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# Advanced technology of transformer winding condition control based on nanosecond probing impulse

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## Abstract

One of the prospects of resource-effective technologies in power industry is control of electric equipment condition. Effectiveness of any electrical energy system strongly depends on stable work of power supply equipment. It, in turn, is defined by timely and reliable control of equipment condition. Power transformers are the key element of an electrical energy system. Winding defects caused by short circuit currents are the reason for an emergency situation. Reliable control of winding condition is an urgent task of modern power engineering technology. This paper deals with the experimental research of pulsed method of transformer winding control. A new approach to the winding condition control technology is described. The proposed method is based on short nanosecond range (compared to typical pulsed technology) probing impulse and front impulse durations. Experimental results of sensitivity growth at the nanosecond probing impulse duration are shown. Experimental equipment and measurements are described. Comparison of experimental results of the proposed pulsed method and FRA is given. It is shown that probing impulse of nanosecond duration allows upgrading sensitivity of diagnostics procedure. The main proposals are confirmed by measurement results obtained in the electric energy system transformer for different types of winding defects.

*Keywords:* Power transformers; failure diagnostics; FRA; pulsed method; winding defect; probing impulse; frequency range; axial and radial shift of turns

## 1. Introduction

Winding damage due to short circuit currents or other factors is developed rapidly. Revealing a defect at an initial stage is an urgent task of the state of the art control procedure. Therefore the development of technologies of controlling active parts condition is one of the main trends in modern electrical engineering. A pulsed method for controlling mechanical condition of transformer windings was proposed and described in 1966 [1]. The method lies in applying a probing impulse of microsecond with an amplitude of 100–500 V to one of the windings. Other windings are short-circuited and the shunt giving a response to a probing impulse is installed in them. The response represents the signal corresponding to the transient, arising in windings, as reaction to the probing impulse influence. First of all, it was necessary to measure the so-called normogram – a response from the winding of the transformer working properly. At the next tests the procedure of sounding is repeated. The comparison of normograms and current sounding (defectograms) allowed making a conclusion about the condition of the winding. The difference between the normogram and defectograms is the evidence of the problem in the winding. Further this method was recognized more than in 45 countries [2] and received the name of the Low-Voltage Impulses method (LVI).

Further in 1976–1978 in the companies Ontario Gydro, Canada, the LVI method was modified and transformed to the method of measuring amplitude-frequency characteristics. The method lies in measuring amplitude-frequency characteristics in one of the transformer windings while a sinusoidal signal with amplitude of about 10 V of various frequencies is applied to the other winding. The obtained amplitude–frequency characteristics are compared with the normograms, obtained in this serviceable transformer. Now this method is called the Frequency-Response Analysis method or FRA Technology and it is widely used around the world [3–5]. A physical FRA interpretation that is based on the analysis of physical electrical parameters is not feasible until now since one of the most

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important parameters, the winding series capacitance, cannot be determined in transformer bulk [5]. Special generators for diagnostic procedure by the FRA technology are produced. The range of frequencies for diagnostics of high-voltage transformers are in the range of 2. . .3 Hz to 1. . .3 MHz.

Both the LVI and the FRA methods do not always provide exact diagnostics and also sometimes have low sensitivity. We suppose that it is the result of rather narrow frequency range of probing signals. The standard storm impulse has the top frequency of about 500 kHz, the FRA method – 1 . . . 3 MHz. Further the increase of the sensitivity condition control procedure could be reached by short probing impulse application. A nanosecond probing impulse (duration range of 400–100 ns) is the advanced technology method of winding condition control. To figure out the effectiveness of the proposed technology compared with FRA, a number of experiments have been carried out.

## 2. Experimental research of state control sensitivity

Our approach to sensitivity enhancement of the LVI method lies in using a probing impulse with frequency range up to 50 MHz. It can be implemented by applying a rectangular probing impulse with amplitude of 200 V and front duration of 5. . .10 ns and impulse duration of 500. . .100 ns to one of the transformer windings. The experimental research of using a short probing impulse has confirmed the prospects of this approach. Both electrical (turn to turn short circuit) and mechanical (axial and radial shifts) damages of the winding were successfully revealed in different defect situations. The shorter probing impulse duration, the more exact the procedure of condition control [6–8].

The main objective of the research of the serviceable transformer is receiving normograms from the transformer windings in operating condition (the transformer was repaired). The next stage of the research is creation of various defects in the transformer windings which often occur using this type of transformer and receiving defectograms for comparing them with the normograms and determining sensitivity of the developed method of nanosecond impulses for specific defects. To compare the sensitivity of the developed method with the existing method of amplitude–frequency characteristics, a study of transformer characteristics by means of the FRA technology has been carried out. The schemes of controlling the condition of windings including the generator of probing impulses of nanosecond range, oscillographs controlling parameters of probing impulse and response signals, the arrangement of phases of high voltage (HV) and low voltage (LV) windings are shown in Fig. 1. Electrical circuits of experiments for impulse and FRA methods are shown in Figs. 1 and 2.

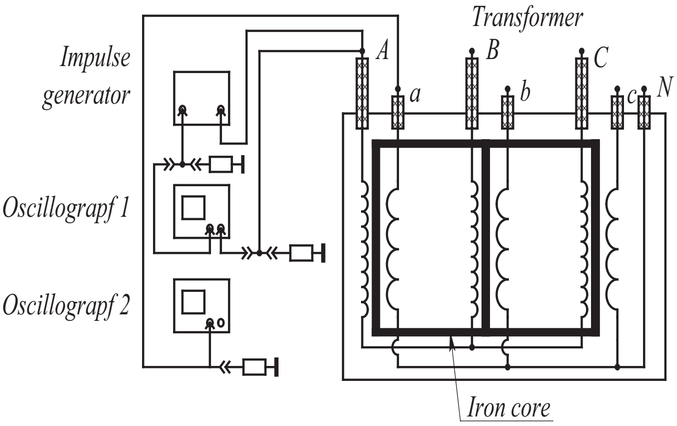

Fig. 1. Scheme of experiment at the condition control by the nanosecond pulsed method.

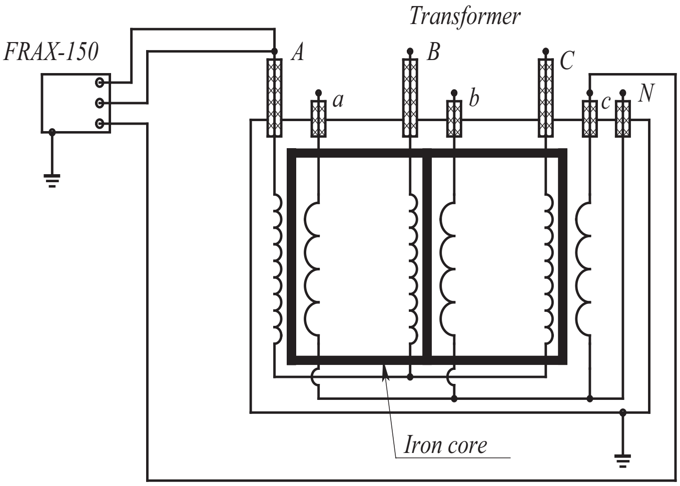

Fig. 2. Scheme of experiment at the condition control by FRA.

The procedure of investigating the windings condition lies in applying a probing impulse to one of the windings, and registering the signal response – normogram – from the other winding. During the study the parameters of a probing impulse varied in order to determine the optimal duration of a probing impulse from the initial one with parameters of 200 V, 500 nanoseconds. The measuring procedure was completely identical to that used in experiments in the physical model of transformer and it is described in detail in Refs. [6–8].

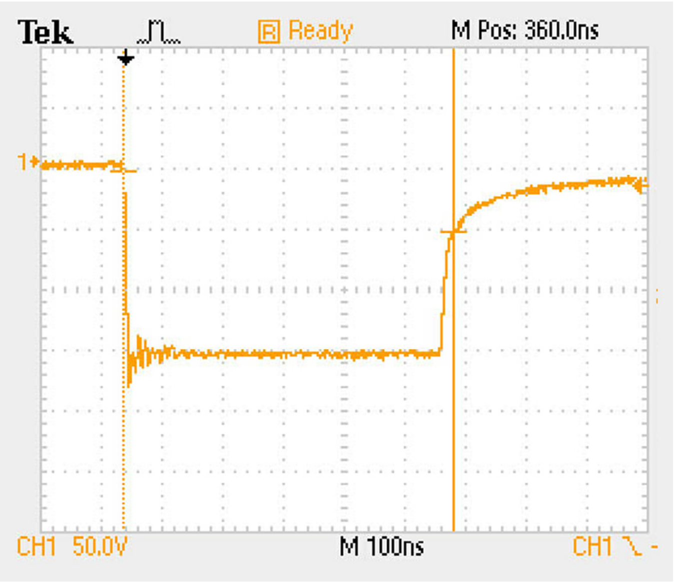

Fig. 3. View of the probing impulse applied to the transformer winding.

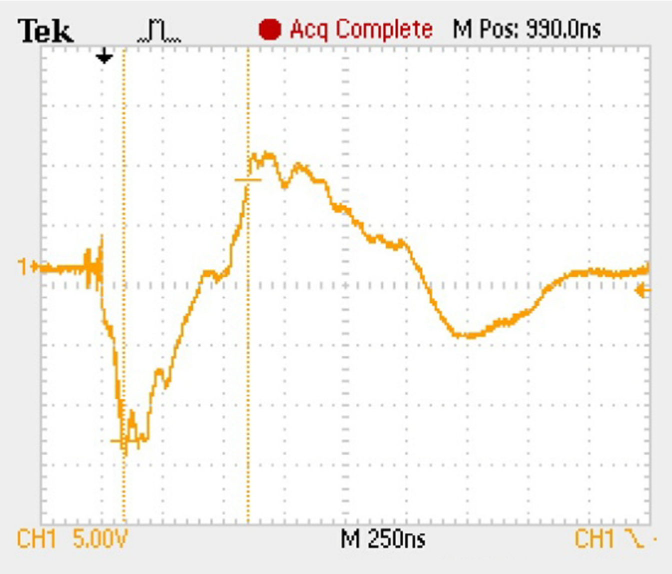

Fig. 4. Oscillogram of the response signal from phase "*a*" of the transformer winding when the probing impulse is applied to "*A*" phase.

In case of using the FRA, the FRA technology was applied which showed amplitude–frequency dependences. The object for experiments is the transformer from the distribution grid of Tyumen electric energy system (Siberian part of Russia). Main parameters of the transformer are as follows: power is 160 kVA, voltage of HV winding is 10 kV, voltage of LV winding is 0.4 kV, winding connection type is star, insulation is transformer oil.

The waveform of the used probing impulse is given in Fig. 3. The view of the response signal is shown in Fig. 4.

All forms of the response signal are identical to other combinations of "place of applying a probing impulse and place of registering the response signal". A special program for response signals comparison – program of digital data processing (PDDP) – has been developed.

Non-repeatability of the impulse response using the PDDP program did not exceed 4% with a sample of 24 oscillograms. According to the rule of the detection of defect, if the impulse response differs from normogram more than 5%, there will be changes in geometry of windings which are diagnosed by the proposed method.

To determine sensitivity of the nanosecond impulses method and the FRA to detect a defect of the type "turn to turn short circuit", the defect was organized in HV winding of the phase "C".

The view of the winding with this defect is given in Fig. 5.

The results of comparison of normograms (a blue curve) and response signals in case of turn to turn short circuit (a red curve) are given in Fig. 6, at various combinations of places of probing impulse feeding and response recording.

The calculation by the PDDP program for the case in Fig. 6 shows the difference integral of $3,4 \times 10^{6}$ Wb (in the range of $0–2,2 \times 10^{-6}$ s). The integral of the normogram (in the range of 0 to $2,2 \times 10^{-6}$ s) equals $1,0114 \times 10^{-5}$ Wb.

The difference integral between the normogram and defectogram of response integral normogram is 34%.

Fig. 5. View of defect "turn to turn short circuit" type made in HV winding.

The calculation by the PDDP program for the case in Fig. 7 shows the difference integral of $9,3243 \times 10^{-7}$ Wb (in the range of $0–2,2 \times 10^{-6}$ s). The integral of the normogram (in the range of $0–2,2 \times 10^{-6}$ s) equals $1,9740 \times 10^{-6}$ Wb.

The difference integral between the normogram and defectogram percentage of response integral is 47%.

The same experimental situation, but by the FRA control, is illustrated in Figs. 8 and 9.

In next experiments a defect of "axial shift of turns" was made in HV winding area of phase A. The view of the winding with this defect is shown in Fig. 10.

The calculation by the PDDP program for the case in Fig. 10 shows the difference integral of $3,3875 \times 10^{-6}$ Wb (in the range of $0–2,2 \times 10^{-6}$ s). The integral of the normogram (in the range of $0–2,2 \times 10^{-6}$ s) equals $9,9884 \times 10^{-6}$ Wb. The difference integral between the normogram and the defectogram of response integral is 36%.

The difference integral between the normogram and defectogram of the response integral for the case illustrated in Fig. 11 is 52%.

The same experimental situation is given for the FRA measurements in Figs. 12 and 13.

## 3. Discussion

So, in case of turn to turn short circuit in HV winding, the pulsed method based on nanosecond probing impulse gives a defference between normal and defect conditions in the winding at 34–47% range (Figs. 6 and 7). The FRA pictures at the same situation show either no difference at all (Fig. 8) or very small difference (Fig. 9).

In short circuit only 3 turns were involved. For the case of defect "axial shift of turns", the nanosecond impulse method gives a difference of 36–52% depening on the combination "place of probing impulse feeding – place of response signal recording" (Figs. 11 and 14). The FRA pictures at the same situation have no difference at all (Figs. 12 and 13). Axial shift

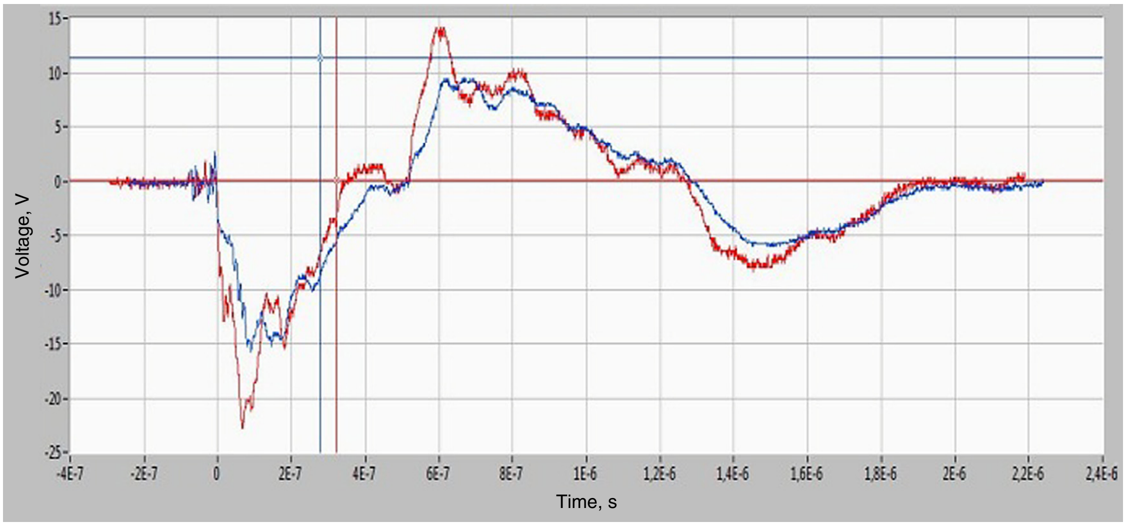

Fig. 6. Result of two signal comparison. The blue curve is the normogram; the red curve corresponds to "turn to turn short circuit" type made in HV winding. The probing impulse is applied to HV winding of phase *A*, the response is recorded in LV winding of phase *a*.

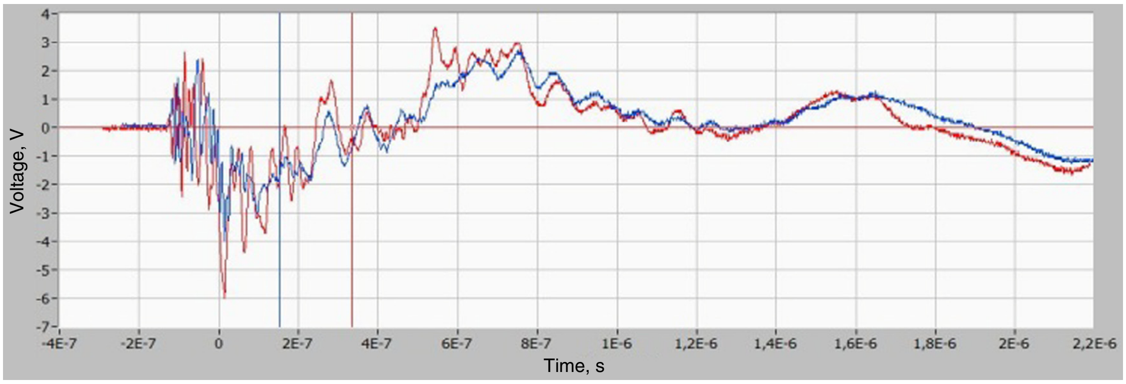

Fig. 7. Result of two signal comparison. The blue curve is the normogram; the red curve corresponds to "turn to turn short circuit" type made in HV winding. The probing impulse is applied to HV winding of phase *B*, the response is recorded in LV winding of phase *c*.

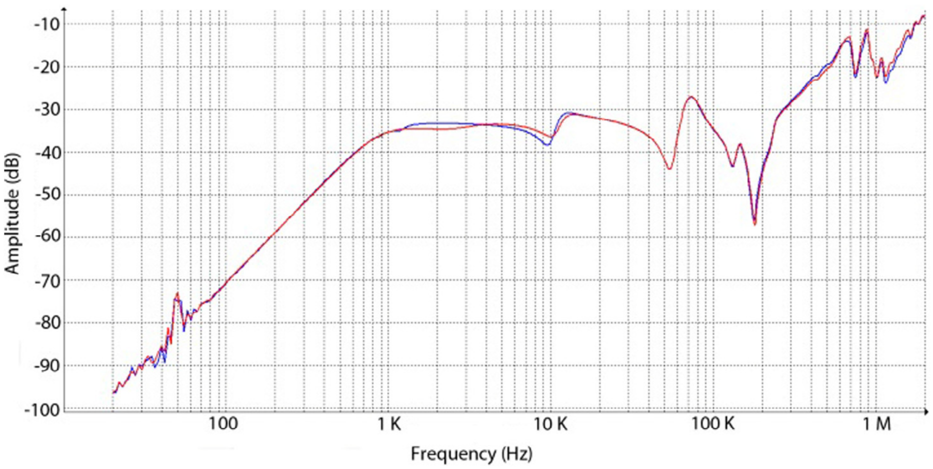

Fig. 8. Result of FRA analysis. The blue curve is the healthy state of winding; the red curve corresponds to "turn to turn short circuit" type made in HV winding. The probing impulse is applied to HV winding of phase A; the response is recorded in LV winding of phase a.

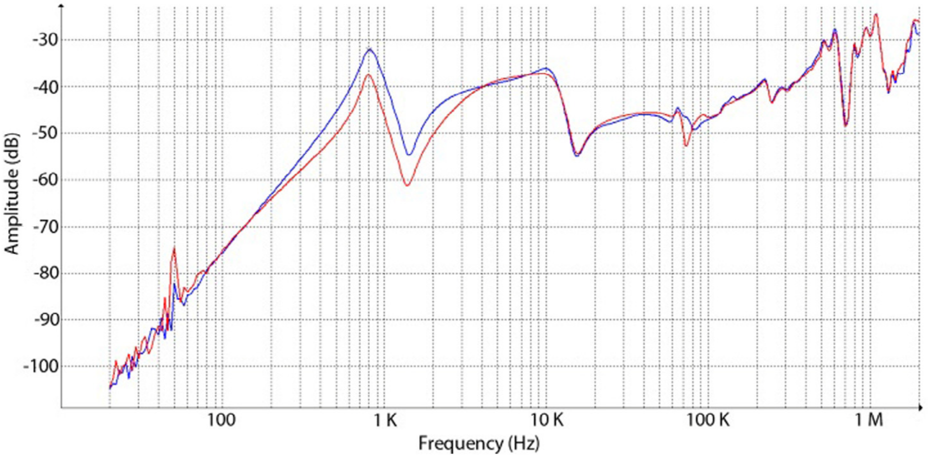

Fig. 9. Result of FRA analysis. The probing impulse is applied to HV winding of phase *B*, the response is recorded in LV winding of phase *c*.

covers 12 turns. It is a typical defect and the beginning of a more serious winding damage due to unrush and short circuit currents. Despite the defect, the FRA data conclude that the winding is in normal condition. The diagnosis fails in this case. At the same time the nanosecond pulsed method shows the signal difference no less than 36%. It is the clear evidence of occurrence of defect condition. A correct diagnosis is made for this situation based on the “nanosecond probing impulse technology” data. The obtained results can be explained by the fact that impulses with shorter front and duration excite contours with higher own frequency.

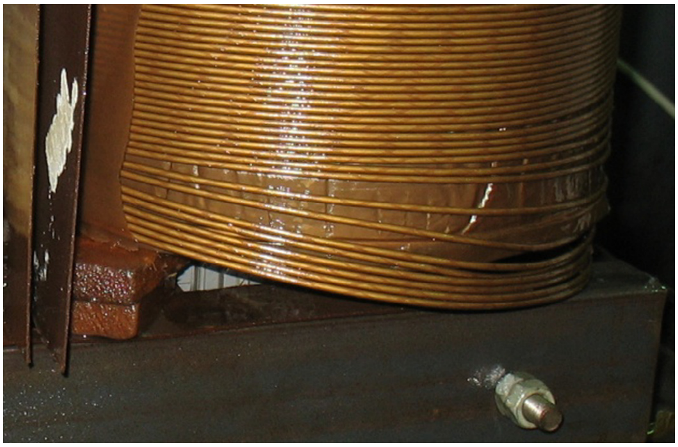

Fig. 10. View of defect “axial shift of turns” type made in HV winding.

Expansion of the probing impulse frequency spectrum at the front of 25 ns up to 25 MHz exceeds considerably the frequency range for the FRA method at high frequencies.

It could be proposed that in order to increase diagnostic sensitivity of the winding condition it is appropriate to use two impulses of different duration: an impulse of long duration could be used for diagnostics of “low-frequency defects” (winding pressing out, short circuit of a large number of turns); short duration impulses (nanosecond range) could be used for diagnostics of “high-frequency defects” (negligible approaching of turns, small radial and axial shifts).

The shorter the impulse, the wider its spectrum and the more relative contribution of high-frequency components of impulse and less noise level contribution in the signal

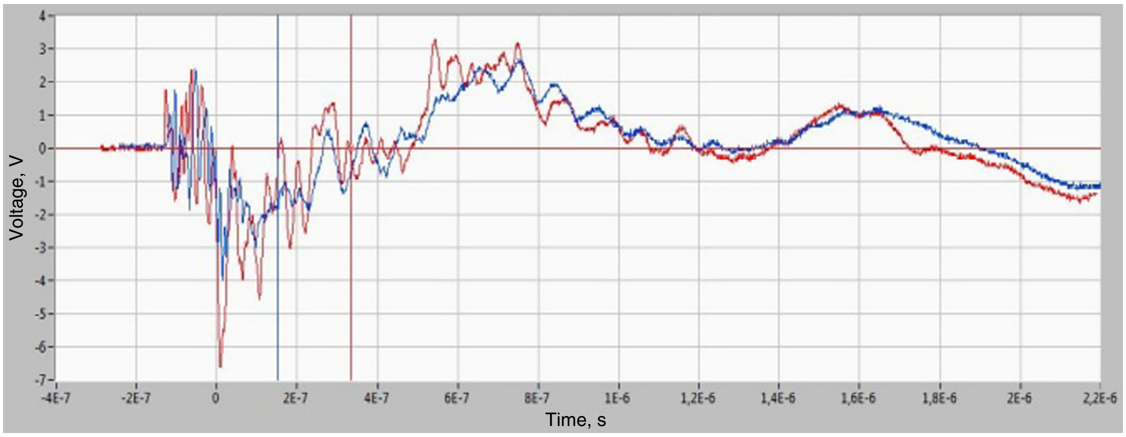

Fig. 11. Result of two signal comparison. The blue curve is the normogram; the red curve corresponds to “axial shift of turns” type made in HV winding. The probing impulse is applied to HV winding of phase *B*; the response is recorded in LV winding of phase *c*.

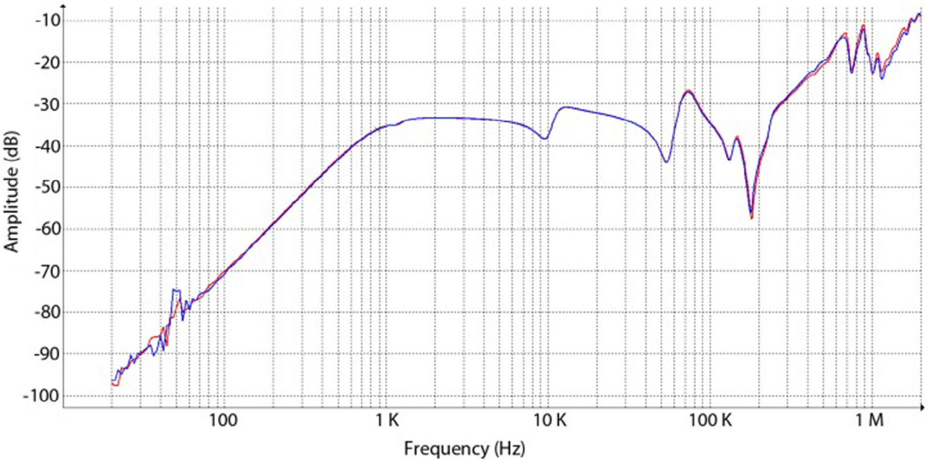

Fig. 12. Result of FRA analysis. The probing impulse is applied to HV winding of phase *A*; the response is recorded in LV winding of phase *a*.

response at the same time. Transition to impulse durations in the range of 500. . .100 nanoseconds will allow marking out the defects at the most initial stage and thus avoiding excessive fluctuations arising in contours with smaller own frequency. This is possible due to the fact that short impulses have a wider frequency spectrum, the range of which is required for excitation of contours having the defect in the initial stage.

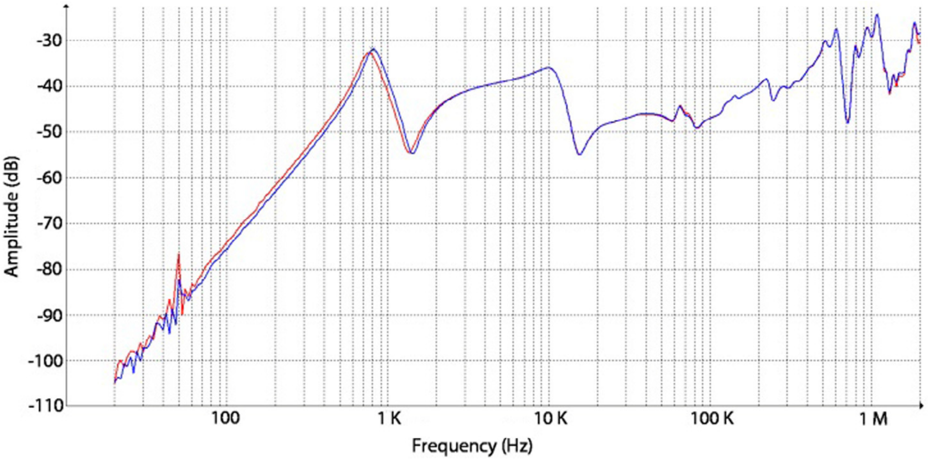

Fig. 13. Result of FRA analysis. The probing impulse is applied to HV winding of phase *B*; the response is recorded in LV winding of phase *c*.

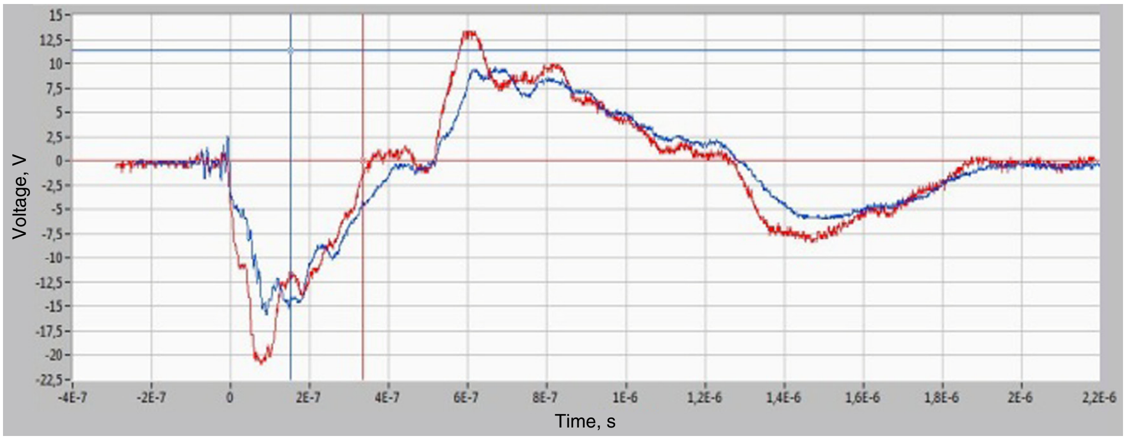

Fig. 14. Result of two signal comparison. The blue curve is the normogram; the red curve corresponds to “axial shift of turns” type made in HV winding. The probing impulse is applied to HV winding of phase *A*; the response is recorded in LV winding of phase *a*.

## 4. Conclusion

The technique for waveforms processing obtained as a result of transformer winding condition control by means of the low-voltage impulse method is proposed.

The technique is based on the comparison of the response impulse integrals for the working winding and the winding containing defects of the type “turn to turn short circuit” and “axial shift of turns”.

It is shown that integrals can vary by 50% for the defect of the type “turn to turn short circuit” and by 36–50% in case of the defect “axial shift of turns”.

The comparison of the results of the LVI and FRA methods sensitivity by the proposed technique has shown that the FRA method does not allow detecting the defects representing closing of few turns (3 winding turns) and mechanical shift of turns in the axial direction.

So, despite many positive characteristics, in some cases sensitivity of the FRA is not appropriate and the percentage of errors when stating the transformer diagnosis is too high. One of the reasons for that is restriction of upper boundary of frequency range. It is around 1–3 MHz. The noise level in a common signal is too high and this restricts top of working frequency range at the FRA.

The difference between the amplitude–frequency characteristics obtained by means of the FRA method is less significant than the difference between the response signals obtained by the method of nanosecond impulses for two conditions in the winding.

The obtained difference in the sensitivity of the LVI and FRA methods for the same winding defects can be explained by wider frequency saturation of nanosecond probing impulse at high frequencies.

The range of frequency spectrum of the used nanosecond impulse reaches 10–25 MHz whereas in FRA technology the maximum frequency is limited to 2 MHz. This confirms the assumption that the smaller the degree of the defect development, the higher frequency of probing impulse is necessary for detecting the defect.

One of the ways of improving the condition control is the use of short probing impulse duration with a rapid front. The application of a probing impulse with impulse duration of 500 ns and front duration up to 25 ns allowed increasing sensitivity of the diagnostic procedure compared to the FRA method at the same winding defects.

It could be concluded that the nanosecond probing impulse technique is a good and advanced instrument in a number of diagnostic methods.

The transformer winding condition control by means of short (probing impulse of nanosecond duration) is an important step toward advanced resource-effective technologies in power industry.

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