NO-LOAD OPERATION OF SINGLE-PHASE TRANSFORMER AT LOW FREQUENCIES

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Abstract

The aim of this paper is to present novel results on the no-load test of the single-phase transformer at low frequencies. The paper reviews briefly requirements of the relevant IEC standard for no-load testing, presents details on laboratory equipment for PC based measurement of no-load current and no-load power loss and gives a detailed discussion of the results obtained.

Keywords: power transformer, no-load test, no-load current, power loss.

INTRODUCTION

The power transformer core is designed according to the rated secondary voltage, the rated frequency and the number of turns in the secondary winding. The voltage and the frequency are predefined, and after choosing the number of turns, the cross-section area needs to be chosen so as to keep the magnetic flux density in the core at low level, since the power loss in the core are directly proportional to the magnetic flux density. Operation of a transformer at voltages and frequencies outside the rated values may lead to the increase of the magnetic flux density and power loss in the core. Such operation should be avoided. However, there are cases when such operation is necessary, especially for small transformers in laboratories during some specific experiments.

Interesting is the case of transformer operation at frequencies lower than rated frequency. Keeping voltage at the rated level and decreasing of the frequency will increase the magnetic flux density in the core. This may lead to the magnetic core saturation and significant increase of power loss in the core. However, there are no significant reports on this effect in the relevant scientific literature.

The easiest way of observing the core saturation is to perform the no-load test of the transformer and to measure the no-load current and power loss. Such test is described in the international standard [1]. It is very shortly presented and discussed in the literature [2, 3]. Usually, it is a part of some comprehensive research on power transformers. To the best of the authors knowledge, there are no valid results of such test at frequencies lower than rated. However, there are in the existing literature references that discuss the presence of sub-harmonics in the supply voltage during the no-load test of power transformer [4-6].

This paper presents results on the no-load test of power transformer at low frequencies. The transformer under study is a single-phase unit with EI core, rated at 1 kVA, 230 V/12 V, 50 Hz. The no-load test has been performed with the sinusoidal primary voltage of 50 V (peak value) at frequencies 50 Hz, 30 Hz, 10 Hz, 9 Hz, 8 Hz, 7 Hz, 6 Hz and 5 Hz. The waveforms of the primary voltage, the secondary voltage and the primary current have been recorded using a PC based measurement setup. Also, the power loss and the RMS value of no-load current have been recorded during the tests. The results obtained and a proper discussion have been given in the paper.

STANDARD REQUIREMENTS ON NO-LOAD TEST FOR TRANSFORMERS

Relevant standard for power transformers are published by International Electrotechnical Commission (IEC). It is a non-profit, nongovernmental organization that publishes international standards relating to electrical, electronic and other technologies (including energy, electromagnetics and other). IEC members are National committees for electrotechnics from countries participant. Technical Committees (TC) play a key role in the preparation of standards and they gather more than 10 000 experts. The IEC currently has more than 80 full and associate members, as well as 174 Technical Committees (TC) and Subcommittees (SC).

Through its members, the IEC promotes international cooperation on all issues from electro-technical standardization and issues related to standardization, such as a rating of conformity with a standard. The goals of the IEC are to efficiently meet global market requirements, to provide the leading role and maximum use of IEC standards and conformity assessment schemes around the world, to establish conditions for interoperability of complex systems, to evaluate and improve quality products and services covered by IEC standards, to increase efficiency industrial processes, to contribute to the improvement human health and safety, and to contribute to the protection of the environment.

General requirements for tests on power transformer are given in IEC 60076-1 standard [1]. The no-load test is the routine test for all transformers and consist of measurement of no-load current and power loss at rated voltage and frequency. The transformer needs to be approximately at ambient temperature. The test power source needs to provide sinusoidal voltages. At the same time, a voltmeter responsive to the RMS value of voltage need to be connected in parallel with the mean-value voltmeter. The test voltage wave shape is satisfactory if the readings of two voltmeters are equal within 3 %.

The standard requires that the RMS value of no-load current and the power loss are measured at the same time.

TRANSFORMER UNDER TEST

The transformer under test is a single-phase unit with EI core. The core has been made of M530-50A non-oriented electrical steel sheets. The transformer is rated at 1 kVA, 230 V/12 V and 50 Hz. A geometry of the magnetic core and a photo of the tested transformer are presented in Fig. 1.

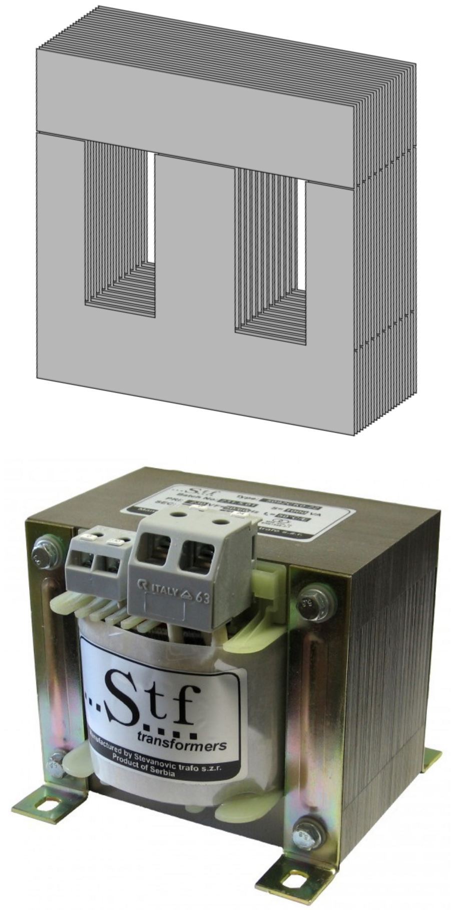

Fig. 1. *Geometry and photo of tested transformer*

MEASUREMENT SETUP AND TEST CONDITIONS

A PC based measurement setup has been presented in Fig. 2.

The time-varying voltage with adjustable frequency and sinusoidal shape has been generated by the power supply. This voltage has been supplied to the primary winding of the tested transformer over the non-inductive resistor R. The no-load current i_1 has been calculated using measured voltage u. The primary voltage u_1 has been measured at the ends of the primary winding and the secondary voltage u_2 has been measured at the ends of the secondary winding. These voltages have been measured using a virtual instrument on PC, made in LabVIEW software, connected to the data acquisition card.

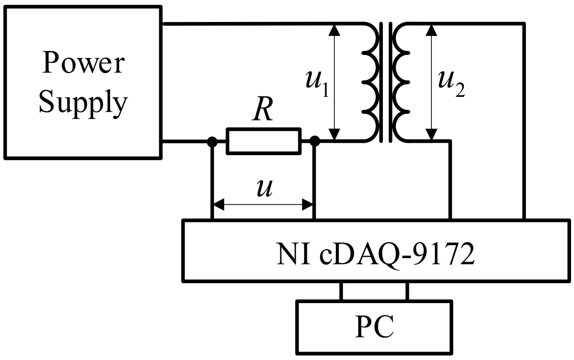

Fig. 2. *Measurement setup based on personal computer*

All measurements have been performed under controlled sinusoidal shape of the primary voltage and with a condition that the measured primary voltage amplitude amounts 50 V. This voltage level is much lower than the rated voltage (230 V) and it has been chosen so to satisfy a condition that measured primary and secondary voltage have a sinusoidal shape during the experiment. A higher level of the supply voltage would cause voltage distortions at lower frequencies and the tests would not be valid. The experiment has been performed at frequencies of 50 Hz, 30 Hz, 10 Hz, 9 Hz, 8 Hz, 7 Hz, 6 Hz and 5 Hz.

During each test, the virtual instrument plots waveforms of the no-load current and the primary and secondary voltage. Also, it calculates and indicates the no-load loss, the RMS value of no-load current, as well as other results of interest. All measured and calculated data has been saved in the memory of the PC.

RESULTS AND DISCUSSION

The most interesting measurement results obtained during the no-load tests on the power transformer are presented in this section of the paper.

A form factor of the primary and secondary voltage in all tests amounted 1.111±1 %, which indicates their sinusoidal time waveforms. Since the primary voltage amplitude has been set to 50 V at each test, the waveforms of this voltage at all frequencies are identical. The secondary voltage amplitude amounted 2.74 V at all frequencies and all the waveforms are identical. Therefore, these waveforms have not been compared graphically.

On the other hand, waveforms of measured no-load currents are different and it is interesting to compare their shapes. Since different frequencies have been applied, a comparison could not be made in the time scale. Therefore, time scale has been replaced with electrical angle scale and the obtained waveforms are presented in Fig. 3. A primary voltage waveform is presented along with the current waveforms in order to prove its sinusoidal shape.

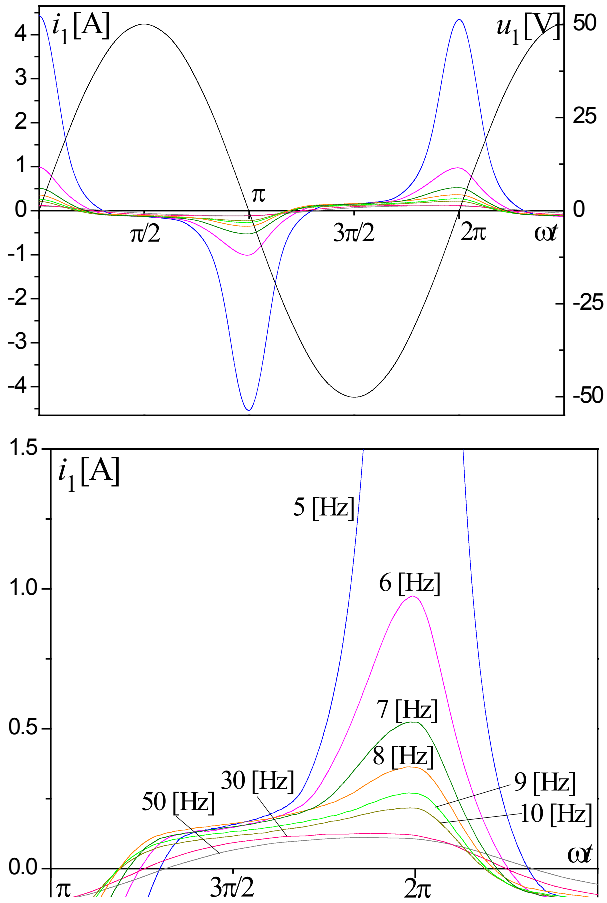

Fig. 3. *Measured waveforms of no-load current at different frequencies*

Lower graph presents zoomed part of the upper graph with frequency data related to each waveform. It can be seen from these graph that amplitude and distortion of the no-load current increases with the decrease of the frequency. The increase is not significant at 30 Hz in comparison to 50 Hz. However, the decrease of the frequency to 10 Hz produces significant distortion and increases the current amplitude. Since the level of the secondary voltage U_2 is kept constant, the decrease of the frequency f causes the increase of the magnetic flux density B, according to (1) [3]:

$$B_{\max} = \frac{U_2}{\sqrt{2}\pi N_2 S f}, \qquad (1)$$

where N_2 is the number of turns in the secondary coil and S is the core cross-section area. The magnetic field in the transformer core will also increase. These two quantities are coupled by the hysteresis effect of the ferromagnetic material, non-oriented electrical steel in this case. Increase of the magnetic field inside the core is followed by the increase of the electric current in the primary coil (no-load current). A further decrease of the frequency causes even larger increase of the magnetic flux density and the magnetic field, as well as the no-load current.

A variation of the amplitudes and RMS values of no-load current with frequency has been given in Table 1.

Table 1

Amplitudes and RMS values of no-load current

$f\,[\mathrm{Hz}]$	$I_{0\max}\,[\mathrm{A}]$	$I_{0RMS}\,[\mathrm{A}]$
50	0.111	0.083
30	0.124	0.095
10	0.218	0.146
9	0.268	0.165
8	0.360	0.204
7	0.525	0.276
6	0.974	0.474
5	4.348	1.821

Therefore, a decrease of the frequency, at the constant amplitude of the primary voltage, during no-load test of the power transformer manifest as the increase of the no-load current. According to the results given in Table 1, ten times decrease of the frequency causes 39 times increase of the amplitude and 22 times increase of the RMS value of no-load current.

Also, a similar effect has been registered on no-load loss. A variation of the no-load loss and the apparent power with frequency has been given in Table 2.

Table 2

No-load loss and apparent power

$f\,[\mathrm{Hz}]$	$P_0\,[\mathrm{W}]$	$S_0\,[\mathrm{VA}]$
50	1.41	2.94
30	2.15	3.38
10	3.46	5.20
9	3.62	5.86
8	3.87	7.19
7	4.30	9.77
6	4.92	16.82
5	7.83	64.48

Consequently, the no-load loss, as well as the apparent power, also increase with the decrease of the frequency at the constant amplitude of the primary voltage. According to the results given in Table 2, ten times decrease of the frequency causes 5.55 times increase of the no-load loss and 22 times increase of the apparent power.

CONCLUSION

This paper discusses a no-load operation of power transformer at frequencies much lower than rated frequency. The no-load current and the no-load loss are the quantities of interest, according to the international standard, that need to be measured during such operation.

The paper presents simple experimental setup based on a PC with LabVIEW software for performing of the no-load test of power transformer. It is designed and made so to provide measurement results of all quantities of interest, primarily the no-load current and the no-load loss. The experiments have been performed on a single-phase transformer with EI core, rated at 1 kVA, 230 V/12 V, 50 Hz. Its core has been made of the non-oriented electrical steel sheets of M530-50A grade.

All measurements have been made under the sinusoidal primary voltage of 50 V amplitude at frequencies 50 Hz, 30 Hz, 10 Hz, 9 Hz, 8 Hz, 7 Hz, 6 Hz and 5 Hz. The waveforms of the primary voltage, the secondary voltage and the primary (no-load) current have been recorded. Also, the power loss and the RMS value of no-load current have been recorded during the tests.

According to the presented results, a decrease of the frequency of primary voltage during the no-load test of the power transformer causes the increase of the no-load current. In the particular case, ten times decrease of the frequency has caused 39 times increase of the amplitude and 22 times increase of the RMS value of no-load current. Also, the no-load loss and the apparent power also increase, 5.55 times and 22 times, respectively. This can be simply explained as follows:

- the decrease of the frequency causes the increase of the magnetic flux density in the transformer core, since the voltage level at the secondary kept it constant,

- the increase of the magnetic flux density is followed by the increase of the magnetic field,
- the increase of the magnetic field inside the core causes the increase of the electric current in the primary coil (no-load current),
- two magnetic quantities are coupled by the hysteresis effect of the core material (non-oriented electrical steel) and the no-load current increases and becomes distorted when the material is approaching saturation,
- finally, the increase of the magnetic quantities, as well of the no-load current, under the same voltage, causes higher power loss in the magnetic core.

The authors consider that presented results and the discussion would be of interest to the engineers who deal with the designing or the operation of power transformers, as well as to the students of the electrical engineering in better understanding of the theoretical and working principles of power transformers.

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