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Short-circuit and load operation of single-phase transformer at low frequencies

***Abstract**. The aim of this paper is to present experimental results on the short-circuit and load test of the single-phase transformer at low frequencies. The paper gives information on PC based measurement setup and presents the results of measurement of primary and secondary voltages and currents and electric power of the transformer. Also, a proper discussion of the results obtained is given in the paper*

Streszczenie.** W artykule przedstawiono rezultaty badania zwarcia I obciążenia jednofazowego transformatora niskoczęstotliwościowego. Przedstawiono system komputerowy do badań i rezultaty pomiarów prądów I napięć w obwodzie pierwotnym I wtórnym. **Badania niskoczęstotliwościowego transformatora w stanie zwarcia i przy zmiennym obciążeniu

Keywords: power transformer, short-circuit test, load operation, power loss.
Słowa kluczowe: transformator jednofazowy, badania, zwarcie.

Introduction

Previous research on the operation of a single-phase power transformer at low frequencies was conducted under no-load conditions [1]. It was found that primary current of the transformer increases with the decrease of the frequency (at constant amplitude of primary voltage). Also, this current becomes significantly distorted from the sinusoidal shape, which indicates increase of the magnetic flux density in the transformer core and approaching to the magnetic saturation [2].

The aim of this paper is to present results of continuation of research on the operation of the transformer at low frequencies in the case of short-circuit or load conditions. General requirements on such testing are given in the international standard [3]. Short overview of these tests exists in the literature [4, 5].

The results of the short-circuit and load test of power transformer at low frequencies are presents in this paper. The transformer under study is a single-phase unit, rated at 1 kVA, 230 V/12 V, 50 Hz. It has an EI core. Tests are performed at different frequencies from 1 Hz to 50 Hz. The amplitude of secondary current has been maintained at 100 A during the short-circuit test and the amplitude of primary voltage has been maintained at 25 V during the load test. PC based measurement setup is used to record time waveforms of primary and secondary voltages and currents. The input power is also recorded during the tests. The paper presents experimental results obtained and gives their discussion.

Standard requirements on short-circuit and load test for transformers

The International Electrotechnical Commission (IEC) publishes relevant standards for power transformers. Published standards are related to electrical and other bonding technologies. IEC members are National committees for electrotechnics from participant countries. Technical Committees (TC) play the main role in the preparation of standards, gathering more than 10 000 experts. Nowadays, IEC is constituted of more than 80 full and associate members, it has 174 Technical Committees (TC) and Subcommittees (SC). The IEC promotes international cooperation on all issues from electrotechnical standardisation and the rating of conformity with a standard.

General requirements for tests on power transformer are given in IEC 60076-1 standard [3]. The short-circuit test is the routine test for all transformers and it should be performed at rated frequency with voltage applied to the terminals of one winding, with the terminals of the other winding short-circuited. The supplied current should be equal to the relevant rated current but should not be less than 50 % thereof. The transformer needs to be approximately at ambient temperature. The standard requires that the short-circuit voltage and power loss are measured during this test.

Operation of power transformer under load conditions is not a subject of IEC standards.

Tested transformer

Tested transformer is a single-phase transformer with EI core. Non-oriented electrical steel sheets (grade M530-50A) are used for production of its core. It is rated at 1 kVA, 230 V/12 V and 50 Hz. A photo of the tested transformer and a geometry of the magnetic core are presented in Fig. 1.

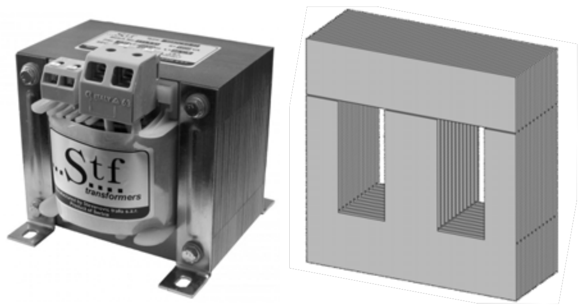

Fig.1. Photo of tested transformer and geometry of magnetic core

Experimental setup and measurements

Scheme of electrical connections for PC based measurement is presented in Fig. 2. Power supply generates time-varying voltage of sinusoidal shape with adjustable frequency. This voltage is supplied to the primary side of transformer over the non-inductive resistor R1. Primary and secondary currents i1 and i2 are calculated using measured voltages uR1 and uR2. Primary voltage u1 is measured using voltage divider connected at the ends of primary winding and secondary voltage u2 is measured directly at the ends of secondary winding. LabVIEW application is made and used in the measurement of these voltages and currents. Its appearance during the measurements under load conditions at a frequency of 5 Hz is presented in Fig. 3.

Measurements for the short-circuit test have been performed under such a condition that the amplitude of measured secondary current amounts 100 A. This is slightly lower than the amplitude of rated secondary current (118 A) and it has been chosen so in order to avoid overcurrent conditions at the primary side of the transformer. Measurement for load test have been performed with a resistive load at the secondary of the power transformer. This load is rated with 0.1 Ω and 40 W. Testing has been performed in such a way that the amplitude of measured primary voltage amounts 25 V and the secondary current is lower than the rated current of the load. The experiments have been performed at frequencies of 50 Hz, 30 Hz, 10 Hz, 8 Hz, 5 Hz, 2 Hz and 1 Hz.

A virtual instrument plots the waveforms of primary and secondary voltages and currents. Also, it calculates and indicates power loss, as well as other results of interest. All measured signals and data of interest have been saved in the memory of a personal computer.

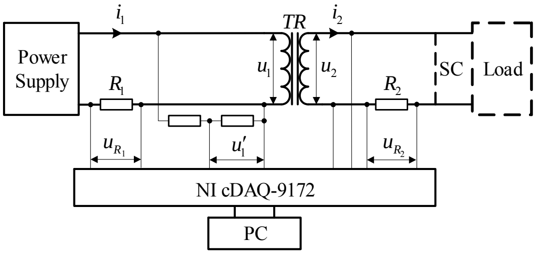

Fig.2. Measurement setup based on personal computer (SC - short-circuit)

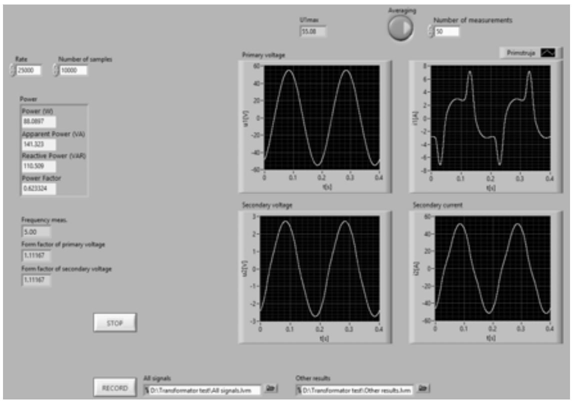

Fig.3. Front panel of LabVIEW application during the experiment

Results and discussion

It is of interest to present waveforms of measured voltages and currents during transformer testing. In order to have a proper comparison of the waveforms obtained at different frequencies, time scale has been replaced with electrical angle scale. Thus, Figs. 4 and 5 respectively present compared waveforms of primary and secondary voltages and currents during the short-circuit and load test obtained at different frequencies. These waveforms show that a distortion from a sinusoidal shape (form factor is 1.11) appears in the measured signals when the frequency is decreasing. During the short-circuit test, this distortion is very pronounced at the lowest frequency of 1 Hz. Very small distortion can be noticed in the primary current at a frequency of 2 Hz, while other signals are not distorted. Also, the signals are not distorted at higher frequencies.

The amplitude of secondary voltage during this test amounted around 0.15 V, which is very low value in comparison to rated 12 V. This voltage is directly proportional to the magnetic flux density in the transformer core (according to Faraday's law) and its low value keeps magnetic flux density at low value, except at a frequency of 1 Hz. Significant increase of the magnetic flux density increases the magnetic field in the core, which requires higher primary current, much higher than the rated primary current, as it has been given in Table 1. The core is near saturation and the magnetising current and induced voltage are highly distorted.

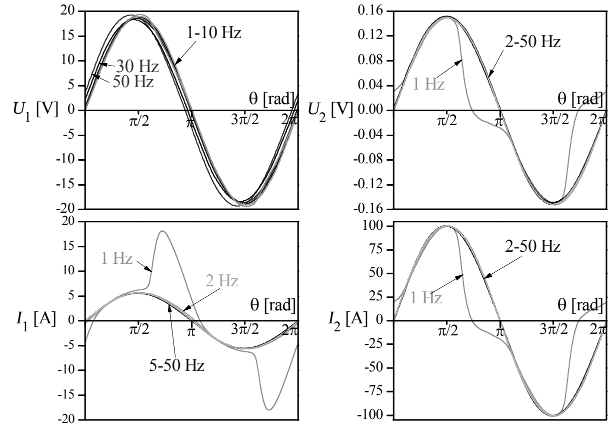

Fig.4. Waveforms of primary and secondary voltages and currents during short-circuit test

Besides amplitudes of primary current I_{1m}, Table 1 gives amplitudes of primary voltage U_{1m}, form factors of primary and secondary voltages k_{U1} and k_{U2}, as well as primary active power P_1, measured at different frequencies f during the short-circuit test. Increase of active power at a frequency of 1 Hz is mostly due to the increase of power loss in the magnetic core of the tested transformer.

Table 1. Results of short-circuit test

f [Hz]	U_{1m} [V]	I_{1m} [A]	k_{U1}	k_{U2}	P_1 [W]
1	19.37	18.14	1.12	1.22	95.30
2	19.00	5.66	1.11	1.11	54.49
5	18.92	5.60	1.11	1.11	53.45
8	18.81	5.61	1.11	1.11	52.89
10	18.56	5.64	1.11	1.11	52.19
30	18.34	5.55	1.11	1.11	50.44
50	19.25	5.55	1.11	1.12	52.27

Waveforms presented in Fig. 5, obtained during load test of the transformer, show higher distortion at a frequency of 1 Hz, including the distortion of the primary voltage, as well as significant distortion at a frequency of 2 Hz. In this case, amplitude of secondary voltage is higher than during the short-circuit test. The magnetic flux density in the core is also higher, which increases the magnetic field in the core and consequently primary current. Primary voltage is influences by this high primary current and it also becomes distorted. Therefore, connecting even small impedance load to the secondary circuit of the transformer is more critical in terms of distortion when the transformer is working at frequency lower than rated frequency, such as 1 Hz and 2 Hz. Furthermore, increase of load impedance may produce distortion even in the case when frequency is in the order of tens of Hertz.

An increase in the distortion can be seen through the results given in Table 2, which contains amplitudes of primary current I_{1m}, amplitudes of primary voltage U_{1m}, form factors of primary and secondary voltages k_{U1} and k_{U2}, as well as primary active power P_1, measured at different frequencies f during the load test. Significant increase of active power at frequencies of 1 Hz and 2 Hz is related to the increase of power loss in the magnetic core.

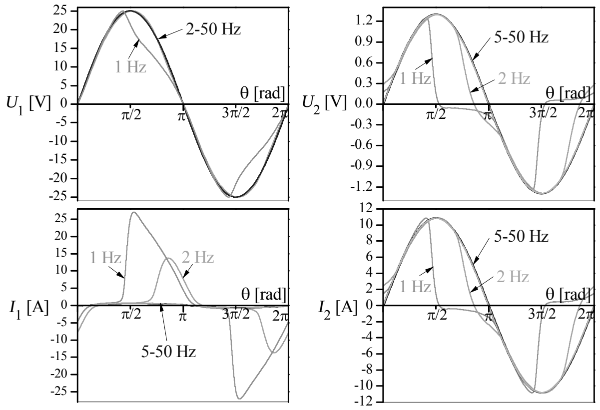

Fig.5. Waveforms of primary and secondary voltages and currents during load test - 0.1 Ω, 40 W

Table 2. Results of load test - 0.1 Ω, 40 W

f [Hz]	U_{1m} [V]	I_{1m} [A]	k_{U_1}	k_{U_2}	P_1 [W]
1	25.11	27.08	1.13	1.43	146.29
2	25.08	13.78	1.12	1.15	35.43
5	25.10	0.69	1.11	1.11	9.05
8	25.02	0.68	1.11	1.11	8.67
10	25.08	0.68	1.11	1.11	8.62
30	25.09	0.65	1.11	1.11	8.00
50	25.05	0.64	1.11	1.11	7.88

In the analysis of working conditions of electrical equipment with ferromagnetic core it is interesting to present harmonic components of the present voltages and currents. Accordingly, the harmonic components of primary and secondary current of power transformer during the short-circuit test and the load test are presented in Figs. 6 and 7, respectively.

It can be seen from these figures that the decrease of the frequency causes an increase of fundamental harmonic and higher odd harmonics of primary current during the short-circuit test. Such a case is evident only at the lowest frequency of 1 Hz, while in the case of load test it is evident also at the frequency of 2 Hz. Fundamental harmonic of the secondary current is decreasing with the frequency, while higher harmonics are increasing. In the case of higher impedance of load and higher voltages and currents, increase of higher harmonics can appear even at the higher frequencies.

Conclusion

This paper presents the analysis of short-circuit and load operation of power transformer at frequencies lower than rated frequency. According to IEC standard, short-circuit voltage and power loss need to be measured during short-circuit operation. There are no specific requirements for operation of transformer with load in secondary circuit.

A simple LabVIEW application has been designed on a PC for measurement of all quantities of interest for used experimental setup. It is made so to provide measurement of primary and secondary voltages and currents, as well as input power of tested power transformer. Magnetic core (EI core) of single-phase transformer has been made of the non-oriented electrical steel sheets of M530-50A grade. Transformer is rated at 1 kVA, 230 V/12 V, 50 Hz.

Measurements have been made at frequencies 50 Hz, 30 Hz, 10 Hz, 8 Hz, 5 Hz, 2 Hz and 1 Hz. The waveforms of the primary and secondary voltages and currents and input power of tested transformer have been recorded during the tests.

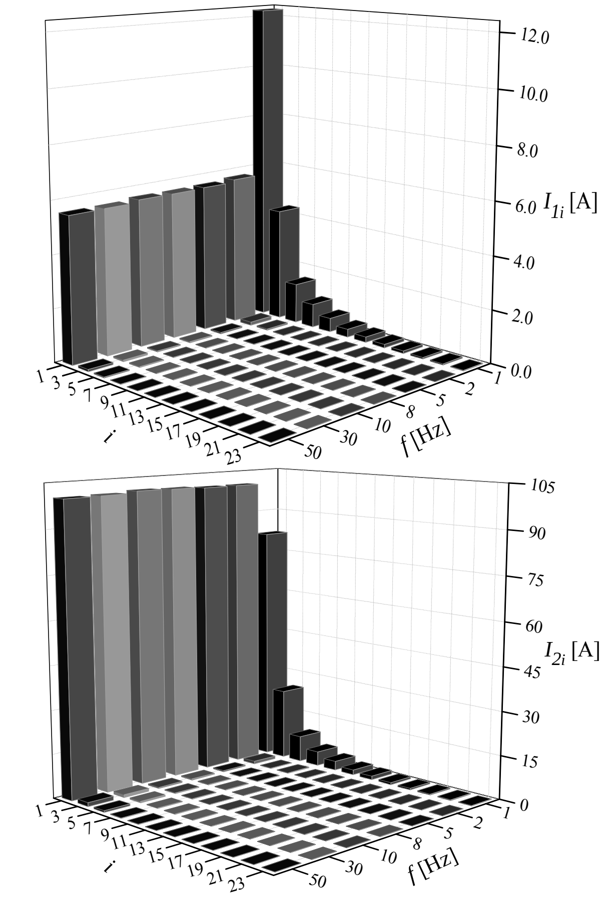

Fig.6. Harmonics of primary and secondary current during short-circuit test

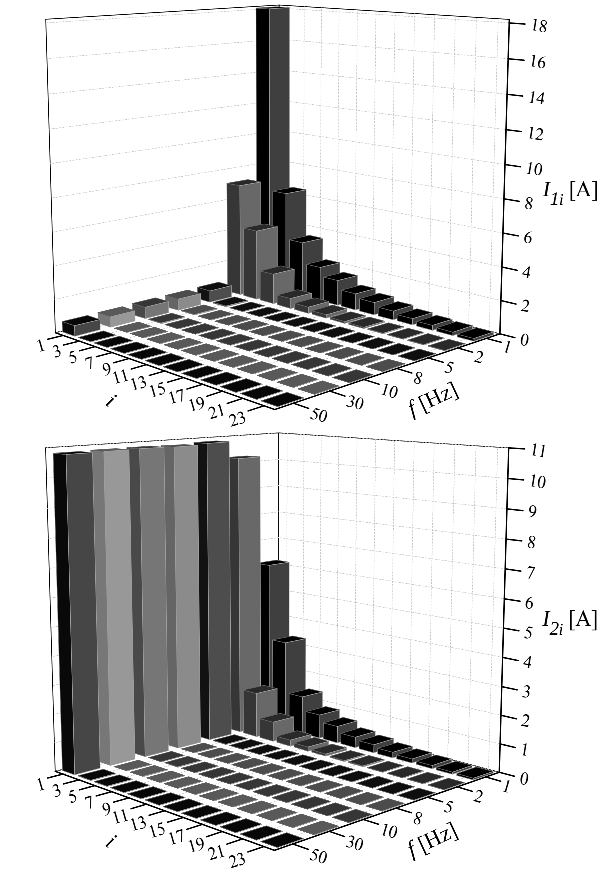

Fig.7. Harmonics of primary and secondary current during load test - 0.1 Ω, 40 W

Results obtained show that a decrease of the frequency of primary voltage of power transformer, while its amplitude is at the same level, causes an increase of amplitude of primary current and it becomes distorted from sinusoidal shape. Also, secondary voltage and current are distorted, without an increase in amplitude. Moreover, input power is increasing with the decrease of the frequency. Such a behaviour is expressed at lowest frequencies of 1 Hz and 2 Hz. However, this can also be the case at highest frequencies if the load is present in the secondary circuit and the amplitudes of voltages and currents are higher than in the presented case.

Additionally, analysis of the harmonic components of primary and secondary current has been performed. It shows an increase of fundamental harmonic, as well as higher odd harmonic, of primary current with the decrease of the frequency. On the other hand, fundamental harmonic of the secondary current is decreasing with the increase of the frequency, while higher harmonics are increasing.

Results presented and its discussion can be of interest to the engineers who are designing power transformers, as well as to the students in the field of electrical engineering for proper understanding of the theory and working principles of power transformers.

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