Experimental Procedure for Determining the Remanent Magnetic Flux Value Using the Nominal AC Energization

Original Scientific Paper

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Abstract *– The laboratory setup and corresponding experimental procedure for determining the remanent magnetic flux in the magnetic core of a single-phase transformer are presented in this paper. Using the proposed method, the remanent flux can be determined without prior knowledge of any parameter or past states of the transformer which is a significant advantage compared to previously known methods. Furthermore, reliable information about the remanent flux could be obtained using less equipment than other methods. Only electrical measurements are needed, without any physical intervention in the core or some other parts of the transformer. However, the major drawback is that some new unknown value of the remanent flux is set after the measuring procedure. Various initial conditions of the remanent flux and the closing voltage angle are set before each energization of the transformer to prove the validity of the proposed method, which can be used to obtain some characteristics of the remanent flux, such as stability over time or its dependence on some external factors.*

Keywords*: inductance, magnetic cores, magnetic flux, transformers*

1. INTRODUCTION

A magnetic core will contain a certain amount of the remanent magnetic flux (Φ_R), also known as residual flux, remanent magnetization or remanence, after the de-energization. An example of a ferromagnetic material's major magnetic hysteresis loop is shown in φ-i characteristics (Fig. 1).

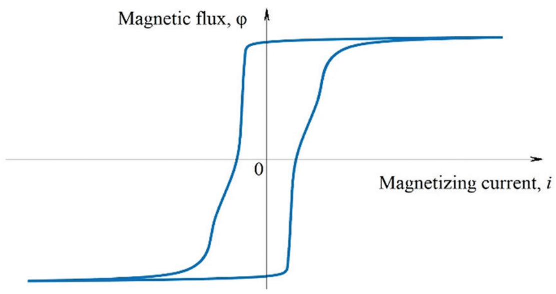

Fig. 1. An example of the magnetic hysteresis loop of a ferromagnetic material

The value of the remanent flux is essential in several areas in practice. One refers to reducing a coil or transformer inrush current by controlled switching [1-4]. Another application area where the remanent flux has an important impact is avoiding current transformer saturation [5-7]. Also, the remanent flux is important as one of the initial conditions in the ferroresonant circuit [8]. In almost all previously mentioned application areas, a magnetic core forms a closed loop, so the remanent flux is closed within the core itself and cannot be measured directly without physical intervention in the core.

However, some methods indirectly determine the remanent flux. The most widely used method is the determination of the remanent flux when de-energizing a coil or transformer by measuring the transformer terminal voltage during the de-energization [8, 9]. The basic idea is to determine the magnetic flux at the instant of de-energization by integrating the port-voltage.

This method is usually used to reduce the inrush current by controlled switching. It is quite simple, but it is unusable if the terminal voltage was not previously measured. Furthermore, the remanent flux can change its value while the coil is not energized if system transients occur [10], or even if there are no external impacts, due to the phenomenon called magnetic viscosity [11]. In that case, the method is unreliable.

Determining the remanent flux can also be done by measuring the leakage flux – the flux near the core is measured and then from the obtained results the remanent flux in the core is estimated [12-14]. Unlike the previous method, all possible changes of the remanent flux after the de-energization are taken into account. Disadvantages are its inaccuracy and high implementation costs – it is challenging to install a magnetic field sensor inside the power transformer tank in an aggressive environment and high temperature. On the other hand, installing the sensor outside the tank will not yield satisfactory results.

The remanent flux can also be determined using the low-voltage DC source for energization [15]. However, an additional DC voltage source is needed to determine the remanent flux utilising this method, while using the proposed method only the nominal voltage source available on-site is required. Furthermore, applying this method, the major hysteresis loop of the observed transformer needs to be obtained before determining the remanent flux, which is not the case in the proposed method. This method can be used in the same application areas as the proposed method.

The remanent flux could also be determined using the inductance value of the winding of a transformer [16]. As in [15], the transformer should be tested before using this method, and the correlation between the remanent flux and the inductance must be established. The conclusion is that the inductance will decrease if the remanent flux is high. However, this method is quite inaccurate – if the remanent flux value changes from zero to the maximum value, the inductance will change only 5% of its value.

Furthermore, the remanent flux could be determined using a minor hysteresis loop without any data regarding the last de-energization [17]. However, the transformer should be tested before using this method, and the relation between the remanent flux and the parameter WQ has to be established. But, it could be used for reducing the inrush current by controlled switching because the determined remanent flux will be preserved after the measurement process.

Finally, there is the method for determining the remanent flux which uses the nonlinear magnetizing characteristics of the core [18]. The basic idea is to energize a coil or transformer with the low voltage DC source and analyze the transient current. Prior to application of the method, the observed transformer should be tested and transient currents should be obtained for all possible remanent flux values. However, after applying this method, some unknown value of the remanent flux after the determination will be established.

There are also demagnetization and prefluxing techniques which actually do not determine the remanent flux, but set it to zero and the maximum value, respectively [19-21]. The basic idea of prefluxing is to set the remanent flux to the maximum positive or negative value prior to operation [22-25]. After demagnetization or prefluxing, the optimal switching angle for reducing the inrush current can easily be calculated. The devices used for demagnetization and prefluxing are simple in construction and operate using low DC voltage.

There is no adequate method for determining the remanent flux which can obtain some features, such as stability over time or how it is influenced by some external factors, except the method shown in [15]. Most of the previously mentioned methods cannot give satisfactory results regarding the precise and reliable value of the remanent flux in a closed magnetic core.

The laboratory setup and corresponding method for determining the remanent flux value will be presented in this paper. Although this paper will discuss only the remanent flux in the transformer core, the proposed method could also be appropriately applied to the iron core coil.

In most cases in practice, the possibility of setting the remanent flux to any value is not used for mitigating inrush current, due to the fact that setting magnetic flux value requests additional devices [20-24]. Thus, the methods most often used rely on integrating the measured port-voltage during the de-energization and assuming that the determined remanent flux will not change until the subsequent energization [2, 3, 9, 26]. The proposed method could be used to check this assumption, where one could consider the time-dependence of the remanent flux. In some cases, the time interval between de-energization and the next energization of the power transformer or coil (e.g. used for compensation of reactive power) could be a couple of months. Furthermore, it is proven that the remanent flux in the core can be changed even if the transformer is not energized [10]. Thus, using the proposed method, it can be investigated how system transients and external magnetic fields affect the remanent flux.

Finally, the remanent flux can be determined without any data about the past states. Furthermore, the parameters of the transformer, except the nominal voltage, should not be known. Only the voltage and current measurements should be conducted, meaning less equipment is required than in the other methods.

2. PROPOSED METHOD

The simple model of the winding of an unloaded transformer can be used as shown in Fig. 2 inside the dashed rectangle.

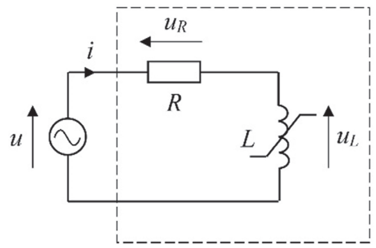

Fig. 2. The model of the winding of an unloaded transformer

The model consists of a linear resistance R in a series with a nonlinear inductance L with φ-i characteristics (Fig. 1) experimentally obtained. The resistance R represents the winding resistance. The model shown in Fig. 2 uses the φ-i characteristics of an unloaded transformer which including nonlinear characteristics with hysteresis. However, only the major magnetic hysteresis loop which is obtained for particular excitation (AC voltage, RMS 39 V, 50 Hz) is defined. The operating point or trajectory could be anywhere inside the loop for some arbitrary excitation. This makes the simulation model appropriate only for the steady state established for the previously mentioned excitation. However, there are some other models more appropriate for simulation, such as the lumped-circuit model by Chua and Stromsmoe [27], the Preisach model [28] and the Jiles-Atherton model [29]. The Chua mathematical model could not be used for the remanent flux simulation, because its nonlinear characteristics of the inductance and resistance are anhysteretic. On the other side, the Preisach and Jiles-Atherton models can be used to explain the remanent flux phenomenon as shown in [30] for the Preisach model. However, even if it is inappropriate for simulation in general, the role of model (Fig. 2) in this paper is to clarify the rationale behind our experimental procedure. Thereby, due to the straightforward physical explainability of the model, it was not necessary, given the focus of this paper, to use simulation as additional validation of the experiment. Our future research will address various already mentioned modeling and simulation methods, but also FEM and BEM modelling [31].

Assume that the AC source voltage is

$$u = \hat{U}\sin\omega t. \tag{1}$$

Kirchhoff's voltage law for the model shown in Fig. 2 equals

$$iR + N\frac{d\varphi}{dt} = \hat{U}\sin\omega t. \tag{2}$$

In the steady state, (2) for the DC components can be expressed as

$$I(0)R + N\frac{d\Phi(0)}{dt} = U(0), \tag{3}$$

where $I(0)$, $\Phi(0)$ and $U(0)$ are the DC components of the magnetizing current (i), the magnetic flux (φ) and the AC source voltage (u), respectively. Considering that the DC component of the AC source voltage, $U(0)$, is zero and concerning (3), the DC component of the magnetizing current, $I(0)$, must also be zero because $\Phi(0)$ has a constant value per definition and, thus, its derivative equals to zero.

Furthermore, considering that the magnetic flux (φ) is an odd function of the magnetizing current (i), as shown in Fig. 1, the DC component of the magnetic flux, $\Phi(0)$, in the steady state must also be zero.

The basic idea is to energize the unloaded transformer at the nominal AC voltage and measure the magnetizing current (i) and inductance voltage (u_L). The inductance voltage can be obtained as the difference between the measured transformer terminal voltage (u) and the product of the current (i) and the resistance (R):

$$u_L = u - iR. \tag{4}$$

Furthermore, the inductance voltage (uL) can also be obtained by measuring the voltage on the secondary unloaded winding and converting it to the primary side using the turns ratio. The magnetic flux (φ) in the core equals

$$\varphi(t) = \frac{1}{N}\int_0^t u_L(\tau)\,d\tau + \Phi_R, \tag{5}$$

where N is the number of the corresponding transformer winding turns, t and τ are the time variables, and Φ_R is the remanent flux value, that is, the magnetic flux at instant $t = 0$. Considering (5), the DC component of the magnetic flux (φ) in the steady state can be expressed as

$$\Phi(0) = \frac{1}{T}\int_{t_{ss}}^{t_{ss}+T}\left[\frac{1}{N}\int_0^t u_L(\tau)\,d\tau + \Phi_R\right]dt, \tag{6}$$

where T is the period of the AC source voltage. Considering that the DC component of the magnetic flux, $\Phi(0)$, in the steady state must be zero and concerning (6), the remanent flux (Φ_R) equals

$$\Phi_R = -\frac{1}{T}\int_{t_{ss}}^{t_{ss}+T}\left[\frac{1}{N}\int_0^t u_L(\tau)\,d\tau\right]dt, \tag{7}$$

Whereby it is crucial to choose the period for calculating the DC component in the steady state, not during the transient state. In other words, the instant t_{ss} must be in a steady state. Consequently, the remanent flux (Φ_R) can be obtained using the measured inductance voltage (u_L), that is, the calculated magnetic flux (φ_C):

$$\Phi_R = -\frac{1}{T}\int_{t_{ss}}^{t_{ss}+T}\varphi_C(t)\,dt, \tag{8}$$

$$\varphi_C(t) = \frac{1}{N}\int_0^t u_L(\tau)\,d\tau. \tag{9}$$

3. LABORATORY SETUP

The measurement circuit with the model shown in Fig. 3 is built to determine the remanent flux (Φ_R) by analyzing the unloaded transformer's inductance voltage (u_L) waveform. Various initial conditions of magnetic flux at the moment of de-energization (de-energization flux, Φ_D) and the closing voltage angle (α) will be set to prove the validity of the proposed method independently of the initial conditions.

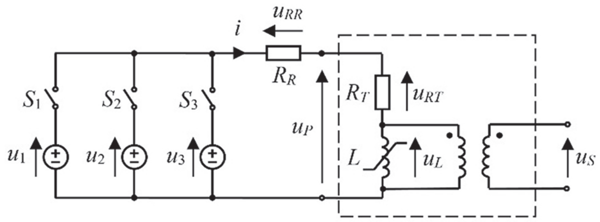

Fig. 3. The measurement circuit model

The measurement circuit model consists of the two winding transformer (inside the dashed rectangle), the resistance R_R, three variable AC voltage sources, u_1, u_2 and u_3, two electronically controlled switches S_1 and S_2, and the ordinary mechanical switch S_3. The transformer is modeled with the resistance R_T and the perfect transformer (ideal transformer with magnetizing inductance L included) connected in a series (Fig. 3). The magnetic characteristics of the nonlinear inductance L are shown in Fig. 1. Physical realization of the measurement circuit is shown in Fig. 4.

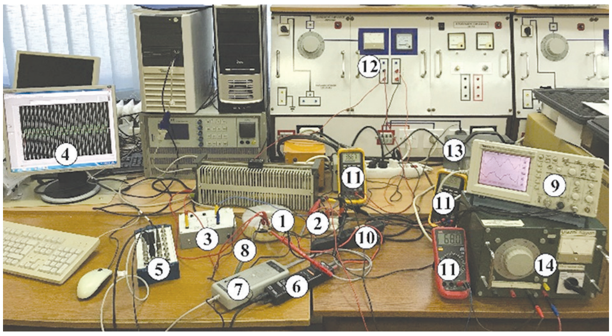

Fig. 4. Realization of the measurement circuit

The measurement circuit consists of: 1 – transformer under test, 2 – resistor R_R, 3 – electronic switching device, 4 – PC with installed data acquisition software, 5 – data acquisition card, 6 and 7 – active differential probes, 8 – passive voltage probe, 9 – oscilloscope, 10 – current probe, 11 – digital multimeters, 12 – variable AC voltage source u_1 used for the energization of the transformer, 13 – variable AC voltage source u_2 used for the setting of the de-energization flux, 14 – variable AC voltage source u_3 used for demagnetization.

The single-phase transformer (1, Fig. 4) is made of a toroidal core with two windings – 47 and 7 turns, both wired with triple wire (each has a round cross-section of 1.3 mm^2). The magnetic core (the cross-sectional area is 20 cm^2) consists of oriented transformer sheets (M5-type). The nominal power is 200 VA, nominal voltages are 30 V and 4.5 V, and nominal currents are 6.5 A and 44.5 A. The resistor R_T equals 0.19 Ω and inductance L equals 0.59 H in linear (non-saturated) area (Fig. 3). The purpose of the resistor R_R which equals 1.22 Ω (2, Fig. 4, also shown in Fig. 3) is to limit the inrush current. If not used, it could reach up to 120 A, devastating for the equipment used. The secondary winding terminals are used only for obtaining the voltage (u_S). The electronic switching device (3, Fig. 4) sets the initial remanent flux. All the measured values (magnetizing current, primary and secondary voltage) are obtained using the data acquisition (DAQ) card National Instruments NI-USB 6212 (5, Fig. 4) and the PC (4, Fig. 4). The waveform of the magnetizing current (i) is obtained indirectly by measuring the voltage on the additional resistor (R_R) using active differential probe GW Instek GDP-025 (6, Fig. 4). Furthermore, the primary voltage (u_P) is also obtained using active differential probe (7, Fig. 4) and the secondary voltage (u_S) using passive differential probe (8, Fig. 4). The sampling frequency was set to 50 kHz. The frequency of all the AC sources is 50 Hz. Furthermore, oscilloscope (9, Fig. 4) and digital multimeters (11, Fig. 4) were used only for monitoring the situation. All the measuring data used in this research is collected using the DAQ card and PC.

4. EXPERIMENTAL PROCEDURE

Every single measurement is carried out in three steps, but only to test the proposed method's validity. In possible application, only the third step of the experimental procedure should be carried out. The first step is AC demagnetization, carried out by slowly decreasing the voltage of the variable AC source u_3 from the RMS value of 36 V to zero in approximately 10 s, as shown in [32]. During the core demagnetization, the switches S_1 and S_2 are open. The demagnetization is important for setting the de-energization flux (Φ_D) value in the second step.

The second step follows up approximately 5 s after the first step, and it is done using the AC source u_2 and the switch S_2, while the switches S_1 and S_3 are open. The second step is described in detail in [15]. The value of the de-energization flux (Φ_D) is set by changing the RMS voltage of the variable AC source u_2 (U_2) and the instant of opening the switch S_2 (when the current is crossing zero value). In total, 25 different de-energization flux values are obtained in this experiment which corresponds to 13 different RMS voltages of the variable AC source u_2 (U_2), including zero value, and two different zero crossings of the magnetizing current in the φ-i characteristics. De-energization flux (Φ_D) values and corresponding RMS voltages U_2 are shown in Table 1. (only positive values due to the symmetry of the φ-i characteristics).

Table 1. Corresponding de-energization flux values and RMS voltages of the variable AC source u_2.

U_2 (V)	Φ_D (mVs)	U_2 (V)	Φ_D (mVs)
36	2.997	18	1.152
33	2.752	15	0.901
30	2.364	12	0.650
27	2.040	9	0.433
24	1.728	6	0.140
21	1.441	3	0.061

The third step follows up in less than 1 s after the second step. Thus, the value of the set de-energization flux (Φ_D) will be considered as the value of the remanent flux (Φ_R) in the core in the moment of energization of the transformer in the third step. This is the usual procedure when determining the remanent flux during the de-energization of the transformer by measuring the port-voltage [33, 34]. The third step of the experimental procedure is the only step which will be carried out in the possible application of the proposed method, and it is energizing the transformer using the AC source u_1 and the electronically controlled switch S_1, while the switches S_2 and S_3 are open. The RMS voltage of the AC source u_1 is set to 36 V which is 20% higher than the nominal voltage of the primary winding. It is done to obtain the steady state faster. Namely, the time constant that affects the length of the transient state is $L/(RT+RR)$ whereby the inductance L is not a constant value, but equals

$$L = \frac{d\varphi}{di}. \tag{10}$$

Thus, when the core reaches saturation, the inductance L is significantly lower than in the non-saturated region. Finally, the lower inductance L, the lower time constant means faster entry in the steady state. This is important because the remanent flux (Φ_R) value is obtained as the negative value of the DC component of the calculated magnetic flux (φ_C) in the steady state. The closing voltage angle (α), is set by the PC over the electronically controlled switch S_1. To prove that the different initial conditions of the de-energization flux (Φ_D) and closing voltage angle (α) do not affect the validity and accuracy of the proposed method, the measurements were carried out by varying the following parameters:

- U_2 = 36 V (-), 33 V (-), …, 0 V, …, 33 V (+), 36 V (+);
- α = 0°, 30°, 60°, 90°, 120°, 150°, 180°;

which in total gives 175 measurements. At the end, the obtained values of the remanent flux using the proposed method will be compared to the set values of the de-energization flux.

5. EXPERIMENTAL RESULTS

The obtained results for each measurement include the magnetizing current (i), the primary winding voltage (u_P), the secondary winding voltage (u_S), and the calculated magnetic flux (φ_C). Examples of the obtained waveforms are shown in Figs. 5, 6, 7, and 8, respectively.

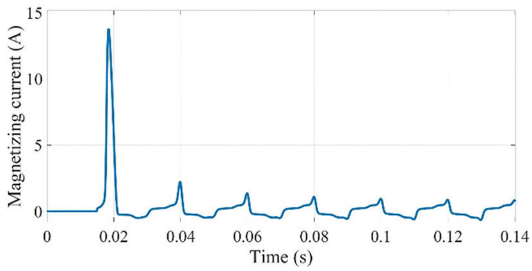

Fig. 5. Magnetizing current (i) for U_2 = 18 V (+) and α = 90°

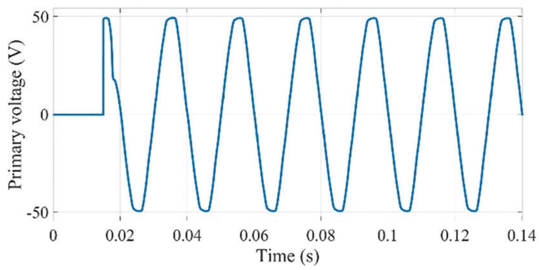

Fig. 6. Primary winding voltage (u_P) for U_2 = 18 V (+) and α = 90°

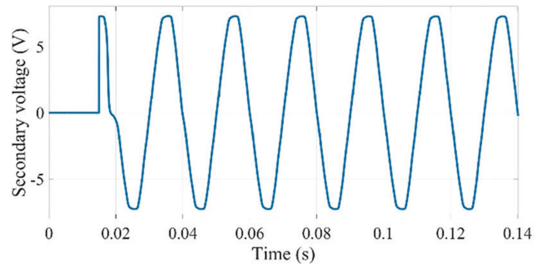

Fig. 7. Secondary winding voltage (u_S) for U_2 = 18 V (+) and α = 90°

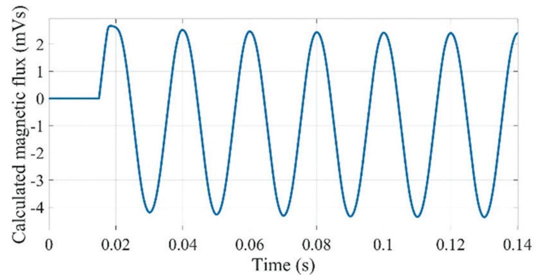

Fig. 8. Calculated magnetic flux (φ_C) for U_2 = 18 V (+) and α = 90°

For each measurement, the remanent flux (Φ_R) value is obtained as the negative value of the DC component of the calculated magnetic flux (φ_C) in the steady state. The obtained remanent flux (Φ_R) values are shown in Table 2, where parameter U_2 is marked with its value and sign (+) or (–) attached, depending on the sign of the set de-energization flux (Φ_D).

Table 2. Obtained remanent flux values

RMS voltage, U_2 (V)	Closing voltage angle, α						
	0°	30°	60°	90°	120°	150°	180°
36 (+)	3.082	3.083	3.085	3.080	3.078	3.079	3.077
33 (+)	2.752	2.788	2.757	2.747	2.748	2.751	2.766
30 (+)	2.123	2.179	2.164	2.369	2.330	2.178	2.337
27 (+)	1.805	1.881	2.104	2.078	1.872	1.864	2.055
24 (+)	1.605	1.721	1.557	1.705	1.664	1.750	1.609
21 (+)	1.323	1.455	1.378	1.344	1.536	1.309	1.242
18 (+)	1.160	1.326	1.041	1.018	1.252	1.189	1.280
15 (+)	1.004	1.072	0.868	1.026	0.913	0.864	0.892
12 (+)	0.584	0.508	0.606	0.687	0.544	0.645	0.650
9 (+)	0.377	0.378	0.445	0.370	0.454	0.353	0.429
6 (+)	0.273	0.331	0.339	0.310	0.340	0.312	0.267
3 (+)	0.167	0.163	0.186	0.151	0.181	0.143	0.148
0	–0.049	0.002	0.002	0.013	0.051	–0.037	–0.023

RMS voltage, U_2 (V)	Closing voltage angle, α						
	0°	30°	60°	90°	120°	150°	180°
3 (–)	–0.155	–0.128	–0.130	–0.139	–0.140	–0.156	–0.151
6 (–)	–0.308	–0.263	–0.278	–0.270	–0.307	–0.342	–0.335
9 (–)	–0.443	–0.386	–0.339	–0.457	–0.381	–0.438	–0.430
12 (–)	–0.714	–0.738	–0.713	–0.692	–0.644	–0.801	–0.614
15 (–)	–0.992	–0.756	–0.802	–0.974	–0.879	–0.887	–0.988
18 (–)	–1.065	–1.126	–1.087	–0.917	–1.006	–1.099	–1.239
21 (–)	–1.458	–1.261	–1.195	–1.447	–1.361	–1.360	–1.208
24 (–)	–1.543	–1.660	–1.771	–1.731	–1.502	–1.591	–1.847
27 (–)	–1.848	–1.825	–1.837	–2.067	–1.850	–2.054	–1.916
30 (–)	–2.159	–2.243	–2.295	–2.180	–2.238	–2.115	–2.291
33 (–)	–2.725	–2.735	–2.727	–2.702	–2.690	–2.749	–2.731
36 (–)	–3.051	–3.049	–3.028	–3.043	–3.048	–3.055	–3.057

For each parameter of U_2, the obtained remanent flux (Φ_R) value should be the same, regardless of the initial condition of the closing voltage angle (α). To evaluate this, for each parameter of RMS voltage U_2, the average remanent flux value ($\Phi_{R\_average}$) is calculated as

$$\Phi_{R\_average} = \frac{\sum_{i=1}^{7} \Phi_{Ri}}{7}. \tag{11}$$

Also, the standard deviation (σ) of the obtained remanent flux (Φ_R) values for each parameter of RMS voltage U_2 is calculated as

$$\sigma = \sqrt{\frac{\sum_{i=1}^{7} \left(\Phi_{Ri} - \Phi_{R\_average}\right)^2}{6}}. \tag{12}$$

Furthermore, the relative standard deviation ($\sigma_{\%}$) is calculated for each parameter of U_2 as

$$\sigma_{\%} = \frac{\sqrt{\frac{\sum_{i=1}^{7} \left(\Phi_{Ri} - \Phi_{R\_average}\right)^2}{6}}}{\Phi_{R\_average}} \cdot 100\ \%. \tag{13}$$

Table 3. Standard deviation and relative standard deviation of the obtained remanent flux values

RMS voltage U_2 (V)	Average remanent flux value, $\Phi_{R\_average}$ (mVs)	Standard deviation, σ (mVs)	Relative standard deviation, $\sigma_{\%}$
36 (+)	3.080	0.003	0.09%
33 (+)	2.759	0.014	0.49%
30 (+)	2.240	0.093	4.17%
27 (+)	1.951	0.114	5.82%
24 (+)	1.659	0.066	3.95%
21 (+)	1.370	0.091	6.63%
18 (+)	1.181	0.109	9.19%
15 (+)	0.949	0.078	8.21%
12 (+)	0.603	0.058	9.69%
9 (+)	0.401	0.037	9.35%
6 (+)	0.310	0.028	9.01%
3 (+)	0.163	0.015	9.42%
0	–0.006	0.031	535.62%
3 (–)	–0.143	0.011	7.43%
6 (–)	–0.300	0.029	9.63%
9 (–)	–0.410	0.039	9.60%
12 (–)	–0.702	0.057	8.06%
15 (–)	–0.897	0.087	9.69%
18 (–)	–1.077	0.092	8.59%
21 (–)	–1.327	0.100	7.51%
24 (–)	–1.664	0.117	7.03%
27 (–)	–1.914	0.097	5.06%
30 (–)	–2.217	0.063	2.84%
33 (–)	–2.723	0.019	0.69%
36 (–)	–3.047	0.009	0.30%

The measurement results show that the relative standard deviation ($\sigma_{\%}$) does not exceed 10% in any case, except for U_2 = 0 V. That exception is because the denominator value (average remanent flux) is near zero when calculating the relative standard deviation ($\sigma_{\%}$). Also, the relative standard deviation ($\sigma_{\%}$) lowers when the RMS voltage U_2 rises. The reason for these deviations could be in the second step of the experimental procedure when magnetizing the transformer, that is, setting the de-energization flux (Φ_D). In the first step of the experimental procedure, the transformer is demagnetized and this is done accurately. But the second step is critical in terms of accuracy, especially at lower magnetizing voltage values. At higher magnetizing voltage values, the relative standard deviation ($\sigma_{\%}$) is less than 1%. In these cases, the transformer goes into saturation even at the steady state, while at lower magnetizing voltage values it does not go into saturation at all. So, at lower magnetizing voltage values, the transformer will slowly enter a steady state because of the higher time constant in these cases. As a result, the magnetizing process in the second step does not always set the aimed de-energization flux (Φ_D) value accurately.

Finally, the obtained average remanent flux values for each parameter U_2 are compared to the corresponding de-energization flux (Φ_D) values shown in Table 1. The results are shown in Fig. 9.

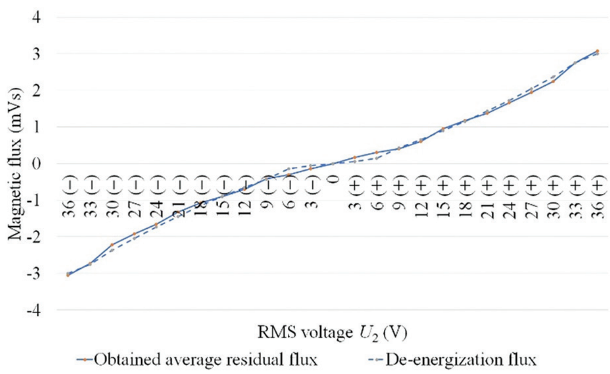

Fig. 9. Obtained average remanent flux values and corresponding de-energization flux values for each parameter of RMS voltage U_2

The obtained average remanent flux value is almost the same as the corresponding de-energization flux value for each parameter U_2, as shown in Fig. 9. Also, symmetry of the results can be seen in Fig. 9, which is the expected result because of symmetrical *φ-i* characteristics. The ratios of the obtained average values of remanent flux (Φ_R) and corresponding values of de-energization flux (Φ_D) are shown in Table 4 for each parameter U_2.

Table 4. Ratios of the obtained average values of remanent flux and corresponding values of de-energization flux

U_2 (V)	Remanent flux / De-energization flux	U_2 (V)	Remanent flux / De-energization flux
36 (+)	102.79%	36 (–)	101.69%
33 (+)	100.23%	33 (–)	98.93%
30 (+)	94.74%	30 (–)	93.78%
27 (+)	95.65%	27 (–)	93.80%
24 (+)	95.97%	24 (–)	96.25%
21 (+)	95.01%	21 (–)	92.07%
18 (+)	102.47%	18 (–)	93.46%
15 (+)	105.28%	15 (–)	99.55%
12 (+)	92.88%	12 (–)	108.08%
9 (+)	92.56%	9 (–)	94.81%
6 (+)	222.05%	6 (–)	214.98%
3 (+)	266.70%	3 (–)	233.93%

The results in Table 4 show that the average remanent flux values are between 93% and 108% of the corresponding values of de-energization flux in most cases. The exceptions appear only for parameters with RMS voltage $U_2 = 3$ V (+), $U_2 = 3$ V (–), $U_2 = 6$ V (+), and $U_2 = 6$ V (–). The reason for these exceptions could be the relatively small absolute values of the obtained remanent flux and corresponding de-energization flux which can cause higher measurement uncertainty. Another reason could be the imprecise setting of the de-energization flux in the second step of the experimental procedure.

6. CONCLUSION

The remanent flux can be determined using the presented experimental procedure without any data about parameters or past states of a transformer, using only electrical measurements. Some of the previously mentioned methods determine the remanent flux during the de-energization, which is very useful for reducing the inrush current by controlled switching. However, most of these methods cannot be used for investigating stability over time and the impact of the external excitations (system transients and magnetic fields) on the remanent flux in the core because they determine it in the moment of de-energization. Namely, those external excitations could change the remanent flux value while the transformer is not even connected to the grid. This means that the remanent flux can have a different value at the end of such an idle state, compared to the de-energization instant. On the other hand, the proposed method determines the remanent flux in the moment of energization of the transformer, that is, after an idle state. This means that the proposed method is unusable for reducing the inrush current by controlled switching because some new value of the remanent flux is established in the core after conducting the experimental procedure. It also means that the determined value will depend on the moment of the previous de-energization. Still, every change of the remanent flux between the previous de-energization and new energization will be taken into account, contrary to the other methods of determination during the de-energization. Thus, some new value of the remanent flux is established in the core after conducting the proposed method, but in investigating the stability over time and impacts of external excitations on the remanent flux, this drawback is not crucial because the goal is to determine how remanent flux was changed during the idle state, that is, its new value established at the end of the experimental procedure is not significant. Although there is a method similar to the proposed one which uses the low voltage DC source to determine the remanent flux, the proposed method could be more applicable because it uses the nominal voltage for energization, which could be easier to obtain on-site. Furthermore, the proposed method does not demand any data about the observed transformer, except the nominal voltage, which is not the case when using the method with the DC energization.

Finally, the other methods which determine the remanent flux during de-energization and the proposed method go along in investigating the stability over time and impacts of external excitations on the remanent flux. Namely, using the previously known methods, the remanent flux will be determined in the moment of de-energization and using the proposed method, the remanent flux will be determined in the moment of new energization, enabling comparison of these two values, that is, detecting the remanent flux changes due to the impact of external excitations.

7. REFERENCES:

[1] U. Parikh, B. R. Bhalja, "Mitigation of magnetic inrush current during controlled energization of coupled un-loaded power transformers in presence of residual flux without load side voltage measurements", International Journal of Electrical Power & Energy Systems, Vol. 76, 2016, pp. 156-164.

[2] J. H. Brunke, K. J. Fröhlich, "Elimination of transformer inrush currents by controlled switching - Part I: Theoretical considerations", IEEE Transactions on Power Delivery, Vol. 16, No. 2, 2001, pp. 276-280.

[3] S. Fang, H. Ni, H. Lin, S. L. Ho, "A Novel Strategy for Reducing Inrush Current of Three-Phase Transformer Considering Residual Flux", IEEE Transactions on Industrial Electronics, Vol. 63, No. 7, 2016, pp. 4442-4451.

[4] J. Song, T. Zheng, Y. Guo, L. Pan, "Suppression Strategy of the Inrush Current in the Transformer Phase Selection Closing Considering the Residual Flux", Proceedings of the 6th Asia Conference on Energy and Electrical Engineering, Chengdu, China, 2023, pp. 140-145

[5] E. Hajipour, M. Salehizadeh, M. Vakilian, M. Sanaye-Pasand, "Residual Flux Mitigation of Protective Current Transformers Used in an Autoreclosing Scheme", IEEE Transactions on Power Delivery, Vol. 31, No. 4, 2016, pp. 1636-1644.

[6] J. Duan, Z. Jin, Y. Lei, "Residual flux suppression of protective current transformers for autoreclosure process", Proceedings of the IEEE International Transportation Electrification Conference and Expo, Asia-Pacific, Harbin, China, 7-10 August 2017.

[7] S. Sanati, Y. Alinejad-Beromi, "Fast and Complete Mitigation of Residual Flux in Current Transformers Suitable for Auto-Reclosing Schemes Using Jiles-Atherton Modeling", IEEE Transactions on Power Delivery, Vol. 37, No. 2, 2022, pp. 765-774.

[8] K. Milicevic, D. Vinko, D. Vulin, "Experimental investigation of impact of remnant flux on the ferroresonance initiation", International Journal of Electrical Power & Energy Systems, Vol. 61, 2014, pp. 346-354.

[9] Y. Husianycia, M. Rioual, "Determination of the residual fluxes when de-energizing a power transformer/comparison with on-site tests", Proceedings of the IEEE Power & Energy Society General Meeting, San Francisco, CA, USA, 16 June 2005, pp. 449-454.

[10] D. Tishuai, Z. Bi-De, F. Chun-En, L. Wei, R. Xiao, C. Chuanjiang, "Influence of system transients on the residual flux of three-phase transformers", Proceedings of the 4th International Conference on Electric Power Equipment - Switching Technology, Xi'an, China, 22-25 October 2017, pp. 970-973.

[11] M. F. Lachman, V. Fomichev, V. Rashkovski, A. M. Shaikh, "Frequency response analysis of transformers and influence of magnetic viscosity", Proceedings of the 77th Annual International Doble Client Conference, 2010, pp. 1-18.

[12] D. Cavallera, V. Oiring, J. L. Coulomb, O. Chadebec, B. Caillault, F. Zgainski, "A new method to evaluate residual flux thanks to leakage flux, application to a transformer", IEEE Transactions on Magnetics, Vol. 50, No. 2, 2014.

[13] J. Horiszny, "Method of determining the residual fluxes in transformer core", Proceedings of the 18th International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering, Lodz, Poland, 14-16 September 2017, pp. 2-3.

[14] H. Zhang et al. "A New Method to Measure the Residual Flux by Magnetic Sensors and a Finite-Element Model", IEEE Transactions on Instrumentation and Measurement, Vol. 72, pp. 1-10, 2023.

[15] D. Vulin, I. Biondic, K. Milicevic, D. Vinko, "Laboratory setup for determining residual magnetic flux value using low voltage DC source", Electrical Engineering, Vol. 102, 2020, pp. 1707-1714.

[16] C. Wei, X. Li, M. Yang, Z. Ma, H. Hou, "Novel remanence determination for power transformers based on magnetizing inductance measurements", Energies, Vol. 12, No. 24, 2019.

[17] D. Vulin, K. Milicevic, I. Biondic, G. Petrovic, "Determining the Residual Magnetic Flux Value of a Single-Phase Transformer Using a Minor Hysteresis Loop", IEEE Transactions on Power Delivery, Vol. 8977, No. C, 2020, pp. 1-10.

[18] W. Ge, Y. Wang, Z. Zhao, X. Yang, Y. Li, "Residual flux in the closed magnetic core of a power transformer", IEEE Transactions on Applied Superconductivity, Vol. 24, No. 3, 2014, pp. 3-6.

[19] T. Zheng et al. "Fast, in situ demagnetization method for protection current transformers", IEEE Transactions on Magnetics, Vol. 52, No. 7, 2016, pp. 1-4.

[20] B. Kovan, F. De Leon, D. Czarkowski, Z. Zabar, L. Birenbaum, "Mitigation of inrush currents in network transformers by reducing the residual flux with an ultra-low-frequency power source", IEEE Transactions on Power Delivery, Vol. 26, No. 3, 2011, pp. 1563-1570.

[21] F. De Leon, A. Farazmand, S. Jazebi, D. Deswal, R. Levi, "Elimination of residual flux in transformers by the application of an alternating polarity dc voltage source", IEEE Transactions on Power Delivery, Vol. 30, No. 4, 2015, pp. 1727-1734.

[22] V. O. De Castro Cezar, L. L. Rouve, J. L. Coulomb, F. X. Zgainski, O. Chadebec, B. Caillault, "Elimination of inrush current using a new prefluxing method. Application to a single-phase transformer", Proceedings of the International Conference on Electrical Machines, Berlin, Germany, 2-5 September 2014, pp. 1717-1723.

[23] P. J. Kotak, P. Jaikaran, "Prefluxing technique to mitigate inrush current of three-phase power transformer", International Journal of Scientific and Engineering Research, Vol. 4, No. 6, 2013, pp. 135-141.

[24] D. I. Taylor, J. D. Law, B. K. Johnson, N. Fischer, "Single-phase transformer inrush current reduction using prefluxing", IEEE Transactions on Power Delivery, Vol. 27, No. 1, 2012, pp. 245-252.

[25] Y. Pan, X. Yin, Z. Zhang, B. Liu, M. Wang, X. Yin, "Three-Phase Transformer Inrush Current Reduction Strategy Based on Prefluxing and Controlled Switching", IEEE Access, Vol. 9, 2021, pp. 38961-38978.

[26] T. Liu, H. Siguerdidjane, M. Petit, T. Jung, J. P. Dupraz, "Reconstitution of power transformer's residual flux with CVT's measurement during its de-energization", Proceedings of the IEEE International Conference on Control Technology and Applications, Yokohama, Japan, 8-10 September 2010 pp. 206-209.

[27] L. O. Chua, K. A. Stromsmoe, "Lumped-circuit models for nonlinear inductors exhibiting hysteresis loops", IEEE Transactions on Circuit Theory, Vol. 17, No. 4, 1970, pp. 564-574.

[28] F. Preisach, "On the magnetic aftereffect", IEEE Transactions on Magnetics, Vol. 53, No. 3, 2017, pp. 1-11.

[29] D. C. Jiles, J. B. Thoelke, M. K. Devine, "Numerical determination of hysteresis parameters for the modeling of magnetic properties using the theory of ferromagnetic hysteresis", IEEE Transactions on Magnetics, Vol. 28, No. 1, 1992, pp. 27-35.

[30] A. Wilk, M. Michna, A. Cichowski, "Simulation of the remanence influence on the transient states of the single-phase transformer including feedback preisach model", Proceedings of the 40th Annual Conference of the IEEE Industrial Electronics Society, Dallas, TX, USA, 2014, pp. 875-880.

[31] M. Marković, Ž. Štih, B. Ćućić, "Power transformer main insulation design improvement using BEM and FEM", Proceedings of Eurocon 2013, Zagreb, Croatia, 2013, pp. 1553-1560

[32] D. Lovejoy, "Demagnetization", Magnetic particle inspection, Springer, Dordrecht, 1993, pp. 149-169.

[33] M. Rioual et al. "Field application of a synchronous controller based on the measurement of residual fluxes for the energization of a step-up transformer", Proceedings of the IEEE Power & Energy Society General Meeting, 2011, pp. 1-8.

[34] G. Petrović, T. Kilić, S. Milun, "Remanent flux measurement and optimal energization instant determination of power transformer", Proceedings of the XVII IMEKO World Congress 22-27 June 2003, Dubrovnik, Croatia, pp. 952-955.