Journal of ELECTRICAL ENGINEERING, VOL 63. NO 7s, 2012, 71-74

MEASURING THE REMANENT FACTOR OF TPY CLASS TRANSFORMERS

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The remanent factor K_r (the ratio between remanent flux density B_r and saturation flux density B_m) is an important parameter of TPY class transformers, which are used in protection systems. This paper focuses on a method for measuring the remanent factor K_r from the dynamic hysteresis loop, and on measuring uncertainty determination.

Keywords: remanent flux density, remanent factor, measuring system, hysteresis loop, transformers

1 INTRODUCTION

This paper focuses on measuring the remanent factor K_r, which is defined as the ratio between remanent flux density B_r and saturation flux density B_m

$$K_r = \frac{B_m}{B_r} \tag{1}$$

This factor is determined on the hysteresis loop of toroidal cores of instrument current transformers (ICTP) used in protection systems. Air gaps in the ICTP core enable large overranging of the rated current without oversaturating the magnetic circuit and without distorting the secondary current. The area where ICTP is not oversaturated depends on the air gaps, and increases with their width. According to the standard for ICTP [1] and [2], this area is determined by the K_r factor, and its value is therefore an important ICTP parameter. Most ICTPs have only a secondary winding wound on a toroid, and the primary winding is formed by one or several turns. The remanent factor K_r must therefore be determined from the hysteresis loop when magnetic field strength H and magnetic flux density B are picked up on a common (secondary) winding at 50 Hz frequency. The uncertainty when determining the K_r factor is also important, and an analysis of the uncertainty is also presented here.

2 THEORY

Hysteresis loops were measured in the layout shown in Fig. 1. A sufficient number of turns of the ICTP secondary winding (typically 1000 up to 2 000 turns) enables magnetization to be provided at sinewave magnetic field density B. This corresponds to the standard ICTP operating conditions. To ensure these conditions, resistor R_H with a value of 0.1 Ω up 2 Ω was used for sensing the strength of the magnetic field. The voltage on the winding corresponding to saturation state reaches values of (100 up to 300) V, so a passive integrator may be used for determining B without a substantive integration error occurring. Hysteresis loops for various air gaps measured using an Agilent 54621A oscilloscope are shown in Fig 2. Corresponding samples of H and B values averaged from 5 periods were fed into a PC by means of a CSV file, and K_r was calculated. The uncertainty when determining K_r is an important parameter for evaluating the measurement results. It depends on the errors in analog processing and also on the transformation into digital form using an oscilloscope. The use of one winding for H and B measurements causes a methodological error when the losses on the resistance of this winding are taken into account. Further errors of imperfect integration and the gain of the analog part of the oscilloscope will also be taken into account. The essential error is caused by the

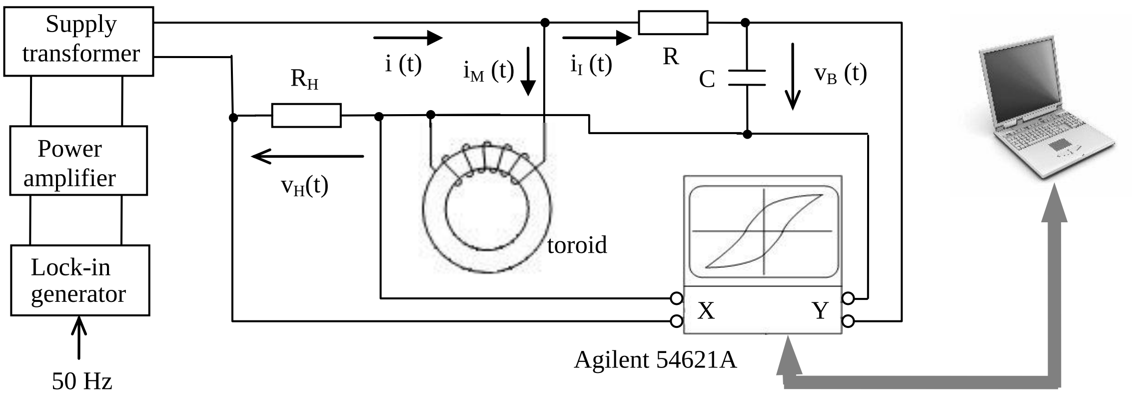

Fig. 1. Scheme of remanent factor measurement using a digital oscilloscope.

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A/D converter in the oscilloscope, which is usually eight-bit. The error caused by the conversion can be reduced by averaging a larger number of picked-up courses. Higher accuracy when determining K_r can be achieved using plug-in cards with fourteen or more bit resolution.

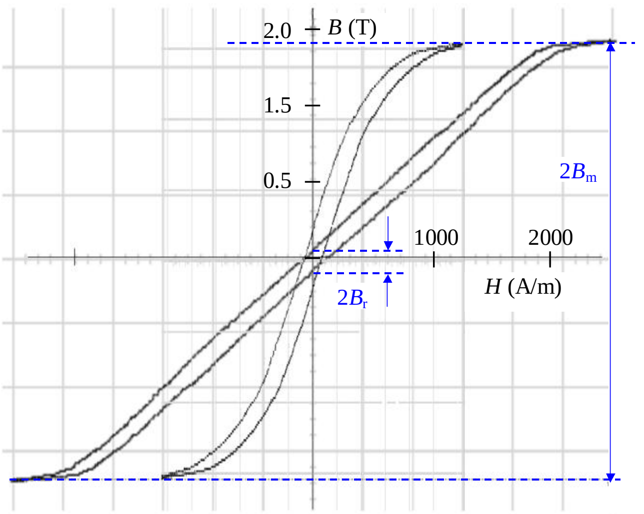

Fig. 2. Hysteresis loops for various air gaps.

3 ANALYSIS OF UNCERTAINTIES AND METHODOLOGICAL MEASUREMENT ERRORS

3.1 Measurement uncertainties

Type B uncertainty of the magnitude of the K_r factor has several components. There is the influence of H measurement, the influence of integrator error, and the influence of B measurement error. Assuming that the toroidal circuit has a sufficiently large air gap, the arms of the hysteresis loop in the non-saturated area may be described as

$$B(t) = k_B H(t) \tag{2}$$

where $k_B = \Delta B/\Delta H$ (TmA^{-1}) is the tangent of the angle formed by the linear arm of the loop and the H-axis. After substitution, instead of $H(t)$ we obtain for a toroidal specimen

$$B(t) = k_B \frac{N}{l_S R_B} v_H(t) = k_C v_H(t) \tag{3}$$

where N is the turn number of the secondary winding, l_S (m) is the mean magnetic path, R_B (Ω) is the magnitude of the pick-up resistor, v_H (t) is the voltage on the pick-up resistor, and k_C (TV^{-1}) = k_B $N/l_S R_B$. In the area of saturation, a part of the loop may be described as

$$B(t) = B(t)_{\max} = \text{const} \tag{4}$$

According to (1) – (4), the type B uncertainty of the K_r factor due to magnetic field strength H measurement uncertainty may be expressed as

$$\mathrm{u}_{K_r}(H) = \mathrm{u}\left(\frac{k_C v_H(t)_r}{v_H(t)_{\max}}\right) \tag{5}$$

where $v_H(t)_r$ is in the ideal case the voltage corresponding to the remanent induction B_r, when $v_H(t)_r = 0$ and $v_H(t)_{max}$ is the voltage in the H-axis corresponding to the maximum induction $B(t)_{max}$. According to (5), the relative value of the K_r uncertainty due to H measurement uncertainty may be expressed as

$$\delta u_{K_r}(H) = \delta v_H(t)_r + \delta v_H(t)_{\max} + \delta_{k_c} \tag{6}$$

where $\delta v_H(t)_r$ is the voltage measurement uncertainty $v_H(t)_r = 0$, $\delta v_H(t)_{max}$ is the voltage measurement uncertainty in the H-axis corresponding to maximum induction $B(t)_{max}$, and δk_c is the uncertainty of the k_c constant. Considering that in saturation the value of $B(t)_{max}$ in dependence on $H(t)$ is almost constant, the $\delta v_H(t)_{max}$ component may be neglected in (6). The uncertainty of k_c depends on the uncertainties of R_B, l_s and k_B. These uncertainties may be neglected when using an 8-bit oscilloscope, because the uncertainty due to sampling is essentially higher. The relative value of K_r uncertainty due to H measurement uncertainty may then be expressed as

$$\delta u_{K_r}(H) = \delta v_H(t)_r \tag{7}$$

which corresponds to the sampling error.

According to (1), the relative uncertainty due to the measurement uncertainty of the voltages corresponding to the B_r and B_{max} may be expressed as

$$\delta u_{K_r}(B) = \delta v_B(t)_r + \delta v_B(t)_{\max} \tag{8}$$

where $\delta v_B(t)_r$ is the uncertainty of the voltage measurement corresponding to induction B_r, and $\delta v_B(t)_{max}$ is the uncertainty of the voltage measurement corresponding to induction B_{max}. In both cases, the uncertainties are caused by the sampling error.

Most widely-used oscilloscopes (e.g. Agilent 54621A) have 8-bit A/D converters, representing 256 levels. The effective number of bits (ENOB) is in fact lower than the number given in the specification. When using signal averaging, the number of bits can be raised by 1 – 2 bits. Because the measurement is at low frequency (50 Hz), it can be calculated with effective bit number ENOB = 8 bit by switched-on averaging. The sampling error then corresponds to the last significant bit LSB, which is 0.4% FS. The error in determining B_r may therefore be (4 – 13)% for K_r = (10 – 3)%. Using an A/D converter with a higher bit number, e.g. 16-bit, the sampling error will be 0.0015% FS, and so the error in determining the magnitude of B_r will be noticeably decreased.

The influence of the integrator on magnetic flux density measurement is given by its time constant $\tau_B = RC$. The choice of a proper time constant is important, because a time constant that is too short causes imperfect integration, and an excessively high time constant means a needless decrease in the output voltage v_B(t). For $\tau_B >> T/2$, where T is the period time of the magnetizing current, the error δ_τ may according to [3] be expressed approximately at a certain point of the magnetizing curve (expressed as a percentage of the saturation induction) as

$$\delta_\tau \approx \frac{T}{2\tau_B} 100\ (\%) \qquad (9)$$

Assuming that $\tau_B \geq 1$ s, it will be $\delta_\tau \leq 1\%$.

According to the previous text, the resulting relative uncertainty of K_r determination may be expressed as

$$u_{K_r} = \sqrt{\delta u_{K_r}(H)^2 + \delta u_{K_r}(B)^2 + \delta u_\tau{}^2} \qquad (10)$$

3.2 Methodological measurement errors

The following methodological errors have an impact in K_r factor measurement on a toroid with one winding:

- The influence of the current flowing through the integrator $i_I(t)$ (see Fig. 1), for which it is necessary to fulfill $i_I(t) << i_M(t)$, *eg*

$$i_I(t) \leq 0{,}01 i_M(t) \qquad (11)$$

where $i_M(t)$ is the magnetizing current.

- The influence of the input impedance of the circuit for evaluating a signal which must be many times higher than the integrator output impedance

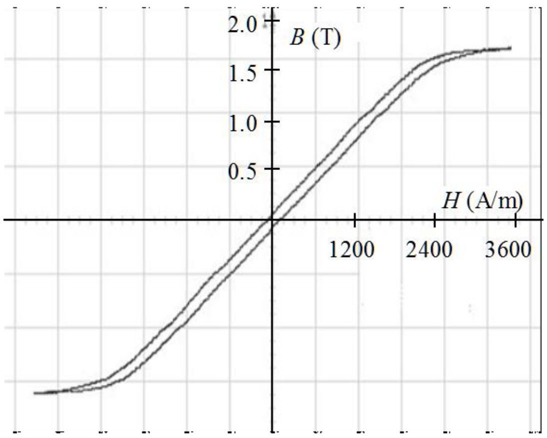

Fig. 4. Hysteresis loop measured by Agilent 54621A using only magnetizing winding

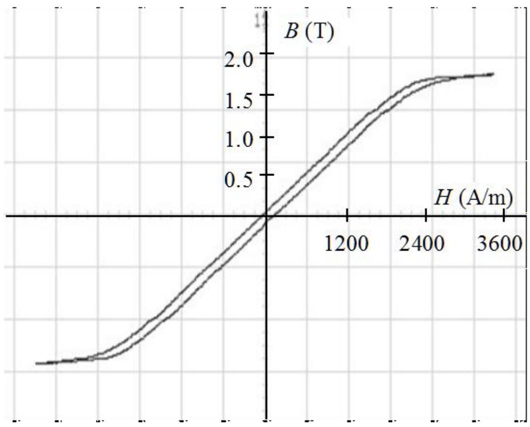

Fig. 5. Hysteresis loop measured by Agilent 54621A using magnetizing and auxiliary winding

The influence of losses in the magnetizing winding resistance of the specimen which were determined as the difference between total losses P_T and losses in the transformer core P_{Fe}. These losses were measured using a digital wattmeter. To measure the losses in the core, an auxiliary winding with 18 turns was wound for measuring B. The magnitude of the total losses was determined as P_T = 3.57 W, and the magnitude of the losses in the core was P_{Fe} = 3.05 W. It follows that the magnitude of the losses in the winding is P_{Cu} = 0.52 W. The magnitude of the losses in the winding amounts to 14.6% of the total losses. The magnitude of these losses has an influence on the area of the hysteresis loop, see Figs. 4 and 5.

4 MEASUREMENT RESULTS

4.1 Measurements using a digital oscilloscope

The measurement was performed on a specimen of a toroidal transformer with a winding of 1 000 turns and with 4 air gaps. For measuring the K_r factor with an Agilent 54621A 8-bit digital oscilloscope at 50 Hz we used a passive integrator with elements R = 100 kΩ and C = 20 μF.. The current $i_I(t)$ passing through the integrator is 3.3 mA, i.e. 0.5% of the magnetizing current $i_M(t)$. According to (9), the integrator error was determined as 0.5%. A pick-up resistor with magnitude 0.1 Ω was used, so the influence of the pick-up resistor may be neglected. The magnitude of the B_r value was determined with an error of 11.5%. It is evident that the methodological error and the uncertainty due to the integrator error is minimal against the sampling error when using an oscilloscope for determining the K_r factor.

The remanent factor K_r was measured using one winding (see Fig. 1) and also using two windings, when an auxiliary winding with 18 turns was wound on the specimen, when the influence of losses in the winding does not come into account. The measured hysteresis loops are shown in Figs. 4 and 5, and it is obvious that the differences between them are minimal. The remanent factor was determined identically as $K_r = (3.5 \pm 0.7)\%$ for coverage factor $k = 2$. From this, we may conclude that there is no essential influence of losses in the winding.

4.2 Measurement using a PC card

A CompuScope 1610 fast 2-channel oscilloscope card with 16-bit A/D converters, sampling rate up to 10 MS/s and 5 voltage ranges from ±500 mV up to ±10 V was used to improve the accuracy when determining the remanent factor K_r for the measured specimen.

An integrator with parameters R = 100 kΩ and C = 10 μF was designed for card input range 1 V. The current through the integrator $i_I(t)$ is 3.3 mA, which is 0.5% of the magnetizing current $i_M(t)$. According to (9), the integrator error was calculated as 1%. A pick-up resistor of magnitude 1 Ω was used, and the influence of the pick-up resistor may be neglected. The magnitude of the B_r value was determined with 0.05% error. The measured hysteresis loop is shown in Fig. 6. Using the CompuScope 1610 card, the magnitude of the remanent factor K_r was determined as (3.30 ± 0.04)% for for k = 2.

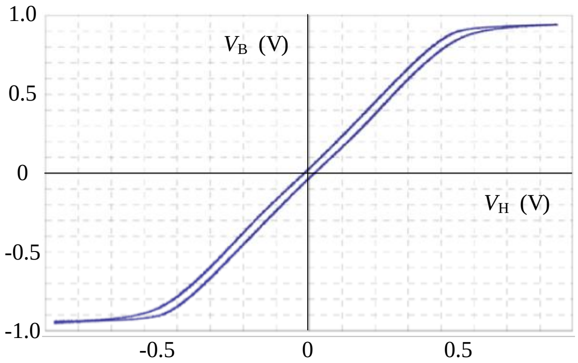

Fig. 6. Hysteresis loop measured by a CompuScope 1610 PC card, using only magnetizing winding

5 CONCLUSIONS

A method for measuring the remanent factor K_r for toroidal transformers with air gaps has been described, and the measurement uncertainties and methodological errors have been analysed. The measurement of the K_r factor was made on a specimen using an 8-bit digital oscilloscope when K_r = (3.50 ± 0.66)%, and using a PC card when K_r = (3.31 ± 0.04)%. The results show that when the measurement is made using an oscilloscope the uncertainty is dependent particularly on the sampling error and partly on the integrator error; other errors may be neglected. However, using a PC card the sampling error is very small and therefore the uncertainty depends mainly on the integrator error, and the influence of losses in the winding comes also into account.

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Received 8 September 2012

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