# On-site Measurement of Load and No-load Losses of GSU Transformer

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*Abstract:* - Present development and production of power transformers with lower losses in addition to replacement of outdated transformers assume regular measurement of losses in both load and no-load regime. These measurements are very demanding especially in the case of on-situ measurements. The complexity of the measurements grows with the size of transformer. This paper presents one typical test of losses measuring in load and no-load regime of power transformer with nominal power of 40 MVA in HPP Perucica.

*Key-Words:* - Load losses, No-load losses, Generator step-up transformer, Uncertainty of measurement

## 1 Introduction

Reduction of losses in electric network can significantly contribute and increase energy efficiency. Sources of losses are different and present in all parts of the system from production, transmission, distribution and supply of electricity. The biggest electricity systems in the world (USA, China, India, and Japan) apply significant efforts in the reduction of losses by replacing old with up to date power transformers.

Further development and production of power transformers with lower losses in addition to replacement of outdated transformers assume regular measurement of losses in both load and no-load regime. These measurements are very demanding especially in the case of on-situ measurements. The importance of measuring power transformer losses has also been extensively elaborated in technical standards and established recommendations which set the norms for the methodology of measurement and determination of losses in the nominal value of current, voltage, frequency and transformer operation temperature [2, 3]. From the metrological point of view, it is especially interesting and delicate to measure the transformer load losses on-site at extremely low power factors (p.f. < 0.1), particularly in the case of high power transformers [1].

## 2 On-site measuring of load and no-load losses

Measuring transformer losses in site is much more difficult than performing such measurement in a laboratory or a testing station. It is a considerable technical problem to provide appropriate measurement equipment, organize its transportation and dislocation in the power plant. Transformer losses measuring requires supply of the high power transformers by a regulated source from several hundred kilowatts to several megawatts, as well as to form measuring circuit for currents up to several kA, and voltages up to several hundred kV. Furthermore, there are additional problems caused by influence of electromagnetic and electric fields and safety aspect of work and measuring in a power plant.

The above problems were faced in practice during short circuit load loss and open circuit no-load loss measurement in a three-phase generator step-up transformers (GSU): rated voltage 121.5 kV / 10.5 kV, rated current 190.9 A / 2200 A, rated power 40 MVA, coupling YNd5, frequency 50 Hz, installed in the hydro power plant "Perucica", Montenegro. This transformer is in permanent exploitation more than 30 years.

### 2.1 Load loss measurement

In a short circuit test of a three-phase transformer, the following relevant values were measured: currents, voltages, active and reactive powers, phase parameters, power factors and frequency. Since the power factor in the short circuit test decreases with the value of the nominal power of the transformer, the problem of accuracy in power measurement is particularly evident in the case of high power

transformers, such as those directly connected to generators or the so-called generator step-up transformers (GSU). Simultaneous measurement of all these values poses technical, as well as metrological problems. Technical problem is shortest time interval to carry out measurement due to temperature rise in the windings. Metrological problem is possible systematic measurement errors due to unstable sources of supply and simultaneous readings, as well as accuracy of applied current transformers.

The measurement results show (Section 5) that the currents are of the order kA and apparent power of the order MVA. The electric scheme of the measurement circuit is shown in figure 1. The measurement of power, voltage, frequency, power factor and phase parameter was performed with a modern power multimeter with the error of ±0.1% of apparent power and current transformers class 0.5 and transformation ratio 2500A/5A. Considering that short circuit voltage is 11% and a voltage measurement range of the power multimeter is 1000 V, voltage transformers were not necessary.
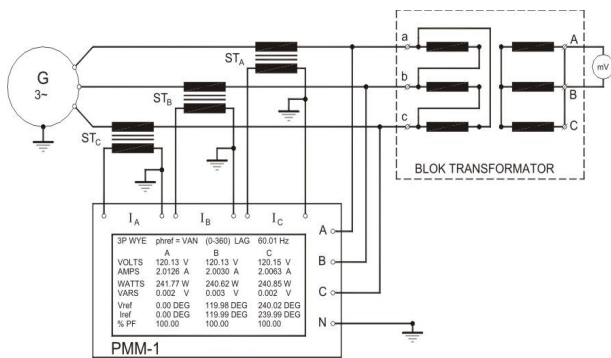


Fig.1 Load loss measurement circuit

The GSU transformer and the entire measuring circuit were supplied by the used power generator. Current transformers were installed by placing flexible conductors of a 180 mm$^2$ cross-section. The effectiveness of these connections points was tested by measuring voltage reduction at one of the short connectors.

## 2.2 No-load loss measurement

No-load losses measurement of GSU transformer was executed with 110 kV secondary circuit open. The transformer was supplied from 10.5 kV primary circuit by generator.

The primary circuit current measurement was performed using current transformer (for each phase). Primary phase voltages were measured by single-pole voltage transformers. Three-phase wire

system method with electronic wattmeter, three voltage instrument transformers and three current instrument transformers was used, figure 2.

During the test the following data were simultaneously measured and stored for each phase: voltage, phase angle of the voltage relative to chosen referent voltage ($\varphi=0°$), currents, phase angle of the current relative to referent voltage, active power, reactive power, power factor. During the measurement the values of the effective and average voltage were measured in order to verify the shape of supply wave and correction of measured power if necessary. The power supply sinusoid and existence of harmonics was performed by measuring of ratio between effective and average voltage level of supplied power. Correction of the measured power value due to harmonics in supply voltage could be calculated using the following equation [4]:

$$P_k = \frac{P_M}{0.5 + 0.5 \cdot (\frac{U_{ef}}{U_{av}})^2} \qquad (1)$$

where: $P_k$ is corrected power, $P_M$ is measured power, $U_{ef}$ is effective voltage level, $U_{av}$ is average voltage level.
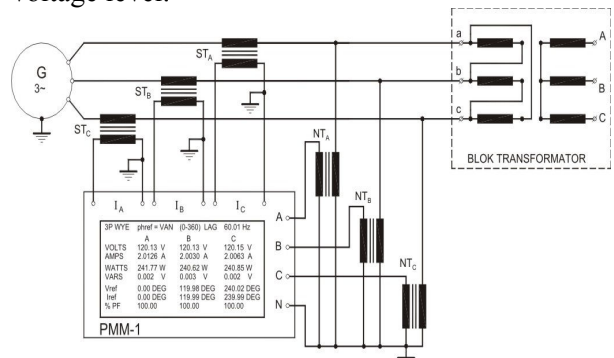


Fig. 2. No-load loss measurement circuit

Equation (1) is empirical and it is recommended for the voltage where the distortion is below 5%.
No load losses apart from frequency are mainly dependent on the supply voltage. No load losses power ($P_o$) is exponentially related to the supply voltage ($U_n$):

$$P_o = f \cdot (U_n^{x}) \qquad (2)$$

The value of exponent x in equation 2, is in the range from 1.5 to 4 depending on the construction of transformer and type of magnetic circuit. The most usual value of the exponent is about 2.

Measurement of losses was performed for several voltage levels in the range from 90% to 110% of nominal voltage.

The following equipment was used for the measurement of no-load losses of GSU transformer: electronic power multimeter for simultaneous measurement of current, voltage, active and reactive power, phase factor, phase and frequency with the error of +/- 0.1% of apparent power in all three phases, three voltage transformers 10500 V /√3 / 100 V/√3, 30 VA, class 0.5, and three current transformers 20 A / 5 A, 10 VA class 0.5.

## 3  Measuring errors and corrections of result

In the case of load losses measurement, the total error in power measuring in a three wire three-phase system with current transformers is defined as the sum of partial errors of the individual components of the measurement system:

$$g = g_W + \frac{1}{3} \cdot \left[ g_C - \delta_C \cdot \tan\varphi \right]_R + \qquad (3)$$
$$+ \frac{1}{3} \cdot \left[ g_C - \delta_C \cdot \tan\varphi \right]_S + + \frac{1}{3} \cdot \left[ g_C - \delta_C \cdot \tan\varphi \right]_T$$

In the case of no-load loss measuring, the total error in power measuring in a three wire three-phase system with current transformers is defined as the sum of partial errors of the individual components of the measurement system:

$$g = g_W + \frac{1}{3} \cdot \left[ g_C + g_V + (\delta_V + \delta_C) \cdot tg\varphi \right]_R +$$
$$+ \frac{1}{3} \cdot \left[ g_C + g_V + (\delta_V - \delta_C) \cdot tg\varphi \right]_S \qquad (4)$$
$$+ \frac{1}{3} \cdot \left[ g_C + g_V - (\delta_V - \delta_C) \cdot tg\varphi \right]_T$$

The following symbols have been used: $g_W$ - error of power multimeter, $g_C$ - amplitude errors of current transformers, $\delta_C$ - phase errors of current transformers, $g_V$ - amplitude error of voltage transformers, $\delta_V$ - phase errors of current transformers, and $\varphi$ - phase angle.

In equation 3 the impact of current transformer phase error is multiplied by the value of tan ($\varphi$), which is also the case with the declared error of the power multimeter. When the value of the phase angle is extremely low, which is exactly this case of load loss measurement, the measurement errors can reach even up to ten percent. The solution lies in the calibration of the power multimeter and current transformers in the range of voltage, current and phase parameter, including the real conditions of measuring losses of a specific transformer. The calibration of the power multimeter was conducted in a laboratory with varying values of current, voltage and phase parameter with power factor from 0.02 to 0.1. As a reference standard power calibrator was applied, who's declared error is less than ± 0.02% of the measured apparent power. In this particular case the power multimeter error did not exceed ± 0.5%, with measuring uncertainty of 0.2%. For calibration of current transformers compensating current comparator method was applied [5] and the calibration error was less than ± 0.005% and ± 50 μrad.

The errors of the power multimeter, current and voltage transformers determined in the calibration process will serve to establish the actual total measurement error, which is the basis for correcting the measurement results. Thus, the current and voltage transformers used in no-load loss measurement were also calibrated in real condition. Amplitude and phase error of used instrument transformers could be treated as systematic errors because they were calculated with measurement uncertainty of less than 0.05% i.e. 1'.

## 4  Uncertainty of measurement

The specified calibration errors are a part of the set of components that have a contribution in determining uncertainties of measurement in measuring transformer losses.

In addition to the above mentioned ones, the contributions of uncertainty of measurements in the case of load loss measurement also include: standard deviation, power multimeter resolution, the effect of the measured current on raising the temperature of transformer windings and the consequent increase of its resistance or power. The standard deviation in 11 repeated measurements was 0.27%. The resolution of measuring with a power multimeter was better for 0.01%; therefore, its weight in uncertainty of measurement can be totally disregarded. The same is with amplitude and phase errors of current transformers obtain by calibration. Consequently, the uncertainty of measurement for power multimeter calibration and the standard measurement deviation have the greatest impact. In determining extended uncertainty of measurement to a confidence level of 95 %, depending on the type of distribution, the standard deviation (normal distribution) is increased by an coverage factor of 2, while uncertainty of measurement in power multimeter calibration (rectangular distribution) is increased by an coverage factor of 1.65 [6]. Calculated in this way, the total (combined and

extended) uncertainty of load loss measurement is 0.72 %.

In the further conversion of the measured power load loss in transformers and bringing it in line with nominal power and reference temperature, the uncertainty of measurement is increased by the errors made in measuring the resistance of windings and the temperature. The error made in measuring the resistance of windings according to the applied U/I method does not exceed ±0.2 % of the measured value. The estimated error in temperature measuring is ± 1°C. Therefore, the uncertainties of load loss measurement brought in line with the reference conditions are increased by these additional error components, and amount to 0.84%.

In the case of no-load loss measurement the contributions to the standard uncertainty of measurement include: standard deviation, power multimeter error and resolution, uncertainty of amplitude and phase errors measurement of current and voltage transformers. Contributions to the standard uncertainty due to power multimeter calibration error and the standard measurement deviation have the greatest impact. In determining extended uncertainty of measurement to a confidence factor of 95 %, depending on the type of distribution, the standard deviation (normal distribution) is increased by a coverage factor of 2. Calculated in this way, the total (combined and extended) uncertainty of load loss measurement is 1.32 %.

## 5 Measuring results

The load losses were measured at different values of primary currents. In accordance with the above mentioned technical standards and recommendations, the short circuit losses and voltage were converted to the nominal current value and reference temperature of 75°C. The results of measurement are shown in Table 1.

The no-load losses were measured at different values of primary voltages, in accordance with the above mentioned technical standards and recommendations. The results of measurement are shown in Table 2.

## 4 Conclusion

The measurement results, as well as the analysis of measurement errors and uncertainty of measurement, indicate that it is possible to measure load and no-load losses in power transformers on-site. Although this is a demanding task, both from

the technical and metrological point of view, it can be performed successfully with the use of modern precise measuring equipment and extensive metrological preparation.

Table 1 Results of load loss measurement

| Measured volatage $U_m$ (V) | 444.24 | 538.65 | 596.32 |
|---|---|---|---|
| Measured current $I_m$ (kA) | 0.994 | 1.205 | 1.332 |
| Measured power $P_m$ (kW) | 40.29 | 59.35 | 73.19 |
| Temperature $t$ (°C) | 27.4 | 27.4 | 27.4 |
| Frequency f (Hz) | 49.96 | 49.95 | 49.96 |
| Measured power factor | 0.037 | 0.037 | 0.037 |
| Measured power at nominal current $I_n$ (kW) | 197.11 | 197.73 | 199.32 |
| Copper losses at nominal current $I_n$ (kW) | 138.8 | 138.8 | 138.8 |
| Added losses at nominal current $I_n$ (kW) | 58.31 | 58.93 | 60.52 |
| Load losses at 75 °C and nominal current $I_n$ (kW) | 214.84 | 213.86 | 215.21 |
| Copper losses at 75 °C and nominal current $I_n$ (kW) | 163.8 | 163.8 | 163.8 |
| Added losses at 75 °C and nominal current $I_n$ (kW) | 49.36 | 49.88 | 51.23 |

Measurement results show that load losses are 0.54% and no-load losses are 0.20% of nominal power.

The standard values of load losses of up to date power transformer 40 MVA is 0.42% i.e. 0.06% for no-load losses. Load losses of the tested transformer are 29% higher than in typical new one. No load losses are 333% higher. The certain improvement in the reduction of losses of up to date transformers is evident, especially no-load losses. This also illustrates necessity of the losses measurements for power transformers with the long exploitation age.

Table 2  Results of no-load loss measurement

| Measured voltage / Nominal voltage $U_m/U_n$ (%) | 89.90 | 96.71 | 101.23 | 106.18 |
|---|---|---|---|---|
| Measured current $I_m$ (A) | 24.16 | 41.36 | 60.68 | 90.00 |
| No-load losses (W) | 51.14 | 65.32 | 77.92 | 95.10 |
| No-load losses corrected (kW) | 52.54 | 67.97 | 82.03 | 101.65 |

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