurement centers are able to minimize 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.

The efforts that transformer manufacturer will do for the efficiency improvement of their designs must be secured by very accurate and defined measurement uncertainties measurement systems. The trend of efficiency improvement will live, only if this improvement can be quantified with the highest degree of confidence.

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