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The investigation of frequency response analysis for power transformers winding condition

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Abstract. In modern electrical transmission and distribution systems, power transformers are critical components within the network. In the event that a failure occurs in service, the impact can be far reaching. The majority of mechanical deformation within power transformers is due to short circuit faults. The ageing transformer population increases the likelihood of failure so a reliable diagnostic tools required to determine the remaining life of these assets. Although, frequency response analysis (FRA) has been recently recognized as the most reliable detection tool for mechanical deformation in transformers, in the event of minor fault, the current FRA interpretation approach may not able to detect any variations between healthy and faulty FRA signatures. This paper focuses on FRA tests for power transformer and interpretation of obtained FRA signatures.

One of the most important problems of transformer maintenance is the monitoring system and technical diagnosis development. More than 40 % of transformers have exceeded their design life (25y, established by standard papers [1]). Nowadays, there are several diagnostic techniques for power transformers, for example, vibration analysis, ultrasonic contact fault detection, dielectric loss angle test and partial discharge [2]. The diagnosis of power transformer can be carried out offline, online and partly. Parameters used for online transformer tests are temperature, pressure, leakage currents, vibration amplitude, noise level, velocity vibration and acceleration vibration. They must have properties, such sensitivity, accuracy of measurement, stability, depth of investigation and simplicity of diagnosis. The transformer defects occur due to unsuitable means of transporting short circuit currents, earthquakes, oil ignition in tank etc [3]. Due to CIGRE working group A 2.26 the most common cause of power transformers fault is inter-disk faults [4].

One of the most effective techniques of condition monitoring for power transformers are Sweep Frequency Response Analysis (SFRA) and Impulse Frequency Response Analysis (IFRA) [5]. Lots of investigations are held to improve this technique at the moment, but from 1978 there is no general opinion how to make a conclusion about technical condition [6].The main advantage of this technique is its high sensitivity: even minor local changes of winding elements(turns, disks) result in dramatic changes on diagnosis signature [7]. Different types of deformations lead to changes in FRA signature in different range. Conventional techniques of condition monitoring are not so sensitive. That’s why FRA is the best technique for inter-disk fault detection.

Frequency Response Analysis has two directions of use: sweep and impulse [3].

IFRA is provided by low voltage impulse given on winding (The impulse form can be rectangular or conventional or exponential). Current or voltage on bushing terminals or frequency current transformers of other windings is measured. The transition process in windings is recorded with the help of analog-digital converters. After that the response is transformed to frequency area using Fourier algorithm. Finally, transfer function as a ratio of injected and measured signal is founded.

SFRA is used in frequency area directly. In this case the sine 10 V signal from sweep generator is injected on the bushing terminal. It’s changes from several Hz to several MHz. The response is measured from other terminals as a function of the variable frequency [3]. Each way has its advantages and disadvantages. For example, SFRA is more sensitive on low frequencies and quite simple maintenance as much as in interpretation results [8]. However the process takes long time.

A foreign power transformer was selected as an object of study. Its characteristics are given in table 1. This transformer was chosen because of its initial data, which were used for modelling.

Table 1. The power transformer parameters

№	Classification	Value
1	Rated power	40 MVA
2	Impedance	13,8 %
3	Primary voltage	66 kV
4	Secondary voltage	11 kV
5	Height of HV winding	1074 mm
6	Height of LV winding	1136 mm
7	Core cross-section diameter	560 mm
8	Insulated core cross-section diameter	579 mm
9	Inner diameter of HV winding	825 mm
10	Inner diameter of LV winding	612 mm
11	Primary turns	1200
12	Secondary turns	200

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The parameters of the frequency characteristics with the parameters of the winding could be correlated because the power transformer winding is a multi-frequency oscillatory circuit [9]. It consists of series resistance, series inductance and series capacitances.

A transformer winding equivalent circuit was compiled in the Multisim software package to carry out the experiments (fig.1).Transformer parameters are:

- series inductance and series resistance of HV and LV windings (L_s, R_s);
- shunt capacitance between HV and LV windings (C_{sh});
- series capacitances between HV / LV windings and the earthed tank / core (C_o);
- series capacitances between the HV and LV windings (C_{HL}).

Table 2. Parameters of the equivalent circuit [10]

№	Parameters of the equivalent circuit	HV	LV
1	L_s [μH], R_s [Ω]	8,91;1	8,91; 0,025
2	C_{sh} [pF]	61,196	115,53
3	C_o [pF]	567,96	333,24
4	C_{HL}[pF]	89,283	

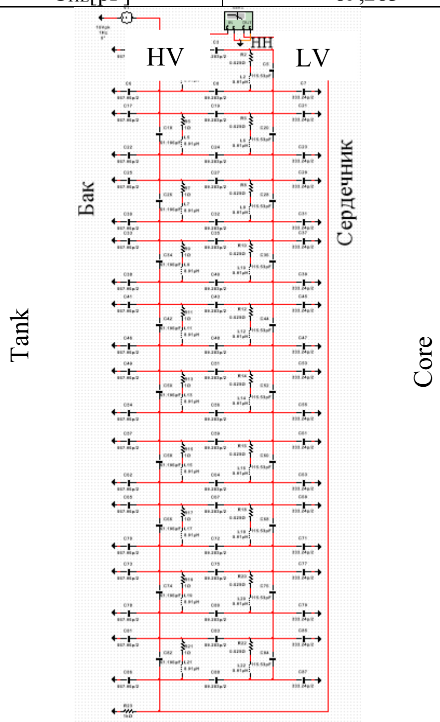

Fig. 1. The equivalent circuit of HV and LV winding

The equivalent circuit of the first HV winding disk is shown in Fig. 2.

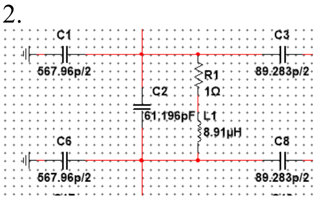

Fig. 2. The equivalent circuit of the first HV winding disk

C_1, C_6 (C_o) – capacitance between first HV winding disk and the earthed tank

C_2 (C_{sh}) – capacitance between first and second HV winding disk.

C_3, C_8 (C_{HL}) – capacitance between first HV winding disk and LV winding.

L_1 (L_s) – inductance of the first HV winding disk.

R_1 (R_s) – resistance of the first HV winding disk.

To conduct tests, the elements implemented in Multisim in the form of blocks were used. They are:

- The generator of sine signal, which allows to change the amplitude, frequency and duration of the signal. The amplitude is10 V.
- BodePlotter, used to get FRA signature.
- Load resistance, which consists of the cable resistance and measuring instrument resistance, etc.

The view of the BodePlotter block is shown in Fig. 3.

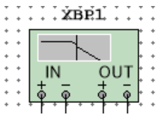

Fig. 3. BodePlotter block

The view of the generator of sine signal block is shown in Fig. 4.

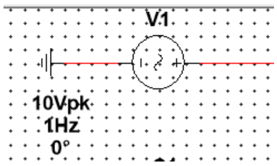

Fig. 4. The generator of sine signal block

The view of load resistance block is shown in Fig. 5

Fig. 5. The load resistance block

During FRA test the transfer function – frequency response was found. This function is the ratio of injected signal on the top of the winding to the measured signal from the winding end. It's a plot, defined by frequency

Each of 10 HV winding disks was short-circuited in this test.

Under the test capacitance C_{sh} (C_2) was enlarged in 100 times. It was made to ensure accurate results. At one plot damaged transformer FRA signature and healthy transformer FRA signature were placed. (fig. 6, fig.7 and fig. 8).

Fig. 6 shows: healthy transformer FRA signature, the first, the second and the third short-circuited winding disk FRA signature. Fig. 7 shows: healthy transformer FRA signature, the fourth, the fith, the sixth and the seventh short-circuited winding disk FRA signature. Fig. 8 shows: healthy transformer FRA signature, the eighth, the nineth and the tenth short-circuited winding disk FRA signature .

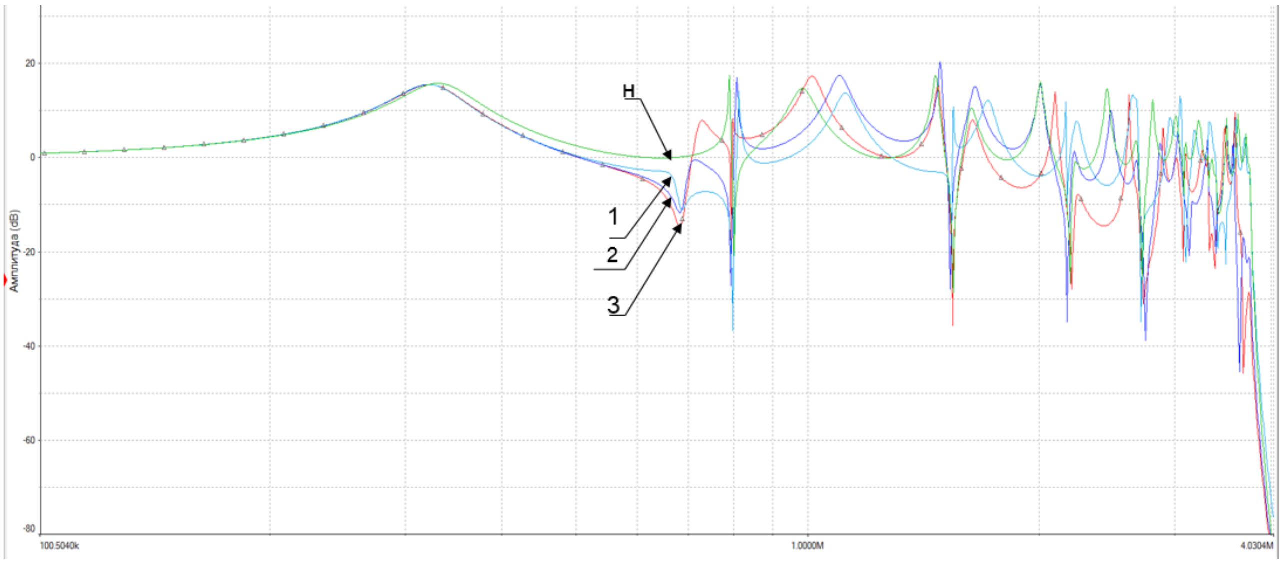

Fig. 6. The plot of transfer function (dB) as a function of frequency. Disk windings short-circuited in series. H – healthy disk windings condition, 1 – first disk winding short-circuited, 2 – second disk winding short-circuited, 3 – third disk winding short-circuited.

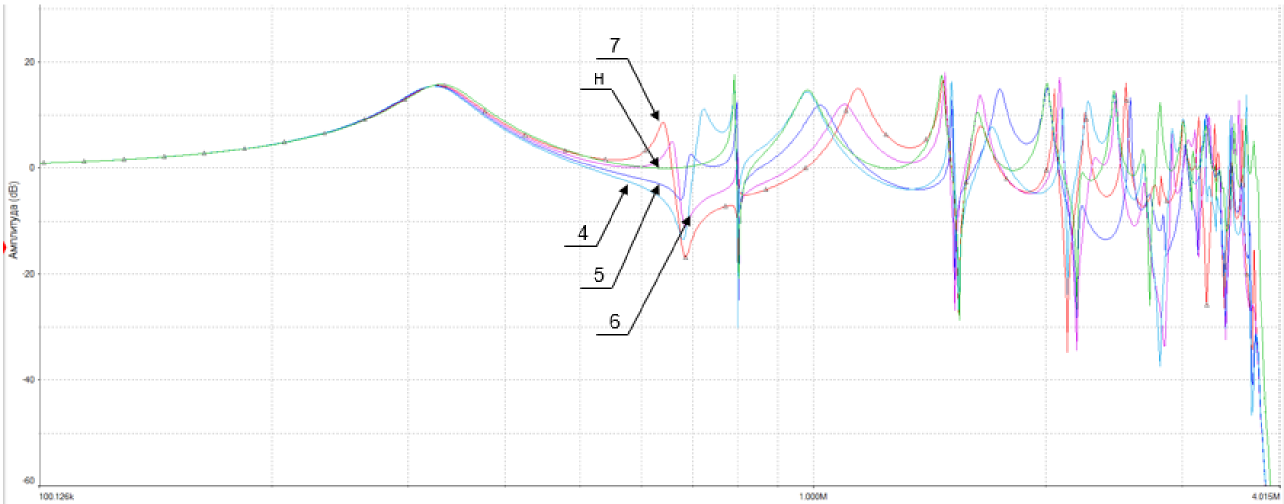

Fig. 7. The plot of transfer function (dB) as a function of frequency. Disk windings short-circuited in series. H – healthy disk windings condition, 4 – fourth disk winding short-circuited, 5 – fifth disk winding short-circuited, 6 – sixth disk winding short-circuited, 7 – seventh disk winding short-circuited.

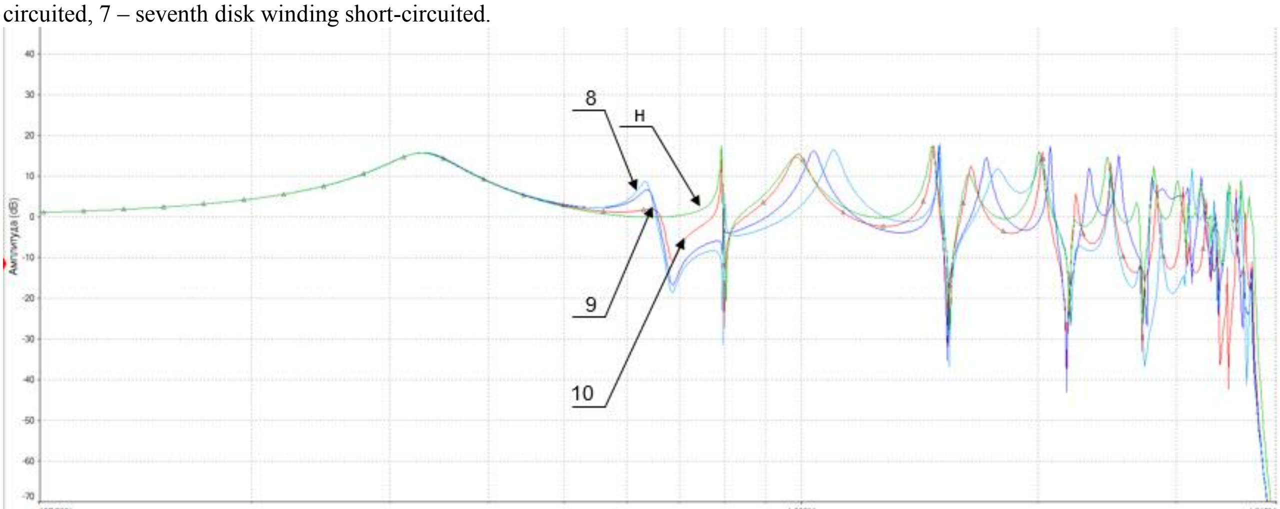

Fig. 8. The plot of transfer function (dB) as a function of frequency. Disk windings short-circuited in series. H – healthy disk windings condition, 8 – eighth disk winding short-circuited, 9 – nineth disk winding short-circuited, 10 – tenth disk winding short-circuite

To compare damaged and healthy FRA signatures it is noticed:

- before 2 MHz changes in curves are noticeable;

The first resonance frequency on heathy winding is about ~320 кГц, and the first antiresonanse is ~800 кГц; When frequency changes from 1,5 MHz to 4 MHz there are lots of resonanses and antiresonanses. When different disk winding short-circuited the next thing should be marked:

- fig.6 shows the growth of resonance amplitude at displacement from 1 disk to 3 disk on ~680 kHz;
- fig. 7 shows the growth both resonance and antiresonanse displacement amplitude at the middle of the winding(from 4 disk to 7 disk);
- The decrease of resonance amplitude is observed at the end of the winding (from 8 to 10 disk);
- The first resonance frequency varies from 500 kHz to 600 kHz, depending of the fault place.

The changes above were observed at ~680 kHz.

The amplitude varies from 18 to -43 dB. After that, the signal is decreasing.

Conclusion

1. FRA could be used as a technique of power transformer winding diagnosis .
2. To explain FRA results the equivalent circuit was made in Multisim. It helps to make an experiments on disk windings
3. To make an experiment the series capacitances, series inductance and series resistance has to be known
4. Using FRA for diagnosis, the algorithm of fault windings determination should be developed.
5. Winding deformation comes to changes in inductance and capacitance, so FRA signature is changing too (number of resonanses, amplitude, location on the curve).
6. The most informative part of FRA signature located from 500 kHz to 600 kHz. The reason is that till 1 kHz there are a lot of electromagnetic noises in power grid and over 2 MHz the response is too much sensitive to all electromagnetic changes.
7. The change of series resistance connected with increase or decrease amplitude of FRA signature.
8. The first antiresonanse frequency moved to the right at the change of fault location from the top to the middle. The amplitude increases.

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