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Assessment of Stresses on Power Transformer Winding Internal Insulation under Resonant Overvoltages

V.S. Larin[1], D.A. Matveev[2]
[1]All-Russian Electrotechnical Institute (VEI),
[2]Moscow Power Engineering Institute (MPEI)
Russian Federation

SUMMARY

Windings of high voltage power transformers are complex oscillatory circuits, the natural frequencies of which are from a few up to several hundreds of kHz. It is well known that if the frequency of voltage oscillations at the input terminals of the transformer is close to one of the winding natural frequencies, such oscillations can initiate the development of high-frequency resonant overvoltages inside the windings, which poses a potential danger to the internal insulation of the transformer.

The most common reason for the appearance of voltage oscillations at the transformer terminals with frequencies from tens to hundreds of kHz is the multiple reflections of electromagnetic waves at the ends of the supply cable lines having a length from tens to hundreds of meters. With the increase of the cable lines rated voltages and with their growing application in recent years, there have been more and more cases of damages of the transformer internal insulation due to high-frequency resonant overvoltages inside the windings.

In order to ensure the ability of transformers to withstand high-frequency stresses, it is important to evaluate the voltages affecting their internal insulation. Recently, the high-frequency white-box models of transformers have received great development. These models make it possible to quantitatively estimate resonant frequencies of transformers and to make qualitative analysis of resonant phenomena development in transformer windings.

However, the limitations of these models, namely the omitting of frequency dependence of losses, do not allow them to provide a reliable assessment of the resonant-overvoltage magnitudes inside the windings.

For a more accurate determination of the voltages at the sections of the winding insulation, it is preferable to use direct measurements of voltages in the windings and transfer functions in a wide range of frequencies.

The paper discusses the application of computational and experimental evaluation of voltages affecting the winding internal insulation by combination of results obtained by modelling and from available measurements.

KEYWORDS

Power transformers, resonant overvoltages, transformer windings, internal insulation, assessment of stresses.

vslarin@vei.ru

1. INTRODUCTION

Windings of HV, EHV and UHV power transformers are complex oscillating circuits having natural frequencies between few kHz and several hundreds of kHz. It is well known that if the frequency of voltage oscillations at transformer's input terminals is close to one of the winding natural frequencies, such oscillations can develop resonant overvoltages inside the windings, which poses a potential danger to internal insulation of the transformer.

The most common reason of oscillations at transformer's input terminals at frequencies from tens to several hundreds of kHz is multiple reflections of electromagnetic waves at the ends of the supply cable lines having a length from tens to hundreds of meters. With the increase of the cable lines rated voltage and the growth of their application, more and more cases of transformer internal insulation damage due to high-frequency resonant overvoltages have been observed last years.

During the period from 2008 to 2013 international CIGRE working group (WG) A2/C4.39 "Electrical Transient Interaction Between Transformers and the Power System" has been working. The result of this work is the publication of two-parts technical brochure [1, 2] in which multiple cases of transformers failure due to transient interaction in different countries are described. The importance of the application of accurate high-frequency transformer models for external network transients simulation as well as the importance of interaction between customers and manufacturers at the design stage to account for probable high-frequency interaction in service are marked in the brochure. In 2015, new WG A2/C4.52 "High-frequency transformer models for non-standard waveforms" which is logical continuation of WG A2/C4.39 started its work.

Resonance phenomena in transformer and shunt reactor windings are potentially dangerous for the internal insulation. For instance, with transformer secondary windings unloaded, resonance phenomena can lead to significant overvoltages on internal insulation during which the voltage on different parts of winding insulation is comparable or higher than the voltage on transformer terminals. External surge arresters located at transformer input terminals are not capable of limiting overvoltages appearing inside transformer windings during resonance.

There exist several combinations of typical configurations of electric circuits and commutations which lead to high-frequency oscillations of voltage in the system "cable line – transformer" with frequencies comparable with natural frequencies of transformer windings, including "cable line – transformer" system energizing and single-phase ground fault at the beginning of supply cable line.

In general, to estimate the possibility of resonant overvoltages development inside transformer windings and to assess the degree of their danger for internal insulation one has to solve following problems.

1) Identification of dominant frequencies of oscillations in power system.
2) Identification of transformer windings natural frequencies.
3) Determination of voltages affecting different parts of transformer insulation during resonant overvoltages.
4) Assessment of transformer insulation dielectric strength at the impact of voltage oscillations induced by resonant overvoltages.

Some information regarding first problem can be found in [3]. Solution to the second problem is described in detail in [4], and approaches to solution of fourth problem are presented in [1].

In the next sections of this paper the influence of winding type on resonance phenomena and the approach to assessment of internal insulation stresses during resonant overvoltages are considered.

2. INFLUENCE OF TRANSFORMER WINDING TYPE ON RESONANT OVERVOLTAGES

Practically, all types of HV windings of power transformers and shunt reactors are subjected to resonant overvoltages.

Continuous disc windings are subjected to resonant overvoltages in the highest degree because such windings are characterized with more nonlinear initial voltage distribution and higher amplitudes of natural oscillations. Interleaved windings as well as continuous windings with complex schemes of wound-in shields connection are characterized with more linear initial voltage distribution and are less prone to resonant overvoltages affection. Combined windings and continuous windings with wound-in shields connecting two adjacent discs are in the middle position. Interleaved disc windings feature relatively low natural frequencies which are – everything else being equal – approximately two times lower that those of continuous disc type.

Last years, the development of transformer equipment construction and manufacturing technologies at one hand and the improvement of circuital and technical solutions regarding the design of power system facilities as well as the application of new kind of equipment at other hand lead to convergence of power system transients frequencies and natural frequencies of windings of power transformers and shunt reactors.

Thus, in earlier times, transformers with rated voltage above 300 kV had totally interleaved HV windings; at substations with rated voltage above 300 kV open switchgears and air circuit breakers were mainly used, and for connection of transformers with switchgears air busbars were used. These solutions featured low natural frequencies of windings and relatively high frequencies of transients in the system “busbar – transformer”.

In modern transformers with rated voltage above 300 kV, HV windings due to technological issues are mainly partially interleaved or continuous with wound-in shields. At switchgears of substations with rated voltage above 300 kV air circuit breakers are replaced with SF_6 circuit breakers; moreover, it becomes more and more common to use hybrid GIS at new facilities. For connection of power transformers and shunt reactors with switchgears XLPE cable lines [9, 10] featuring significant capacitance and lower velocity of electromagnetic waves propagation in comparison with traditional air busbars are often used. Such combination of technical solutions determines the proximity of the frequencies of windings oscillations and “busbar – transformer” system transient oscillations (fig. 1, *b*).

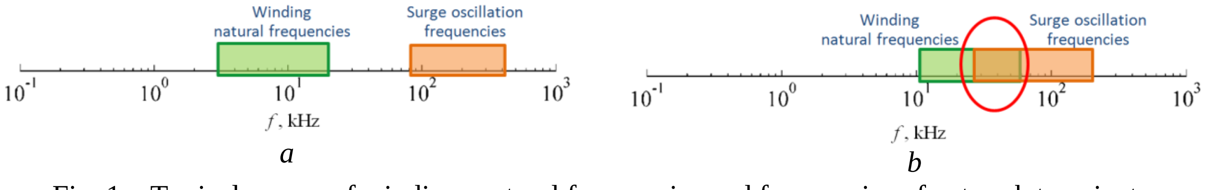


Fig. 1 – Typical ranges of windings natural frequencies and frequencies of network transients

HV winding damages have been also observed in 6–35 kV distribution transformers, including dry-type transformers. Regarding resonant overvoltages, the following features of 6–35 kV transformers may be highlighted:

1) 6–35 kV transformers are mainly distribution transformers having power rates between hundreds kVA and few MVA. It causes low size of active part, low electrical length of HV winding and relatively high natural frequencies of HV winding (from tens to hundreds of kHz). Hence, the development of resonant overvoltages in HV windings is possible with lower length of supply cable lines. With lower length of supply cable lines, the input impedance (input capacitance) of transformer has a strong influence on fundamental frequency of voltage oscillations in the “cable line – transformer” system, which causes decrease of this frequency, especially in the case of delta-connected HV winding [7].

2) In the oil-immersed 6–35 kV transformers HV windings are usually cylindrical with multiple layers. Regarding the possibility of resonant overvoltages development, such windings are between continuous disc windings (the most affected to resonant overvoltages) and fully interleaved windings (the least affected).
3) 6–35 kV transformers are characterized by relatively low test voltages and can be manufactured with dry-type insulation. In dry-type transformers with air-barrier insulation, continuous disc windings (transformers with open windings) and disc windings (transformers with cast insulation) are mainly used. Their constructive features are appearing as follows. Firstly, disc windings have lower series capacitance in comparison with layer windings, which defines more nonlinear voltage distribution at high frequencies and higher amplitudes of voltage oscillations in windings during resonant voltage rise. Secondly, dry-type transformers generally have lower insulation safety factors in comparison with oil-immersed transformers, especially for 20–35 kV transformers. Thirdly, solid insulation (on the contrary with paper-oil and oil-barrier insulation) is not self-restoring, hence, initial particle discharges in microscopic defects lead to their gradual increase, increase of particle discharges intensity and subsequent breakdown; this defines the possibility of cumulative effect when winding is repeatedly exposed to resonant overvoltages. The consequence of these factors is high exposure of 6–35 kV dry-type transformers to failure due to resonant overvoltages.
4) In 6–35 kV networks with isolated neutral high-frequency processes in one phase affect more than one phase of supplied transformer HV winding. On the other hand, if HV winding is delta connected, the beginning and the end of windings of each phase are connected to different phases of the network, which causes the possibility of superimposing of transients related to windings of different phases.

3. APPROACH TO EVALUATING STRESSES ON THE INTERNAL INSULATION OF TRANSFORMER WINDINGS

3.1. Approximation of the voltage spatial distribution

In [4] the issue of measuring the spatial distribution of voltages along the windings in the frequency range was considered. The spatial distribution of voltage in the winding can be obtained by measuring the transfer functions at individual points of the winding and then gluing the transfer functions into a three-dimensional graph. To measure the transfer functions, frequency analyzers can be used, as well as FRA measuring systems in which the input impedance of 50 Ohms on the response channel is replaced by a high-impedance probe with an input capacitance of no more than 10–20 pF.

With a sufficiently large number of internal points of the winding available for measurements, including the input parts of the windings, the gradients – voltages across the elements of longitudinal insulation (turns, layers, coils) – can be obtained at resonant frequencies quite accurately from the spatial distribution. However, this is not always possible for windings of real transformers, even at the manufacturer workshop, due to difficulties with connecting to the internal points of the windings.

When designing winding insulation, it is necessary to know the voltages not only on the insulation between layers or discs, but also on the interturn insulation. For the latter, measurements of resonant voltages between adjacent turns is practically difficult due to the large number of turns on the one hand and on the other – due to the possible strong influence of the measurement leads, the length and capacitance of which are comparable to those of a single turn. To assess the voltages on the interlayer and interturn insulation, one can resort to approximating the voltage values measured at individual points of the winding and finding the derivative of the approximating function.

The spatial voltage distributions in the winding at the first few natural frequencies are continuous, and cubic splines can be used as an interpolating function. However, for a limited number of winding points available from measurements, the presence of significant deviations of the fitted curve from the actual spatial voltage distribution in the spacings between the measurement points can occur. As an alternative to spline interpolation, approximating functions in the form of expressions obtained from the theoretical solution of differential equations of transients in windings can be used.

In the case of uniform winding, steady-state voltage $U(x, t)$ under application of sinusoidal voltage with frequency equal to i-th natural frequency of winding may be approximated as follows [5]:

$$U(x,t) \approx u(x,0)\sin\omega_i t + A_i \sin i\pi x\left(\frac{1}{4}\sin\omega_i t + \frac{\omega_i}{2\gamma_i}\cos\omega_i t\right) \qquad (1)$$

where x is the relative coordinate of the point of the winding; $u(x,0)$ is the initial voltage distribution along the winding; A_i, ω_i and γ_i are the amplitude of oscillations, the angular frequency and the damping factor of i-th harmonic correspondingly.

Equation (1) can be simplified [6]:

$$U(x,t) \approx u(x,0)\sin\omega_i t + A_i \sin i\pi x \cdot K_i \sin\left(\omega_i t + \varphi_i\right) \qquad (2)$$

where K_i is the ratio of resonant voltage rise (Q-factor of oscillating circuit); φ_i – phase shift between winding voltage and source voltage.

In equations (1) and (2), the multiplier $\sin i\pi x$ describes spatial distribution of voltage in the case of uniform winding without accounting for mutual inductance between parts of the winding. When accounting for this inductance, equation (2) can be in the case of uniform winding rewritten as follows:

$$U(x,t) \approx u(x,0)\sin\omega_i t + \left[A_i \sin\alpha_1 x + B_i\cos\alpha_1 x + C_i \mathrm{ch}\alpha_2 x + D_i \mathrm{sh}\alpha_2 x\right]\cdot K_i \sin\left(\omega_i t + \varphi_i\right) \qquad (3)$$

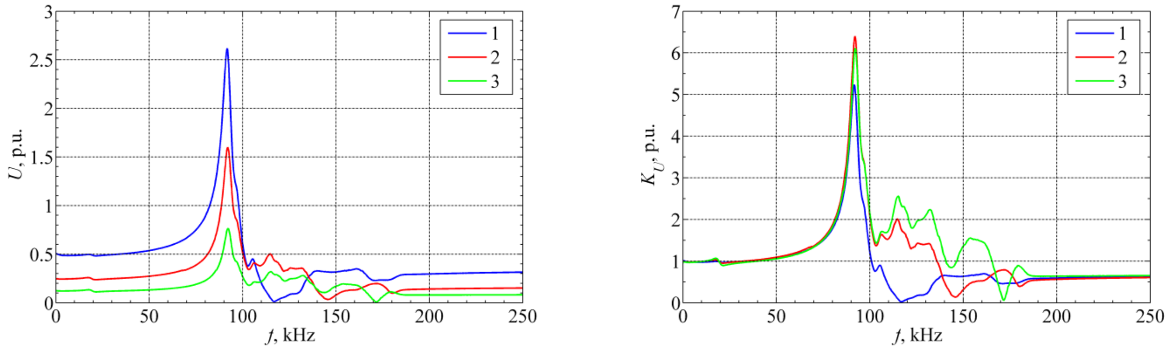
With the application of boundary conditions $U(0, 0) = 1$ and $U(1, 0) = 0$, coefficients C_i and D_i can be expressed as $C_i = -B_i$; $D_i = -\left(A_i \sin\alpha_1 x + B_i \cos\alpha_1 x - B_i \mathrm{ch}\alpha_2 x\right)/\mathrm{sh}\alpha_2 x$.

Equations (2) and (3) as well as measured steady-state voltages at intermediate points of windings can be represented using complex numbers which makes it possible to write two equations for each available point of the winding – separately for real and imaginary parts of voltage. If the number of points in the winding available for measurements is enough, coefficients of approximating functions can be found using least squares.

The following is the example of measured transfer functions and voltage spatial distributions of dry-type transformer with rated power of 630 kVA and rated voltages of 10/0,4 kV. HV windings with cast insulation consist of 8 discs. For the convenience of measurements, the beginning and the end of each disc are led out onto HV winding surface.

Fig. 2 illustrates measured transfer functions for nodes no. 5, 7 and 8 which correspond to relative electrical length of windings from point of voltage application x = 1/2, 3/4 and 7/8.

From fig. 2 the feature of disc windings of dry-type transformers with cast insulation (which have relatively high series capacitance and low ground capacitance) can be seen: all natural frequencies starting from the second are located near the first one; resonant rise of winding voltage at the first natural frequency is significantly higher than winding voltage rise at next natural frequencies, and this determines practical interest mainly for the first natural frequency in the case of such windings.



a *b*

Figure 2 – Voltage transfer functions of nodes no. 5 (1), 7 (2) и 8 (3):
a – with reference to input voltage; b – with reference to node voltage at 50 Hz.

Fig. 3 and 4 illustrate HV winding spatial voltage distribution which has been obtained by measurement of transfer functions of particular HV winding nodes at wide frequency range. At fig. 4 frequencies of 92 kHz and 115 kHz correspond approximately to the first and the second natural frequencies, and frequencies of 106 kHz and 126 kHz are some close intermediate values, results for which are shown for comparison.

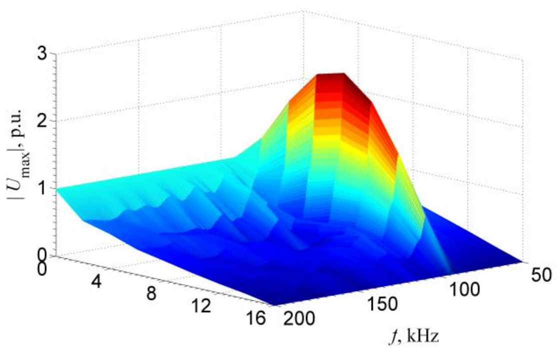


Figure 3 – Spatial-frequency voltage distribution of the winding

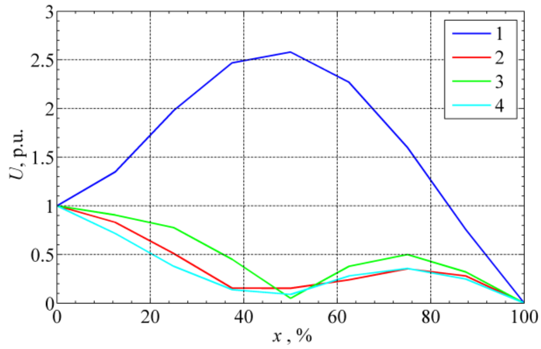
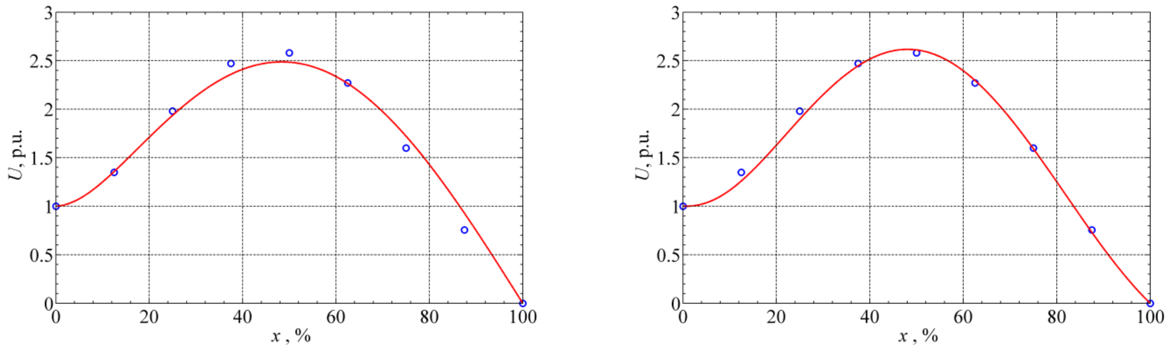


Figure 4 – Spatial voltage distributions of the winding at the frequencies of 92 (1), 106 (2), 115 (3) and 126 (4) kHz

Fig. 5 illustrates approximations of spatial voltage distribution described by equations (2) and (3) at first natural frequency obtained using least squares; blue dots correspond to measured values.



a *б*

Figure 5 – Approximations of measured voltage distributions using equations (2) and (3) (*a* and *b* correspondingly)

As can be seen from fig. 5, approximation obtained by equation (3) leads to better convergence of approximated and measured voltage distributions which is important for subsequent determination of voltage gradients at different parts of longitudinal insulation of a winding. However, approximation using simpler equation (2) in the considered case of disc winding which in comparison with layer windings features lower magnetic coupling between electrically unconnected turns is also acceptable.

Fig. 6 illustrates voltage gradients obtained by differentiation of approximating functions using equations (2) and (3) (curves 2 and 3) and the assessment of measured voltage gradient (curve 1) defined as the relative difference of measured voltages of subsequent nodes.

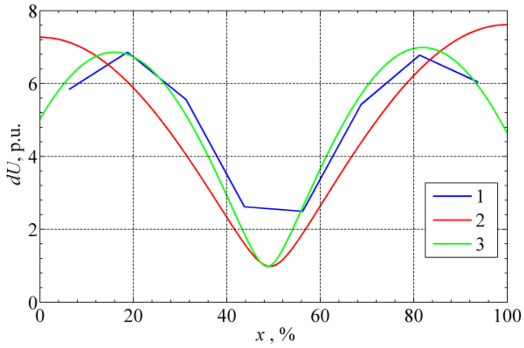


Figure 6 –Voltage gradients in the winding at 91 kHz

It can be seen from fig. 6 that the approximation obtained by equation (3) leads to more accurate result. Approximation obtained by equation (2) leads to somewhat overestimated values of voltage gradient at the beginning and the end of the winding. However, regarding maximum value of gradient, both approximations are in good accordance with measurements: estimation obtained from measured voltage – 6,86; by equation (2) – 7,62; by equation (3) – 7,00.

3.2. Estimation of voltage at longitudinal insulation using values measured at available points of winding

Above mentioned measurements were performed at transformer HV winding which possesses large number of intermediate points available for measurements. However, for windings of typical dry-type transformers with cast insulation there is an access only to the terminals of regulating part of HV winding.

Typically, regulating part is located in the middle of HV winding where the maximum of spatial voltage distribution at the first natural frequency is observed, which makes it possible to measure resonant voltage rise at the first natural frequency directly. Moreover, the minimum of spatial voltage distribution at the second natural frequency is observed in the middle of HV winding, consequently, the measurements at the middle point of winding are poorly informative for the estimation of resonant voltage rise at the second natural frequency.

Along with the measurement of transfer functions at the available points, the oscillography of transient resonant voltage rise at resonant frequencies with the winding supply from the undamped sinusoidal voltage source can be performed. Such oscillography allows to investigate the dynamics of the resonant voltage rise and to obtain corresponding time constants as well as to analyze the dominant natural frequencies.

Fig. 7 illustrates measured oscillograms of voltage at the middle point of HV winding at voltage supply frequencies of 91 and 114 kHz. It is important to note that as the result of the transient the maximum voltage at the frequency of 91 kHz corresponds to the steady-state value whereas at the frequency of 114 kHz the maximum voltage at the first instant is significantly larger than the steady-state value. Thus, in general, assessment of stresses performed using transfer functions characterizing steady-state voltage may lead to underestimation at intermediate frequencies. However, at resonant frequencies which are characterized by the largest voltage rise ratios the assessment of voltage at longitudinal insulation of windings using transfer functions is acceptable.

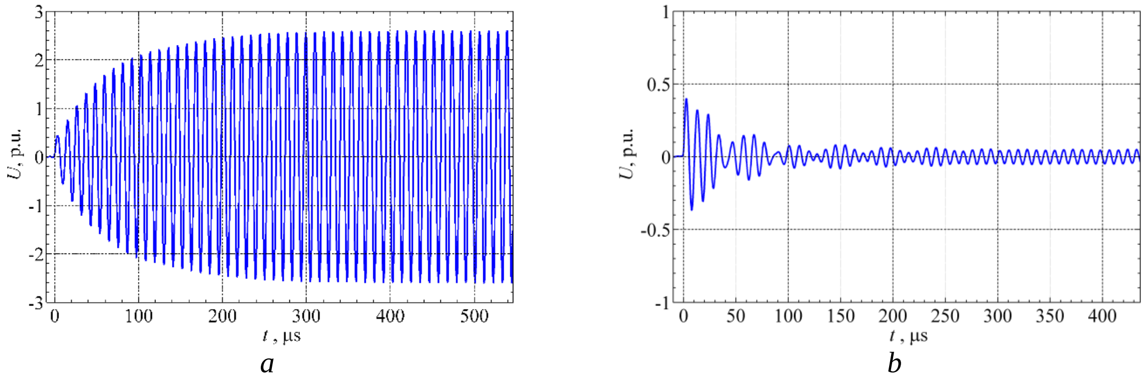


Figure 7 – Measured oscillograms of the voltage at the middle point of HV winding at the frequencies of 91 kHz (*a*) and 114 kHz (*b*)

Voltage oscillogram at the first natural frequency can be approximated as follows:

$$U(t) = u(0)\sin\omega_i t + A_1 K_i \sin\left(\omega_i t + \varphi_i\right)\cdot\left(1-\exp(-\gamma t)\right) \qquad (4)$$

Coefficients $u(0)$, A_1K_1, φ_1 and γ_1 can be expressed as follows:

$$\gamma = -\frac{\ln\left(1-\frac{U(nT)}{B_1}\right)}{nT};\; U_0 = B_2 - \frac{B_2 - U\left(T/4\right)}{e^{-\gamma T/4}};\; \varphi = \mathrm{arctg}\left(\frac{B_1}{B_2 - U_0}\right);\; A_1K_1 = \frac{B_1}{\sin\varphi},$$

where T is the period of supply voltage oscillation; n is an integer number; B_1 and B_2 are imaginary and real parts of steady-state voltage: $B_1 = \mathrm{Im}(U(t\to\infty))$; $B_2 = \mathrm{Re}(U(t\to\infty))$.

It should be noted that the equation (4) does not account for possible deviations of the frequency of the supply voltage from natural frequency as well as the harmonics oscillations which can lead to some deviations of measured curves from approximations at first periods. For improvement of the accuracy, one can choose the value of parameter n equal to 5 or greater.

In the considered case, calculated coefficients of approximations are: $u(0)$ = 0,37; A_1K_1 = 2,48; φ_1 = -75,4°; γ_1 = 0,0156. Obtained approximation represents measured oscillogram quite accurately (fig. 8).

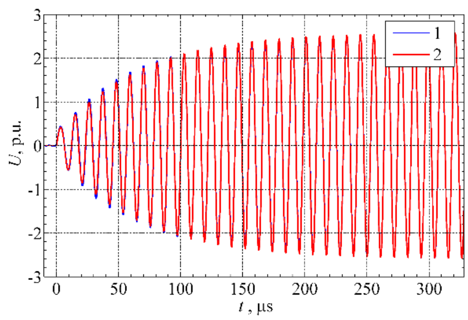


Figure 8 – Measured oscillogram (1) of the voltage at the middle point of HV winding at 91 kHz and its approximation (2)

Using approximation coefficients obtained using equation (4) one can find approximation of spatial voltage distribution (2) and voltage gradients at longitudinal insulation of a winding.

CONCLUSIONS

1. Estimation of voltages affecting internal insulation of transformer windings during resonant overvoltages can be performed using measurement and subsequent approximation of spatial voltage distribution in a winding at resonant frequencies. Such approximation can be performed with acceptable accuracy using equations obtained by theoretical solution of differential equations describing winding transients.

2. The most accurate approximation is obtained using theoretical solution for spatial voltage distribution comprising hyperbolic sine and cosine. At the same time, theoretical solution comprising only one sine is also acceptable for disc windings which feature relatively weak coupling between electrically distant turns.

3. Approximation coefficients for spatial voltage distribution at the first natural frequency can be obtained by oscillography of transient voltage at the middle point of a winding when supplied by undamped sinusoidal voltage source.

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