

Development of impulse method for transformer winding condition control technology

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Abstract. Mechanical shift of windings is serious problem of power transformers which belong to the very significant components of power engineering system. Mechanical displacements and following insulation failure due to short circuit and inrush currents can lead to an emergency situation. That's why the effective control technology of windings is an relevant task of a current power engineering. A new approach to winding state control technology is described in the paper. The described technology is based on nanosecond probing impulse duration with short (no more than 20 ns) rapidness of front impulse. The experimental results of sensitivity growth at decreasing front pulse duration are shown. The experimental equipment and research are described. It is established that duration of probing impulse has optimum value around 100ns. It is shown that it is possible to do a condition control under operating voltage. It is shown that both shorter probing impulse and front of probe pulse duration allows upgrading common effectiveness of the diagnostic technology.

1. Introduction

The Electrical strength of windings insulation is a necessary condition of a power transformer stable operation. It is impossible to realize without sensitive and reliable condition control technologies. The appropriate technology to control a mechanical state of transformer windings was proposed in 1966 [1]. The principle of the method consists in applying probing standard lighting impulse of 1.2/50 microsecond with the amplitude of 200 – 300 V to one of the windings. Other windings were short-circuited and the shunt which gave a response to a probing impulse was installed in them. The response represents the signal corresponding to transient, arising in windings, as a reaction to a probing impulse. At first, it is necessary to measure the normogram. This is a response from the winding of the working transformer. The process of sounding is repeated at the next test. Comparison of normograms and current sounding (defectograms) allows making a conclusion about winding state. The difference in the normogram and defectograms represents the problem in the winding. Further, this method was very popular in European, American countries [2] and was called the Low-Voltage Impulses method (LVI).

Furthermore, in Canada, the LVI method was modified and transformed into a method of measurement of amplitude-frequency characteristics. It was done to avoid at the measurement errors due to strict rules to measurement procedure. The principle of amplitude-frequency method consists in measuring the amplitude-frequency characteristics from one of the transformer windings when applying to the other winding a sinusoidal signal with the amplitude around 10 V of various frequencies. Then the amplitude-frequency characteristics are compared with the normograms, received on the serviceable transformer. This allows to avoid strong influence of circuit parameters to measurement results. Nowadays this method is called a Frequency-Response Analysis method or a



FRA Technology and it is widely used around the world [3–7]. The FRA interpretation that is based on the analysis of physical electrical parameters is not feasible since one of the most important parameters, the winding series capacitance, cannot be determined in transformer bulk [5]. Special generators for the diagnostic procedure by the FRA technology are being produced. Frequencies for diagnostics of high-voltage transformers are in range from 1 Hz to 2.5 MHz.

Both the LVI and the FRA methods not always provide exact diagnostics and sometimes have low sensitivity. We consider that it occurs due to rather narrow frequency range of probing signals. The standard storm impulse has the top frequency about 500 kHz, the FRA method – 2.5 MHz.

Our approach is to upgrade common efficiency of the LVI method by means of a probing pulse using the frequency range up to 50 MHz. It can be implemented by applying to one of the transformer windings a probe pulse with the amplitude of 300 V and a short front duration of and pulse duration of 20...500 ns. A short probe impulse is a way to increase sensitivity of the diagnostic procedure. But to determine optimal parameters of probing impulse the experiments both on model and real transformer should be done. Main goal of research is to determine probing impulse parameters which provide maximum efficiency of winding condition control.

2. Experimental research of condition control on transformer model

Experimental facility consists of a generator of nanosecond impulses, physical model of three-phase two-winding transformers and oscilloscope Tektronix TDS 2024. The model of three-phase transformer includes three low voltage coils inserted in high voltage ones. The turn number at the low voltage coil is 20, at the high voltage coil – 120. A nanosecond impulse of rectangular form with front duration 5-25 ns was supplied to enter of the high voltage coil. The response signal was measured on exit of the low voltage coil. Oscilloscope Tektronix TDS 2024 was used to control the parameters of a probe impulse as well as response signal. The electric circuit of the facility is shown in Figure 1.

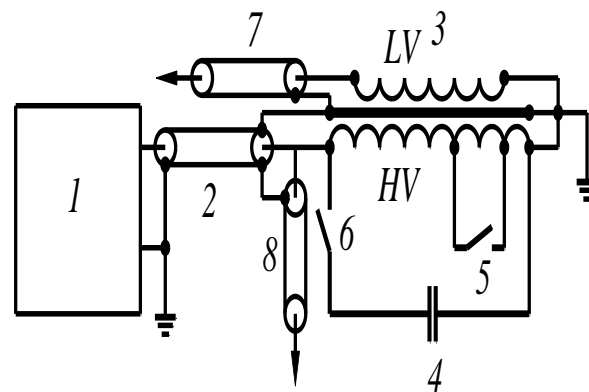


Figure 1. Electric scheme of the transformer model experiment: 1 – the generator of probing impulses, 2 – the connecting coaxial cable impedance of 75 Ohms, 3 – the diagnosed transformer (HV—high voltage, LV – low voltage), 4 – the condenser for change of the front of a probing impulse, 5 – short-circuit of turns (common turn number is 120), 6 – the switch for connection of the condenser 4; 7, 8 – probes for connection to an oscilloscope TDS 1024.

Some changes of windings geometry due to tilting, bending, axial or radial shifts, faults as a result of short-circuit currents, cause changes of capacities and inductances along winding. As result, a influence of probing pulse lead to changes in response essence as a winding reaction. Preliminary experiments proved the prospect and common opportunity and good efficiency of the nanosecond approach as a diagnostics method [8–10].

The impulse of rectangular form generated by the pulsed scheme is put to a high-voltage winding, the impulse-response is fixed on a low-voltage winding of the transformer. Windings had no loads (a case of completely switched-off transformer). Fail type turn to turn short circuit including three turns

was simulated at the high voltage winding of phase A. The front of a probing impulse was changed and had meanings durations 25 and 400 ns respectively. Results of winding control for two cases with turn to turn fail and without one are described below. A comparison of an impulse of the normogram and an impulse of the response for both given cases is presented in Figure 2. It is established that duration of a probing impulse front of 25 nanoseconds the response at a fail winding differs strongly enough in comparison with the response at duration of a probing impulse of 400 nanoseconds.

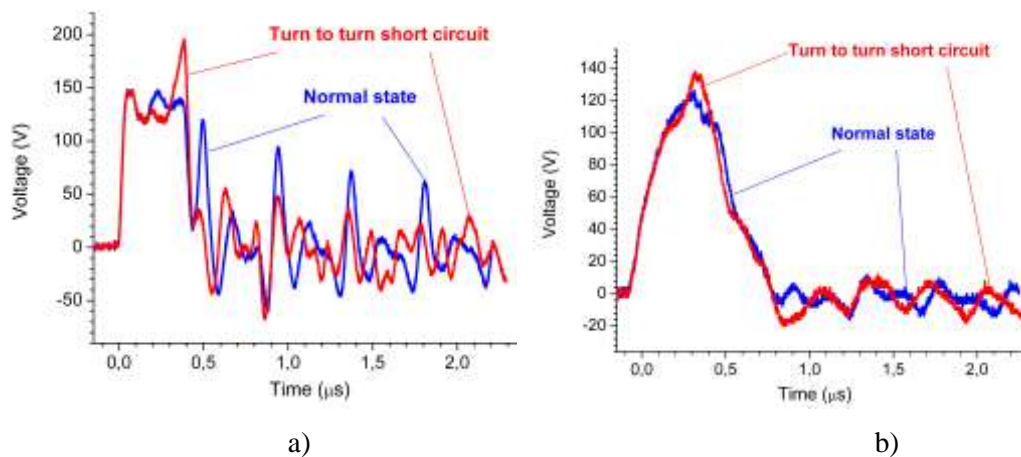


Figure 2. Comparison of impulses of the normogram and responses for probing impulses with the different duration of the front and identical defects in a transformer winding: a) duration of a probing impulse front of 25 nanoseconds, b) duration of a probing impulse front of 400 nanoseconds.

3. Experimental research of condition control on real equipment

Next research run was carried out on real high voltage transformer. Main parameters of the transformer are as follows: total power is 160 000 VA, voltage of HV winding is 10 kV, voltage of LV winding is 400 V, three phases, winding connection type is star, insulation is transformer oil. The schemes of experiment of monitoring the condition of windings including the generator of probing impulses, oscilloscopes measuring parameters of probing impulse as well as response signals, are shown in Figure 3. Scheme of condition control is traditional for low voltage impulse method. Probing impulse is supplied to a high-voltage winding of the transformer A, the impulse-response is measured on a low-voltage winding of the transformer a. Oscilloscope 1 is for measure of probing impulse parameters. Oscilloscope 2 is for response signal registration. To research a dependence of winding condition control efficiency versus probing impulse duration, special pulsed generator was designed and engineered. Picture of this is shown on the Figure 4.

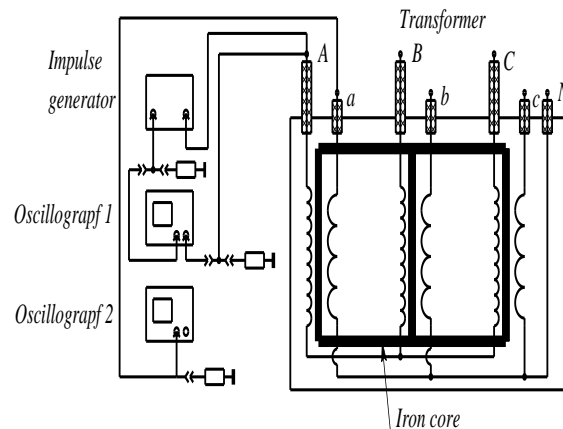


Figure 3. Scheme of experiment at the condition control by the nanosecond pulsed method.



Figure 4. Common view of probing pulsed generator.

The generator produces probing impulses with different pulse duration, namely, 520, 260, 100, 60 and 20 ns. Two types of fail were simulated on the high voltage winding of real high voltage transformer. Defect number 1 is turn short circuit of three rounds. Defect number 2 is axial shift of turns at the bottom of winding (lodging conductors). Main goal of experiments on real high voltage transformer is research of influence of both pulse and pulse's front durations to effectiveness of winding condition control at two different fail types. Views of fails are shown on the Figures 5.

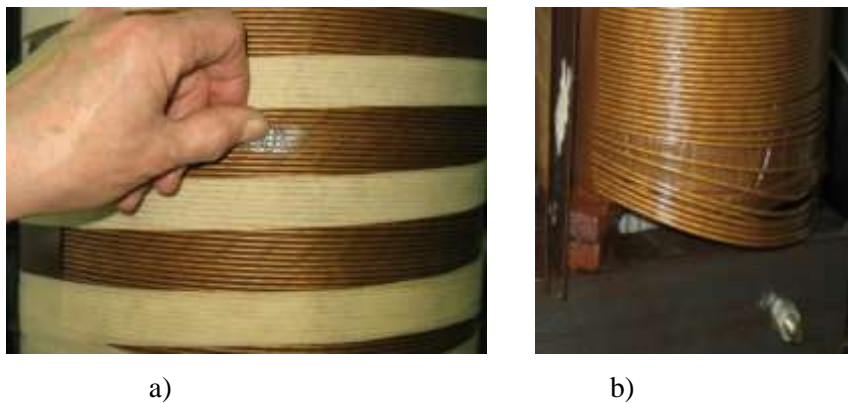
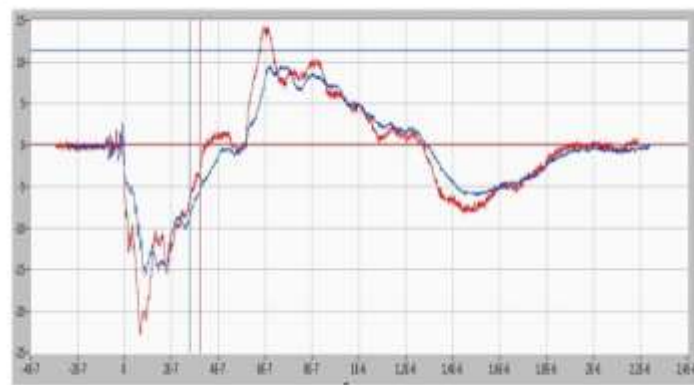


Figure 5. View of faults: a) fail turn to turn short circuit, b) fail axial shift of turns type

To research a dependence of winding condition control efficiency versus probing impulse duration probing impulse with five different durations is applied to winding. Three cases were researched – normal winding condition, winding with defects number 1 and 2. To research a dependence of winding condition control efficiency versus probing impulse front rapidness, a capacitor is placed in parallel between probing pulse generator and HV winding of phase A. 4 different value of capacitance were used – 330, 2200, 4700 and 9100 pF. The more capacitance value the more front duration is. For probing pulse duration 520 ns, front has following values: 5 ns without capacitor, 66 ns for capacitance 330 pF, 512 ns for capacitance 9100 pF. In last case front duration is practically equal to pulse duration. The same measurements were carried out for all pulse durations – 520, 260, 100, 60 and 20 ns.

To determine an effectiveness of condition control process, special program for response comparison were design and used. The results of comparison of normograms (a blue curve) and response signals for both defects (a red curve) are given in Figures 6 and 7.

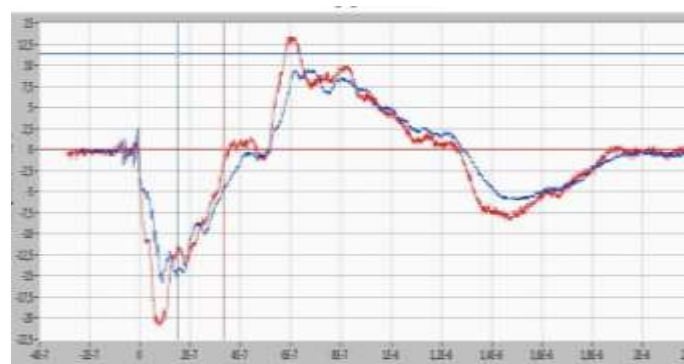
Voltage, V



Time, s

Figure 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.

Voltage, V



Time, s

Figure 7. 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.

The calculation by the comparison program for the case in Figure 7 shows the difference integral of 3.4×10^6 Wb (in the range of $0 - 2.2 \times 10^{-6}$ s). The integral of the normogram (in the range of 0 to

2.2×10^{-6} s) equals 1.0114×10^{-5} Wb. The difference integral between the normogram and defectogram of response integral normogram is 34%. The calculation by the comparison program for the case in Figure 8 shows the difference integral of 9.3243×10^{-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 1.9740×10^{-6} Wb. The difference integral between the normogram and defectogram percentage of response integral is 47%. So, efficiency of condition control is expressed in percentages.

Result of detailed research of influence of pulse and front of probing pulse duration to effectiveness of winding condition control is shown on Figures 8 and 9.

It is established that optimum pulse duration is in 100 – 110 ns. At this parameter condition control efficiency has maximum value for both types of different defects. The decrease in efficiency to the left side of the maxim is due to the fact that a short pulse does not penetrate into the winding. The decrease in efficiency to the right of the maximum, in our opinion, is explained by a decrease in the degree of excitation of the winding circuits as the duration of the probing pulse increases. According to above experiments it is established that the less front duration the more condition control efficiency. This statement is valid for defects of both types and for whole range of probing impulse duration.

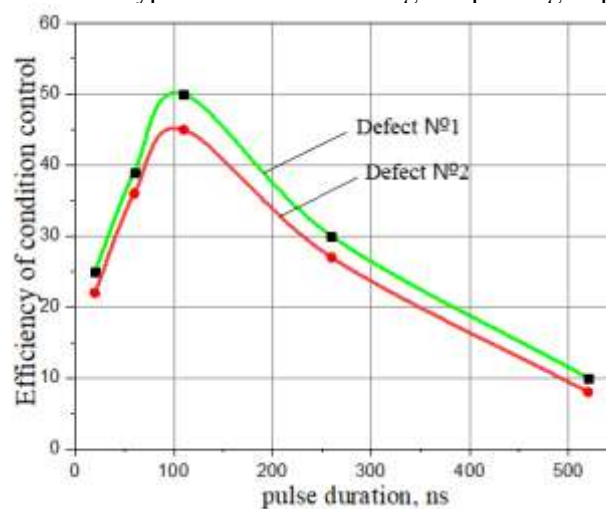


Figure 8. The dependence of the efficiency of monitoring the winding condition from probing impulse duration for two defects.

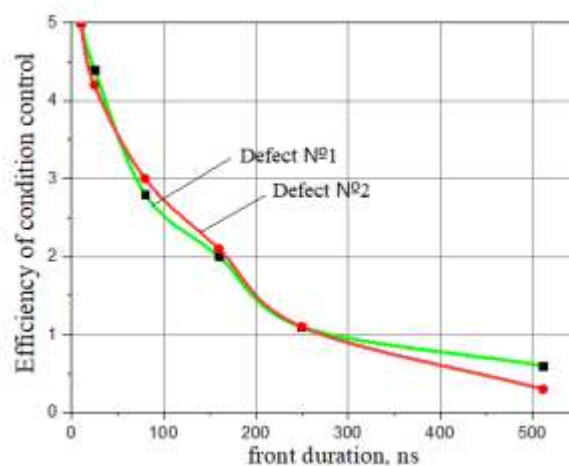


Figure 9. The dependence of the efficiency of monitoring the winding condition from front of probing impulse duration for two defects.

Optimum point for efficient diagnostics around 100 ns pulse duration could be explained as following. Impulses with duration more than 100 ns can't penetrate to winding without big losses. These losses influence sensitivity of diagnostics negatively. Impulses, with duration less than 100 ns, due to skin effect come to surface of investigated winding and stop to participate in condition control process. As for the front of probing impulse duration, it is established that high frequency part of common spectrum depends on it. The shorter front rapidness the more high frequency part comes to winding. Namely high frequency part is responsible for initial fail reveal. That fact makes short front more appropriate for sensitivity increasing.

4. Experimental research of winding condition control under operating voltage

In order to investigate the fundamental possibility of monitoring the state of the transformer windings at an operating voltage between the probe pulse generator and one of the phases of the transformer, an isolating coupling capacitor was installed. The experiments were carried out for model as well as real high voltage transformer. Separator condenser parameters: type K15-4; rated voltage 40 kV, capacity 2200 pF. In the measuring circuit used the same capacitor to obtain response signal under operating voltage. Thus, the probe pulse generator and measuring equipment were isolated from the transformer windings, which can be applied in practical work to monitor the state of the transformer windings in the operating mode. In Figures 10 and 11 are shown probing impulse and response for cases of without and under operating voltage.

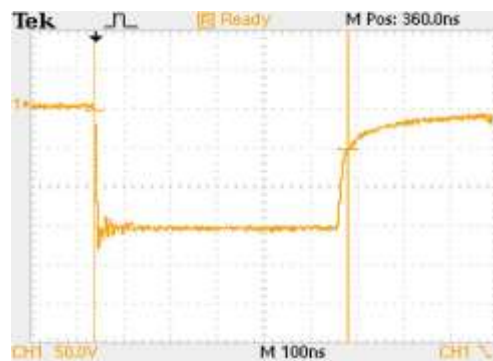


Figure 10. View of the probing impulse applied to the transformer winding



Figure 11. Oscillogram of the response signal from phase LW “a” of the transformer winding when the probing impulse is applied to HV “A” phase.

The signals have been taken in the same experimental conditions in the presence and absence of a coupling capacitor. Operating voltage was in 5–10 kV range. The signals in both cases are completely identical, which indicates the absence of extraneous signals and distortions in the measuring circuits.

The results of the experiments clearly demonstrate the fundamental possibility of implementing a diagnostic procedure under operating voltage.

The established fact that it is possible in principle to carry out a diagnostic procedure under operating voltage is important and has a significant prospect, as it allows monitoring the status of transformer equipment without shutting down and balancing, which is an undesirable (and often impossible) factor in the process of electric power systems.

5. Discussion

It is shown that optimum pulse duration is in 100–110 ns. At this parameter condition control efficiency has maximum value for kind of different defects. The decrease in efficiency to the left side of the maxim is due to the fact that a short pulse does not penetrate into the winding. The decrease in efficiency to the right of the maximum, in our opinion, is explained by a decrease in the degree of excitation of the winding circuits as the duration of the probing pulse increases.

The short probe pulse measurement also allows determining not only the initial stage of the defect, but also the place of the defect.

The shorter impulse, the wider its spectrum and the more relative contribution of the pulse high – frequency components and less noise level contribution in the signal response at the same time. Transition to impulse durations of 50...100 nanoseconds will allow marking out the defects in the most initial stage and thus avoiding the excessive fluctuations arising in contours with a smaller own frequency. It is possible since short impulses have a wider spectral structure which is in the range of frequencies which are required for excitation of contours arising from just initial defects (defects type like the most initial stage of turn to turn short circuit or axial shift).

6. Conclusion

Insulation destruction, deterioration of dielectric properties of the main and turn insulation of the transformer, electrical defects and mechanical deformations are influence of consequences of electro-dynamic forces of short circuit currents. To prevent all these consequences, the reliable methods of diagnostics should be used.

Despite many positive characteristics, in some cases sensitivity of most popular technology for these goals FRA makes a lot mistakes during the transformer diagnostics. One of the possible reasons for that is the fact that upper boundary of the frequency range is restricted by 2 MHz of frequency. Appropriate way to solve a problem is using a probing impulse with duration 100 ns with a rise time of 5 ns. Experiments confirm the effectiveness of this approach.

The established fact that it is possible in principle to carry out a winding condition control under operating voltage or ON-LINE regime is important and has a significant prospect, as it allows monitoring the status of transformer equipment without switching down. This fact opens new prospects before pulse detection method.

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