Loss measurement accuracy as key factor for energy saving programmes

ABSTRACT

Most government efficiency programmes focus on reducing energy losses in the distribution network and for some of them even provide metrics for these improvements. A large amount of these losses comes from 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 of transformer costs. The need for accurate loss measurements is therefore increased if the manufacturers do not want to their efforts to be affected by the measurement uncertainties of a measurement system. Proving a small improvement in efficiency, even at high cost for the manufacturer, will be difficult if the measurement system cannot measure this improvement accurately. Accuracy of measurement systems and comparison of the accuracy are of the utmost importance and have been a topic of discussions among experts for years. The article will describe how a modern measurement system can be accurate, assess its accuracy for every measurement performed and confirm the stability of their accuracy over time. In this approach, not only is the measurement important, but also the complete chain, data management, reporting and accuracy assessment of the measurement have to be automatically computed for the end user.

KEYWORDS

efficiency, loss-measurement, uncertainties, accuracy, temperature, accuracy assessment

Analysis of current situation

Transformer loss measurement is a well known field. All transformer manufacturers have to perform loss measurement tests to confirm the technical data of their products especially for load losses and no load losses. It is stated in many studies and articles that general loss of the transmission and distribution network is around 9 % in total [1]. The losses generated by transformers form the second largest 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 - approximately twice the annual consumption of Poland [2]. Efficiency programmes worldwide are trying to force manufacturers to invest in R&D and production to achieve lower losses. Speaking of losses, we have to state that the efficiency values of transformers are already in a quite high range. Fig. 1 shows the efficiency values for liquid filled transformer tiers.

Figure 2 shows a variety of international programmes for energy efficiency and illustrates

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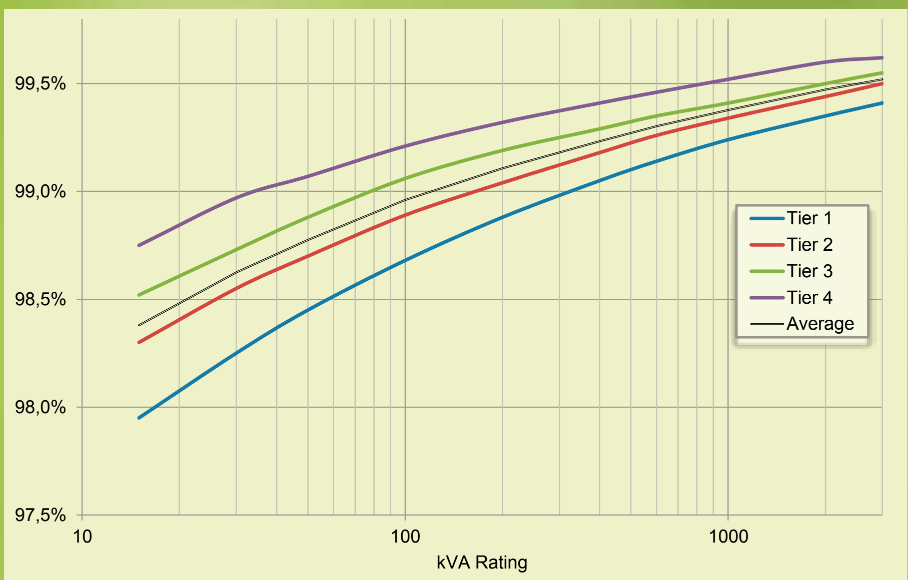

Figure 1: Liquid filled transformer tiers – efficiency values [1]

a trend for the future. Many countries will propose programmes like this to force transformer manufacturers to reduce the losses of their products.

This overview data shows the importance of highly efficient transformer materials and the necessity of optimising each part in the transformer. On the other hand it poses an important question about reaching those goals very clearly: *What about transformer testing and the measuring uncertainties involved in this testing process?*

All efforts done by transformer manufacturers to reduce losses are in vain if the expensive improvements are wasted by measurement uncertainties of the transformer testing equipment. This means that:

- Measurement uncertainty has to be as small as possible
- Measurement uncertainty has to be known. And to be known means not having general (theoretical) uncertainty of a test system. It means that the actual uncertainty during each measurement has to be known and stated in the test report.

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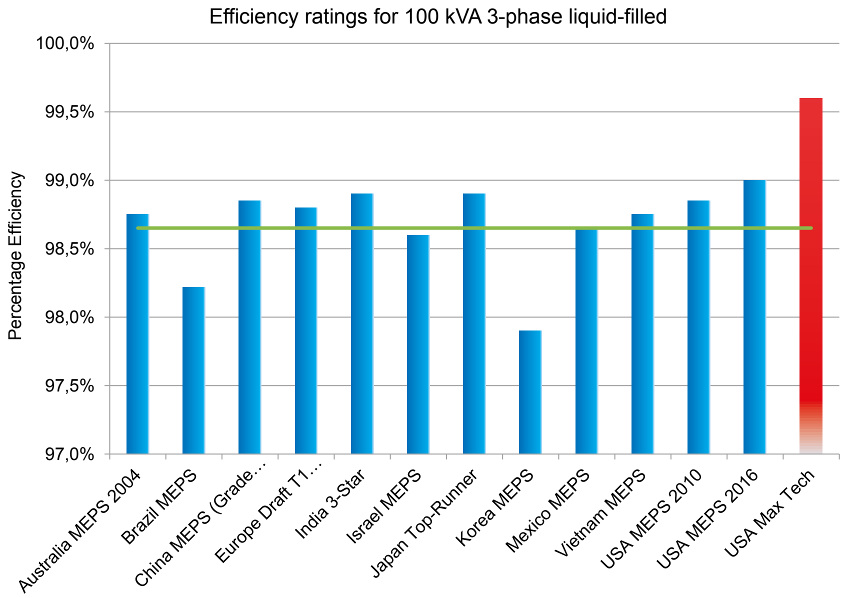

Figure 2: Efficiency criteria at 50 % load for 100 kVA liquid filled transformers in different countries [1]

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 [3], Chapter 3.2. In this example, applying a system accuracy of 0.1 % on measurement losses (including uncertainties to clearly illustrate this example) will automatically yield 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 the loss measurement system

Measurement uncertainties have been studied and discussed for years since the first well known publication [4] of the National Bureau of Standards in the eighties. This publication had already stated the issue of efficiency improvement and the needs for accurate loss measurements in order to correctly assess these improvements. Although the issue is not new, the IEC has only published IEC 60076-19 - its part about the determination of uncertainties in loss measurement for transformers and reactors in 2013.

In the eighties the NBS publication has pointed out that a measurement uncertainty statement in such systems can only be delivered 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 of a worst case scenario or RSS (root square of the sum). Even to someone with low mathematical background, it is obvious that smaller amount of factors in the measurement chain may bring less uncertainty than a larger amount of uncertainty factors.

System calibration and long-time stability

All calibration methods are based on a standard alignment of the measurement system with the higher level standards in order to keep measurement traceability. The alignment of the standards provides a very good accuracy at the time of the calibration but the question remains on the long-term stability of this calibration. Can a measurement system manufacturer prove that a system will be stable enough to adhere to the specifications it has provided? And which measurement uncertainty can be used to assess this assumption?

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 is known for being very accurate and stable and therefore requires very long calibration intervals.
- a well-known variation that has to be proven using statistical methods and one that can be compensated during the measurements. This is mostly the case of electronic front-end in the measurement chains, which is subject to change with temperature or other environmental aspects.

The loss measurement methods and their accuracy

The evaluation of the accuracy of power measurements for the losses was described in the standards a long time ago but is still of the utmost importance.

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

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

Every part of the chain brings its uncertainties and these uncertainties are combined as a sum of a worst case scenario or RSS (root square of the sum)

The measured power losses are expressed as

$$P = U \cdot I \cdot cos\ (\varphi) \qquad (1)$$

where:
U stands for voltage,
I stands for current, and
φ stands for phase angle.
For the composite relative error the formula gives:

$$\frac{\partial P}{P} = \frac{\partial U}{U} + \frac{\partial I}{I} - \frac{sin\varphi}{cos\varphi} \cdot \partial\varphi \qquad (2)$$

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

Analysing the calculation of current and ratio, another point goes into account as the loss measurement usually deals with high voltages or high currents. This point is the ratio of the divider used during the measurements. Reducing the uncertainty of voltage and current measurements is mandatory. However, as explained in the standards, the ratio of the instrument transformer can be compensated in the calculations of power to improve their accuracy. In order to compensate these ratios, the ratio deviation must be exact and most accurate, and must be very stable and independent from temperature, humidity, or electromagnetic noise.

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, and applying the equations from [1] leads directly to curves like in the Figure 3.

The typical curve of the Figure 3 was obtained by assuming current and voltage at ±200 ppm and a phase error of maximum 0.4 min.

Parameters that degrade the accuracy

• Electromagnetic noise

Because of its random nature, electromagnetic noise is definitely the most difficult source of error to identify 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 factories and the frequency converter can also be an important source of noise.

These electronic power supplies are switching power supplies and emitting a wide spectrum of electromagnetic noise. This noise at high frequencies can be transmitted to the measurement devices themselves or to the connecting cables. A modular system with front-end digitalization as near as possible to the instrument transformers reduces the effect of electromagnetic noise.

• Electronic instability, e.g. range switching

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

For example, measurement devices including range switching with relays influence the impedance in the measurement circuits and bring 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 utmost importance that the electronic contains a system of self-verification to ensure that the measurements are still conducted to the best accuracy. The verification and the calibration must be conducted 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 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 between 0-10 A, 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 of accuracy

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

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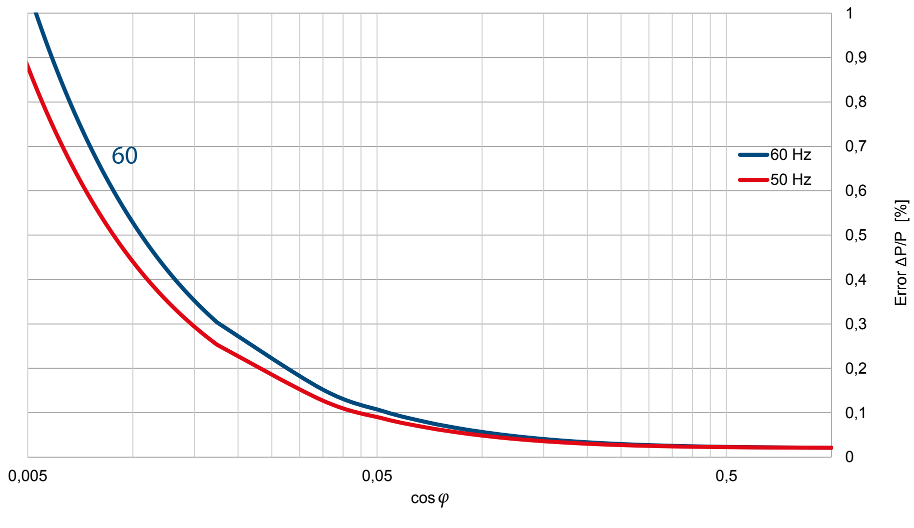

Figure 3: Power measurement uncertainty in relation to the power factor

Accuracy is influenced also by the user of the measurement system, quality of the equipment and temperature at which the measurement is conducted

Figure 4: State of the art user interface for measurement system

• Influence of the system user

The use of digital measurement devices has reduced uncertainties compared to the user reading the old measurement devices with pointers. 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 for these types of measurements.

The latest user interfaces with touch screen or other displays guide the user during the tests in order to avoid any failure during the measurements. The use of intuitive graphics is of the utmost importance to go through the requirements of the standards without forgetting any measurement or action.

• Equipment quality

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

Inductive standard transformers offer the highest level of accuracy in voltage/current measurement and also in phase angle. State of the art standard transformers should really offer accuracies between +/-0.005 % and +/- 0.01 %, and a phase angle uncertainty of no more than 0.5-1.0 min, depending on the rated voltage and current.

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

Using of electronics in transducers must be very careful as the electronics can directly affect the measurement quality. First, the power supply needed by the electronics can carry conducted electromagnetic noise from external sources; second it will bring its own uncertainties with the uncertainties of the equipment. Keeping the transducer simple remains most efficient.

The measurement system can compensate the transducers ratio and phase displacement only if long term stability is proven. It can otherwise cause some errors in the measurements.

• Temperature measurement

A very good example of one of the most overlooked parts of the loss measurement, perhaps 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 laboratories take an approximated measurement of the temperature to correct the loss according to the standards.

The following example shows how important is 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:

$$P_{LL} = P_j(I_r,\ T) \cdot \frac{T_k + T_r}{T_k + T} + P_a(I_r,\ T) \cdot \frac{T_k + T}{T_k + T_r} \quad (3)$$

Where:

$P_j(I_r,\ T)$ stands for ohmic losses at I_r and T.
T stands for temperature measurement, in °C.
$P_a(I_r,\ T)$ stands for additional losses at I_r and T.

Table I: Effect of the temperature uncertainty on measurement uncertainty

Measurements		Calculations	
P	T	RT	PLL (W)
90,0 W ± 291,0 ppm	70,0 °C ± 0,0 °C	0,727 Ω ± 0,0 ppm	88,55 W ± 435,0 ppm
	70,0 °C ± 0,3 °C	0,727 Ω ± 984,0 ppm	88,55 W ± 926,0 ppm
	70,0 °C ± 1,0 °C	0,727 Ω ± 3279,0 ppm	88,55 W ± 2757,0 ppm
	70,0 °C ± 5,0 °C	0,727 Ω ± 16390,0 ppm	88,55 W ± 13620,0 ppm

A measurement system must include an accurate measurement of the temperature synchronised with the power measurement

I_r stands for EUT assigned current, in A.
T_k stands for temperature coefficient of EUT windings
P_{LL} stands for load losses, in W.
T_r stands for assigned temperature, in °C.

Taking a small academic example to calculate the consequences of a poor temperature measurement uncertainty gives the following with:
T_r = 75 °C, assigned temperature, in °C.
I_r = 10 A, EUT assigned current, in A.
T_k = 235 (Copper), temperature coefficient of EUT windings.
RT_r = 0.715 Ω ± 0 ppm EUT windings resistance at the temperature T_r

This example shows the importance of temperature measurement in computed results. It is obvious from these results that a measurement system must include an accurate measurement of the temperature synchronised 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.

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The best practice which arose from possibilities of modern data processing is that a measurement system directly provides accuracy of every measurement. These assessments are then stored as the calibration documents and are traceable to the national standards.

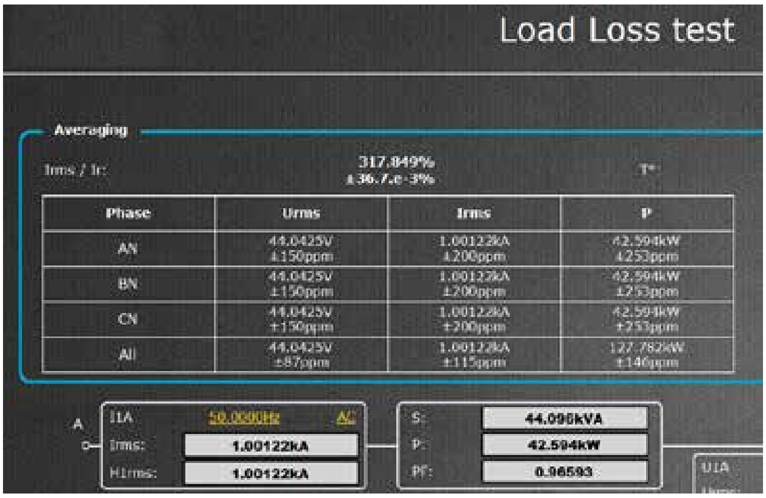

Figure 6: Live accuracy and printout of uncertainty in modern measurement system

Conclusion

This article shows that modern measurement systems are complex. The task of instrument transformers is not easy and requires various tradeoffs. Modern measurement systems are able to minimise the total uncertainty of the measurement process. Therefore, some characteristics should be guaranteed. The structure of the measurement system can help minimising tradeoffs and uncertainties. The combined structure of electronics and automation with well proven inductive measuring devices brings advantages of the two worlds together. The end user has to focus on easy handling, security and accuracy. All these points are important and greatly effect the process and the productivity of a lab.

The efforts that transformer manufacturer will make 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 prevail only if this improvement can be quantified with the highest degree of confidence.

References

[1] Scholand, M., Blackburn, T., Hopkinson, P., Sampat, M.: *SEAD Distribution Transformers Report Part 3*, www.superefficient.org, 2013
[2] Fogelberg, T.: *Transformer Losses – European commission Regulations and European Standards*, IEEEMA Trafotech Technical Papers, 2014
[3] Scholand, M., Blackburn, T., Hopkinson, P., Sampat, M.: *SEAD Distribution Transformers Report Part 2*, www.superefficient.org, 2013
[4] Metha, S. P., Petersons, O., NBS Technical Note 1204 – *Calibration of Test Systems for Measuring Power Losses of Transformers*, National Bureau of Standards, 1985

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