The method of power transformers and autotransformers windings condition determination

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Abstract. In article advantages and shortcomings of a method of the frequency analysis of a condition of windings of transformers are considered. This control method of a condition of windings of the transformer is based on comparison of the amplitude-frequency characteristics (AFC) of the diagnosed transformer with its amplitude-frequency characteristics in good repair. It is reported that in various frequency ranges it is possible to find manifestations of various defects and bruises of windings of power transformers and autotransformers. Using a pulse frequency analysis method, the amplitude frequency response spectrum is examined in frequency ranges from zero to 2 MHz. Types and places of defects of transformer winding are determined from value and direction of frequency offset of amplitude-frequency characteristic lines. Such types of defects can include changes in the state of windings, violations of the pressing mechanism, displacement of winding turns relative to each other. In order to determine the type and magnitude of the defect, this method creates a mathematical model of the transformer. An important task in the simulation of transformer windings is the connection between strain types and transformer elements.
Keywords: method of the frequency analysis, amplitude-frequency characteristic, transformer winding, defect of a winding.

1. Introduction

Electric equipment of electrical power systems and networks has to be in operating state throughout all serviceable life. The power transformers (PT) are one of electrical power systems and networks major elements, and reliability of power supply of consumers depends on their correct work. In electrical networks of any tension transformers and autotransformers of single-phase and three-phase execution are used. According to GOST 11677-85 and GOST 52719 2007 the manufactured transformers till 2008 have standard endurance of 25 years and after 2008 – 30 years. Now, about 50% of the transformers which are on stream have endurance more than 30 years and developed the standard resource. [1-3].

For life extension of transformers methods of their monitoring and diagnostics are constantly improved. Early detection of defects in the transformer allows to reveal possibility of a contingency situation and to make the decision on a planned stop without interruption of power supply of consumers. On the basis of results of comprehensive examination of the transformer recommendations about the mode of its further operation and volume of the repair work necessary for life extension of the transformer up to 40 years and more are developed. [1].

According to the conducted researches power transformers at power plants and substations are affected by following hazards:

- turn–on magnetization currents at inclusion of which lead to damage of windings because of development of electric and mechanical transition phenomena;
- the storm and switching overvoltages causing damages of the major and coil insulation at small stocks of electric strength;
- increases in a running voltage because of the noncompensated charging power of power lines which lead to saturation of cores of power transformers;
- short-circuit currents making mechanical impacts on windings. External short-circuits have also larger danger. They can lead to deformation of windings at their insufficient dynamic firmness;
- an overload of power transformers which leads to additional heating and as a result, to decrease in endurance because of an isolation aging;
- the geomagnetic and induced currents arising at the strong geomagnetic storms. These currents proceed on the grounding windings of power transformers and cause saturation of cores. It leads to an increase in nonsinusoidal magnetization currents, to increase in heating of structural elements of power transformers. In this case there is a malfunctioning of relay protection and automatic equipment and indexes of quality of electric energy go down. On extended high-voltage air-lines the magnitude of geomagnetic and induced currents reaches the working values of currents in lines [4-6].

The main methods of diagnosing and the revealed defects of power transformers are given in table 1 [7].

Table 1. The main methods of diagnosing and the revealed defects.

№	Diagnosing method	The revealed defects
1	Measurement of insulation resistance	The strong humidification, pollution
2	Measurement of a complex admittance, dielectric losses and capacity of isolation	Humidification, local destruction by categories, deterioration in characteristics of oil
3	Definition of the absorptive characteristics of isolation	Humidification
4	Definition of physicochemical characteristics of oil	Humidification, aging, overheating, pollution, thermal decomposition of materials
5	The analysis of the gases dissolved in oil	Thermal and electric breakdown of structural elements
6	Measurement of partial categories	Local defects (inclusions), change of distribution of tension on designs, electric destruction
7	Measurement of resistance of current carrying parts	Damage of current carrying elements and switches of devices of regulations of tension
8	Measurement of losses of a no-load operation	Violation of isolation of elements of a magnetic circuit
9	Measurement of resistance of a short-circuit	Deformations of windings, interturn short circuits
10	Measurement of the frequency characteristics of windings	Deformations of windings

2. Materials and Methods

For decrease in damage from the emergency shutdowns of transformers and autotransformers, also for decrease in economic damage from errors of measurements of transformers of tension and current, it is developed and the system of various control of their state is exercised. One of the modern and effective control methods of a condition of windings of transformers is the continuous and pulse methods of the frequency analysis (MFA). In various frequency ranges, as a rule, from 10 kHz to 1 MHz it is possible to find manifestation of defects and bruises of windings of power transformers and autotransformers. The changes of the inductive and capacitive characteristics of a winding arising at emergence of various defects of a winding significantly influence an amplitude-frequency characteristic. Modeling of defects is performed if change of winding dimensions and accordingly change of winding electrical parameters are known. The connection between strain types and transformer elements is an important task in the simulation of transformer windings. The main defects of power transformer windings include the following.

1. Winding displacement - When the winding is displaced, the distance between the winding coils changes. At the same time the natural inductance of coils does not change, but their mutual inductance changes. Longitudinal capacity between coils increases as distance decreases and decreases as distance between coils increases.

2. Increase in a winding - leads to increase in length of a winding at the size ΔL that leads to reduction of inductance and longitudinal capacities.

3. Compression of part of turns - reduces the distance between turns or coils, if the winding is completely affected, the whole height of the winding decreases. This results in an increase in inductance values and longitudinal capacitances.

4. Local deformation (crease) of turns to winding axis changes the diameter of turns, which leads to reduction of inductance values and increase of transverse capacitance values.

5. Local deformation (increase) of rounds from a winding axis - the mentioned part of a winding takes the ellipse form, diameter increases in one party and decreases in another, it leads to increase in inductance and reduction of transverse capacitance.

6. Winding part twisting - leads to reduction of diameter of affected winding part, winding size by height does not change, its radial size also remains unchanged. Such a defect results in a decrease in the respective inductance values and an increase in the respective transverse capacitance values.

7. Winding short circuits between turns are the end result of destruction of paper insulation, loss of electrodynamic resistance of windings under the action of operational factors and, first of all, short circuit currents with further breakdown of insulation in the place of deformation. The winding voltage is reduced and the transformation coefficient is increased, as well as the temperature is increased and the winding overheats, the number of turns in the winding is reduced and the ohmic and inductive resistance of the turn is accordingly reduced and the longitudinal capacitance is increased.

8. Ground turn closure - the affected turn acquires zero potential and the ground capacity becomes zero.

9. When the winding is bent, the transverse capacitance and inductance of the substitution circuit are changed by 20%, as a result, it is obtained that resonances are shifted towards higher frequencies, with subsequent appearance of a difference between amplitude-frequency characteristics.

10. Damage of magnetic circuit is simulated by change of successive elements, and curve of amplitude-frequency characteristic is shifted towards higher frequencies.

11. Oil leakage leads to changes in parallel capacity and conductivity, amplitude-frequency response changes towards decreasing frequencies. The effect of the tank and oil on the amplitude-frequency response is more noticeable at a frequency of 10 kHz and more.

The method of the frequency analysis of windings is based on comparison of the amplitude-frequency characteristics of the diagnosed transformer with the amplitude-frequency characteristics removed in good repair. But for successful application of a method of the frequency analysis for the purpose of monitoring of a condition of windings it is necessary to have transformer amplitude-frequency characteristics in operating state. All newly produced power transformers and autotransformers have factory (reference) amplitude-frequency characteristics. For transformers released earlier than 2005, such factory characteristics are largely absent. For primary monitoring of the state of power transformer windings, which do not yet have reference amplitude-frequency characteristics, a number of techniques have been developed: a) comparison of amplitude-frequency characteristics of different phases of the same transformer; b) comparison of amplitude-frequency characteristics of identical phases of different single-type transformers. The method of diagnostics consists in definition of intervals of frequencies of separate spectral components of an amplitude-frequency characteristic of a winding at accidental variations of electric parameters of efficient power transformers and autotransformers.

The method of the frequency analysis originally called method of low-voltage impulses (LVI) was offered in 1966 (LechandTuminski) for diagnostics of deformation of windings of power transformers [8]. The method of the frequency analysis is more sensing and exact method in comparison with other methods of diagnostics. In 50 - the 60th years the frequency method was generalized on lumped parameter systems of management. In 1978, the Disk and Egvin were among the first who used a method of the frequency analysis for detection of deformation in windings of the transformer [9]. The method of the frequency analysis was included in the standard of the Republic of China in 2004 [Frequency response analysis on winding deformation of power transformers // The electric power industry standard of people’s Republic of China. Promulgated on December 14th, 2004, executed from June1st, 2005]. The principle of a method of the frequency analysis is based on use of Impluls-9 installation which includes the laptop with the plateaus established in it for record and processing of signals and a square wave-form oscillator. The software under the name IFRA allows to make calibration, testing of a metering circuit, record of signals, filtration, preservation in the database, comparison of oscillograms, means of their processing and the analysis. A conclusion about existence or lack of deformations in windings is accepted on the basis of the criteria put in the program.

In a method of the frequency analysis two approaches are used: the continuous and pulse [10-12]. Depending on the scheme and group of connection of windings of a power transformer, measurement by method of the frequency analysis is taken in the different ways. Generally windings of low tension are connected in a one-piece triangle. At such connection of windings the source of the testing signal is connected to one of winding conclusions, and the response is removed from other conclusion. At such scheme of connection, all three phases of a winding are excited. In certain cases, at removal of a tank of the transformer it is possible to take measurements at which windings of low tension are disunited [13]. In this case each phase is excited separately. The way of measurements with the disunited winding of low tension demands opening of the transformer that is a heavy work and takes a lot of time. At connection of a winding in a star each phase is excited separately, and the testing signal is given on an entrance of one phase, and the response is photographed from a generic neutral point.

The pulse method of the frequency analysis (IFRA – Impulse Frequency Response Analysis) is that on one of windings of the transformer the short square-wave probing pulse of low tension about 100 ÷ of 600 V and lasting about 1 microsec of (figure 1) moves.

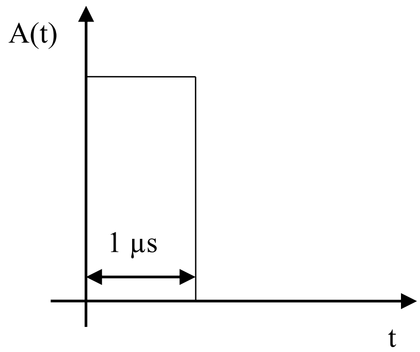

Figure 1. Form of a signal of the Impulse-9 device given on the studied winding.

Impulse-9 device is used in frequency analysis method. Transient process is excited in examined winding. Digitization of amplitudes of input and output signals with different sampling rate is performed (in Impulse-9 device maximum sampling rate is 200 MHz). The ratio of the output signal and the input signal gives a time-dependent value of the transmission coefficient of the winding K(t). Impulse-9 has built-in Fourier transform function of signals depending on frequency [10]. Fourier transform of output signal produces pulse amplitude-frequency response of winding. Since the amplitude of the input signal in the frequency range depends on the frequency, the ratio of the output signal to the input signal, that is, the value of the transmission coefficient, is determined.

Dependence of transmission coefficient obtained in pulse mode using Impulse-9 device coincides with amplitude-frequency characteristic of winding obtained at smooth continuous change of frequency of input sinusoidal signal of fixed amplitude. The thus obtained amplitude-frequency characteristic of the winding of the analysed transformer is compared with the amplitude-frequency characteristic of the same winding of the transformer, previously recorded in its serviceable condition. Such amplitude-frequency characteristic recorded at the factory or during operation of the transformer prior to occurrence of the defect is called a normogram. The amplitude-frequency characteristic recorded after the possible occurrence of a defect is called a defectogram. If the correlation coefficient between the normogram and the defectogram is greater than 0.96, the transformer is considered usable. If the correlation coefficient is less than 0.96, it is considered that the defects in the transformer require immediate elimination, and the transformer must be taken out for repair. The type and number of defects within the frequency analysis method are not determined. In order to link the defect in the winding to the change in the amplitude-frequency spectra, it is necessary to create a theoretical model of the winding with distributed parameters (type of long line model).

Recently, works have appeared in which attempts have been made to apply standard spectroscopy methods to the analysis of amplitude-frequency characteristics of transformers in order to increase the information value of the frequency analysis method and to obtain information on the type of defect, its value and position in the winding before the beginning of repair with opening of the transformer tank.

The procedure of measurement by a pulse method is explained by the key diagram represented in figure 2 and the scheme of connection of devices in figure 3. After start-up of the program, control of parameters of measurements and selection of the command "Start" is launched the generator of the probing impulses via the control unit connected to an entrance of the Start-up generator. At this Analog-to-digital converter (ADC) it is automatically transferred to a waiting mode of record of signals. From the output of the Impulse – 9 generator the square-wave probing pulse passes on the internal connector and a measuring cable on an entrance of the coordinating (connecting) block installed on a transformer tank cover.

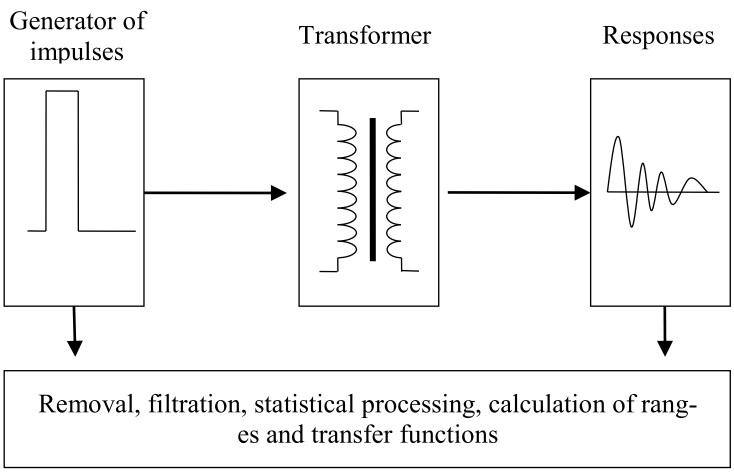

Figure 2. The basic scheme of measurement by a pulse method of the frequency analysis.

Further, from the output of the coordinating block via the external connector connected to one of inputs of the transformer (input of a neutral, input of a winding or connection of inputs of windings of one tension) by means of a clip, the probing impulse enters on an object winding. From the same input the signal via other external connector coordinating the block, a measuring cable, the internal connector and a divider of K1 (1:20) enters on the 1st ADC channel. Reaction of windings (responses) to influence of the square-wave probing pulse from inputs of three phases sequentially enter via the external connector coordinating the block and a measuring cable on the 2nd ADC channel – through a divider of K2 (1:5) or immediately on ADC.

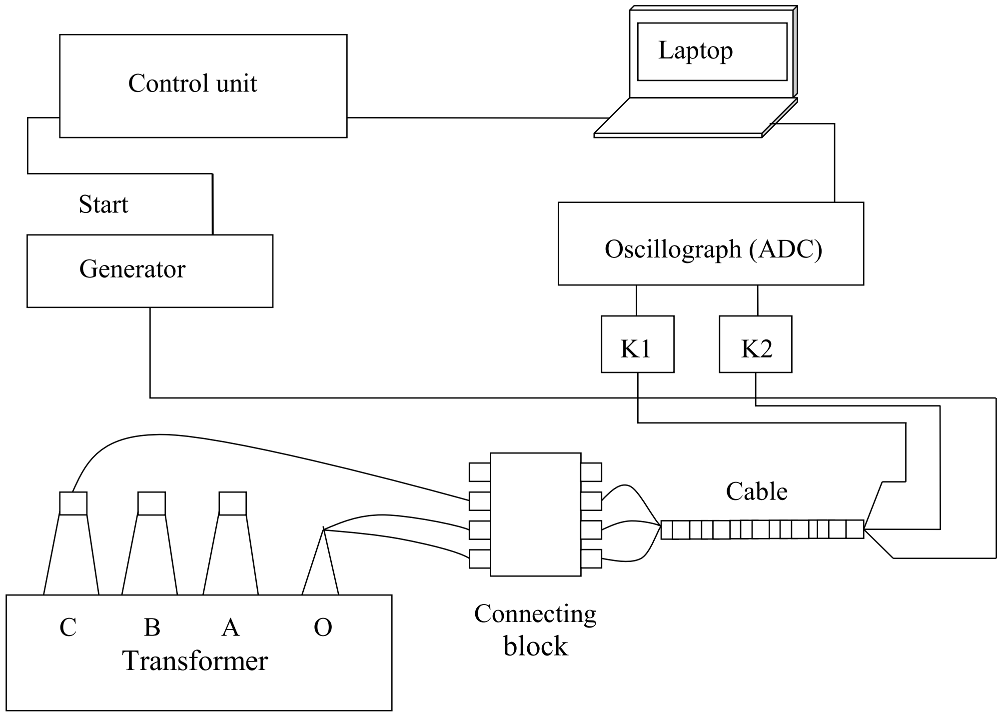

Figure 3. Scheme of connection of devices at measurement by a pulse method of the frequency analysis.

The Impulse-9 installation represented in figure 3 includes:

- square-wave pulses generator;
- laptop;
- to ADC plateau;
- control unit;
- the software (IFRA) providing the procedure of measurements, processing, the analysis and assessment of results of diagnostics.

Also are included in the installation package the calibrator, dividers, cables, connectors coordinating the block, the instruction (user's guide).

3. Results

Failure of windings of transformers makes in the sum about 44% of total number of damageability. Ranges of amplitude-frequency characteristics change depending on the changes of parameters of inductance and capacity of a winding caused by change of sizes of windings of the transformer. It does a method of the frequency analysis sensitive to internal parameters of a winding. Model operation of defects is made if change of the sizes of a winding and respectively change of electric parameters of winding dimensions is known. Communication between types of deformation and elements of the transformer is an important task at model operation of windings of the transformer. For example: – at a winding bend, the cross capacity and inductance of the equivalent circuit for 20% changes, as a result it turns out that resonances are displaced towards the highest frequencies, with the subsequent emergence of a difference between amplitude-frequency characteristics; – damage of a magnetic circuit is modelled by change of serial elements, and the curve of an amplitude-frequency characteristic is displaced towards the highest frequencies; – oil leak, as shown in [10, 14], leads to changes of parallel capacity and conduction, the amplitude-frequency characteristic changes towards decrease of frequencies. Influence of a tank and oil on an amplitude-frequency characteristic more considerably with a frequency of 10 kHz and more.

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4. Discussion

According to authors [15], vertical displacement of a winding is found with a frequency of 100 kHz, and radial deformation – with a frequency up to 10 KHz and is higher than 100 kHz.

Authors of work [16] claim that different types of defects lead to change in different ranges of a range of an amplitude-frequency characteristic. Deformation in a magnetic circuit, residual magnetization, interturn short circuits and splitting of chain of a winding can be found on changes in a frequency range from 20 Hz to 2 kHz. In the range from 2 kHz to 400 kHz it is possible to find deformations in windings and in the device of regulation of tension under loading. In the range from 400 kHz to 2 MHz the shift and clamping of wires of a winding in the device of regulation of tension under loading is found. Such assumption allows to estimate location of defect quickly.

In [17] assessment of a deviation of resonances through calculation of coefficient of a percentage deviation of resonances for finding of the place of defect is used. Such approach of localization of defect is defined in the larger ranges that can cause monitoring errors. It is known that destruction or deformation of windings happens because of mechanical influences of electrodynamic forces at rated currents and currents of short-circuits. It is possible to refer deformation of windings to internal damages of windings of the transformer (compression, drowning, twisting, a swelling, shift etc), interturn short circuits, partial categories, humidification, pollution by solid impurity, gaseous inclusions and others. Above-mentioned types of defects come to light by means of application of various control systems of a state. In work [18] consideration of longitudinal and lateral deformations is given in the transformer winding conductor, caused by short circuit current, and the useful ratios allowing to estimate lengthening and shift of conductors in a winding at the known current.

5. Conclusion

It is known that the method of the frequency analysis, as a rule, is the comparative method applied to detection of defects of windings of transformers. In case of lack of input datas of the transformer, results of measurement of an amplitude-frequency characteristic are compared to data of other phases (interphase comparison) or with data of the same transformers. A number of shortcomings, such as distinction of amplitude-frequency characteristics of extreme windings and the winding which is in the middle of a magnetic circuit, various serviceable lifes of the same transformers, or distinction of issue dates has this approach. These distinctions influence ranges of amplitude-frequency characteristics and complicate applicability of a method of the frequency analysis. To lower the listed above shortcomings, it is necessary to develop techniques of definition of frequency ranges which can serve as reference data for the same transformers. In work [10] the spectral method of processing of observed datas which demands initial model operation of the experimental range and finding of characteristics of lines is used. For increase in effectiveness of monitoring of a condition of windings of transformers the method of the frequency analysis in [10] offered a technique of decomposition of a range of an amplitude-frequency characteristic on separate lines of a range. Such technique allows to determine types and places of defects of a winding by the size and the direction of shift of frequencies of lines. To determine type and size of defect by this technique it is necessary to create mathematical model of the transformer. As each type of the transformer has an individual amplitude-frequency characteristic, the model has to be made for each of the existing types of transformers. Usually, when using a pulse method of the frequency analysis the range of an amplitude-frequency characteristic is investigated in frequency ranges from zero to 2 MHz. Some researchers work in higher frequencies (up to 10 MHz) [19].

In work it is reported about a method of definition of a condition of windings of power transformers and autotransformers on the basis of amplitude-frequency characteristics of these transformers. Windings of a power transformer are presented to models by the long line with various number of RLC elements depending on the frequency of a signal and length of a winding. On shift of resonance lines of a range it is possible to judge type and size of defect of a winding of the transformer. It is possible to refer changes of geometry of windings as a result of influence to such types of defects round short circuits, violations of the mechanism of pressing, drowning of rounds, shift of rounds of a winding relatively each other which can lead to loss of dynamic stability and emergency subsequently.

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References

[1] L`vov M Yu 2010 Analiz povrezhdaemosti silovy`x transformatorov napryazheniem 110 kV i vy`she [Analysis of damageability of power transformers of 110 kV and above] *E`lektrichestvo* **2** 27-31 [In Russian]

[2] Abdallah J 2009 Using Frequency Response analysis (FRA) in transformers internal fault detection *WSEAS Transactions on Power Systems Issue* **9(4)** 297-306

[3] Wang M and Vandermaar A J 2002 Review of condition assessment of power transformers in service *IEEE Electrical Insulation Magazine* **6** 12-25

[4] Elovaara J 2007 Finnish experience with grid effect of gic's *Space Weather* Ed J Lilensten (Dordrecht, Netherlands: Springer) pp 311-26

[5] Kappenman J G 2010 *Geomagnetic storms and Their Impact on the U.S. power grid* (Goleta, CA: Metatech Corporation)

[6] Pulkkinen A et al 2010 Solar shield: Forecasting and mitigating space weather effects on high-voltage power transmission systems *Natural Hazards* **53(2)** 333-45

[7] Sanchez J 2011 *Assistant to the diagnosis of defects of the transformers of power* [Thesis to get the rank of Docteur, supported publicly on June 21st, 2011] (Grenoble: University of Grenoble)

[8] Lech W and Tuminski L 1966 Detecting transformer winding damage by the low voltage impulse method *Electrical review* **179(21)** 768-72

[9] Al-Amar E, Karady G G and Hevia O P 2007 Improved technique for fault detection sensitivity in transformer maintenance test *IEEE Power Eng. Society, General Meeting* (Tampa) pp 505-8

[10] Il`darxanov R G 2011 *Sovershenstvovanie metoda ocenki sostoyaniya obmotok silovy`x transformatorov na osnove ix chastotny`x xarakteristik* [Perfecting of a method of assessment of a condition of windings of power transformers on the basis of their frequency characteristics] (Kazan: KGEU) [In Russian]

[11] Islam A, Khan S I and Hoque A 2011 Detection of mechanical deformation in old aged power transformer using cross correlation co-efficient analysis method *Energy and Power Eng.* **3(4)** 585-91

[12] Wang M, Vandermaar A J and Srivastava K D 2004 Transformer winding movement monitoring in service – Key factors affecting FRA measurements *IEEE Electrical Insulation Magazine* **5** 5-12

[13] Vikash M, Sharlinprija K and Ilampoornan M K 2012 Transformer fault detection by frequency response analysis *Int. J. of Computer Science and Electrical Eng.* **2** 26-31

[14] Kalpana P, Narottam D, Abu-siada A and Syed I 2013 Power transformer winding fault analysis using transfer function *Australasian Universities Power Eng. Conf.* (Hobart, Australia) pp 1-3

[15] Hidalen H K, Brede A P and Lundgaard L 2001 Transformer winding diagnosis using the transfer function approach *Nordic Insulation Symposium Stockholm* (Stockholm, Sweden) pp 113-120

[16] Gonzalez A A, Jacobo J C and Ruiz S S 2012 Incipient failure detection in power transformers through *Frequency Sweep Response Proceedings of the World Congress on Eng. and Computer Science* vol 2 (USA, San Francisco) pp 4971-8

[17] Barzegaran M R, Mirzaie M and Shayegani Akmal A 2009 Frequency response analysis in power transformer for detection of winding short-circuit using *Quasi-static Finite Element and Circuit-based Method World Applied Sciences J.* **7(8)** 1006-15

[18] Isaev Yu N, Elgina G A and Lavrinovich V A 2013 Opredelenie deformacij provoda obmotok transformatora sobstvenny`m magnitny`m polem [Definition of deformations of a wire of windings of the transformer internal magnetic field] *Izvestiya Tomskogo Politexnicheskogo Universiteta* **4** 176-9 [In Russian]

[19] Ilampoornan M K and Vikash M, 2012 Transformer fault detection by frequency response analysis *IOSR Journal of Electrical and Electronics Engineering* **1(4)** 27-32