Investigation of Overvoltages in Distribution Transformers

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***Abstract*—Nowadays voltage transients in electrical power systems can take different shapes related to properties of distortion source and physical phenomenon appearing in systems. Usually overvoltages contain oscillation components of different frequencies, which are propagating along lines reaching transformer terminals. Overvoltages impact power transformer insulation systems in spite of used overvoltage protection. Analysis of overvoltages in winding insulation systems have strong importance in proper and reliable work of transformers. Due to complex configuration of transformer winding different overvoltages levels can occur inside winding than at winding terminals. This article presents investigation of internal overvoltages in distribution transformer windings. Analysis was based on measurements results of transient voltages and frequency characteristics. Investigation of resonance frequencies based on winding admittance measurements was made also.**

Keywords: distribution transformers, insulation systems, overvoltages

I. INTRODUCTION

Terminals of power transformers in electrical power systems, are exposed on transient voltages with various shapes and maximal values. Voltage wave penetrate transformer winding and can be transferred to other coupled windings on different voltage level. Nonlinear distributions of capacitances and inductances of turns in winding can influence on voltage transient distribution along coil causing amplification of wave, which can affect on insulation system life time. Distribution of voltage along winding is also related to shape of overvoltage wave at transformer terminals [1-6]. Transient voltages in electrical power systems occur during lightning strikes, switching operations and some failure states [7]. Shape of transient is related to wave propagation phenomena in particular network, nonlinear characteristics of surge arresters and network topology. While maximal values of overvoltages exceed protection level of surge arresters, resulting overvoltage has shape similar to rectangular wave otherwise transients pass overvoltage protection without changing its waveforms [7-9]. In last case surge arresters behaving like linear elements with high resistance. Overvoltages shapes in electrical networks consist of high frequency damped oscillation components imposed on slow slope carrier, or steep slope surges. Oscillation in overvoltage waveform propagating along power lines can match with resonant frequency of this system and will be magnified or will travel without damping. Steep slope surges consist of wideband spectrum which highest frequency (HF) limit is related to maximum steepness in wave, energy spectrum of this kind of wave decrease in frequency rise [9].

Analysis of overvoltages in power transformers are usually aimed at one voltage level of transformer terminals which is exposed to overvoltage. While transients voltages appearing at one side terminals of power transformer, overvoltages are transferred to windings on other voltage level due to electro-magnetic couplings between them. Detailed analysis of insulation systems of transformer due to exposure on transferred overvoltages form other windings should be also made [8-15].

Article presents investigation of internal windings overvoltages in distribution transformer. Analysis covered measurements of internal overvoltages and transferred overvoltages during acting of rectangular surge, measurement of frequency characteristics of internal overvoltages and transferred overvoltages. Rectangular surges imitates overvoltages resulting from overvoltage protection operation, frequency characteristics are showing predictive behavior of transformer on oscillation components of overvoltages.

II. CHARACTERISTIC OF TEST OBJECT AND SCOPE OF MEASUREMENTS

As a test object was 20 kVA distribution transformer with 15/0.4 kV ratio. Nominal electrical parameters are presented in Table I, and mechanical parameters of transformer windings are placed in Table II.

TABLE I. NOMINAL PARAMETERS OF TEST TRANSFORMER

Parameter					
S_n, kVA	U_n, kV	U_z, %	ΔP_{fe}, kW	ΔP_{Cu}, kW	I_0, %
20	15/0,4	4,2	0,114	0,525	2,8

Parameters and construction design of transformer winding are diverse, due to winding type, number of turns and geometrical dimensions (Table II). This properties determines different electrical and magnetical parameters of windings.

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TABLE II. MECHANICAL PARAMETERS OF TRANSFORMER WINDINGS

S_n, kW	20	
U_n, kV	15/0,4	
winding, -	high voltage (HV)	low Voltage (LV)
winding type,	coil	layer
number of coils/layers, -	8	2
inner diameter, mm	220	157
outer diameter, mm	270	205
number of turns, -	5840	180
coil height, mm	280	

Scope of measurements covered:

- measurements of internal overvoltages in power transformer winding and transferred overvoltages to low voltage (LV) and to high voltage (HV) side of transformer,
- frequency characteristics of internal overvoltages in winding and transferred overvoltages to coupled winding,

Measurements were done with arbitrary waveform generator, with maximum voltage up to 20 V. In measurements with rectangular surge time rise to maximum was set to t_r = 5 ns. Source voltage was connected to terminals of winding on one side of transformer. Measurements were taken at half of the same winding or at full and in the middle of coupled winding. For fast transients, high frequency oscillation and small signal influence of magnetic core of transformer can be neglected. Only capacitive coupling between windings and core should be considered [16].

III. ANALYSIS OF OVERVOLTAGES IN TRANSFORMERS

A. Transient Overvoltage Measurements

Measurement results of internal overvoltages inside 20 kVA transformer winding, while attacking with rectangular surge whole winding are presented in Fig. 1. Waveforms in the middle of HV winding have form of damped oscillations with resonant frequency equal to f_{rHV} = 14 kHz. Maximum voltage reach $u_{sHV0.5}$ = 0,79 p.u.. Therefore overvoltage factor, calculated with relation to nominal voltage [7] at specific point of winding at steady state, reach value up to 1.58. In LV winding oscillations and overvoltages are not observed for rectangular surges. Results presented in Fig. 1 are normalized to excitation voltage.

From analysis of overvoltages transferred through test transformer windings (Fig. 2), during acting of rectangular surge wave at coupled winding of the same phase, it can be seen that overvoltages in coupled windings have form of damped oscillations with low and high frequency components. Main resonant frequency of overvoltages transferred from LV to HV is equal to f_{tHV} = 10 kHz. Overvoltages in LV winding have resonant frequency f_{tLV} = 205 kHz. Results presented in Fig. 2 are normalized to excitation voltage and transformer ratio. Maximal value of overvoltage at full HV winding is u_{HV1} = 1.37. Overvoltage in the middle of winding is $u_{HV0.5}$ = 1.08. Corresponding overvoltages values in LV winding are, u_{LV1} = 2.03 and $u_{LV0.5}$ = 1,04 respectively. In the LV terminals HF distortions related to measurement system are observed. Analysis of maximal overvoltage shows that overvoltages in LV have higher maximal values related to nominal voltage than overvoltages in HV winding, overvoltages measured in half of winding have higher overvoltage factor than calculated for full winding.

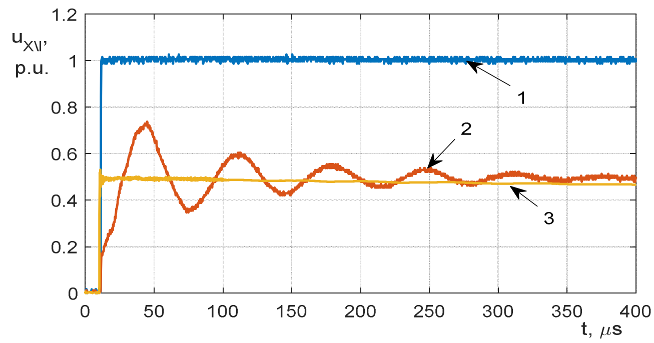

Fig. 1. Internal overvoltages of transformer windings measured in the middle of 20 kVA transformer winding (Table 1,2), during acting of rectangular surge at full winding: 1 – overvoltage at full winding, 2,3 – overvoltage in the middle of winding, 2 – HV winding, 3 – LV winding

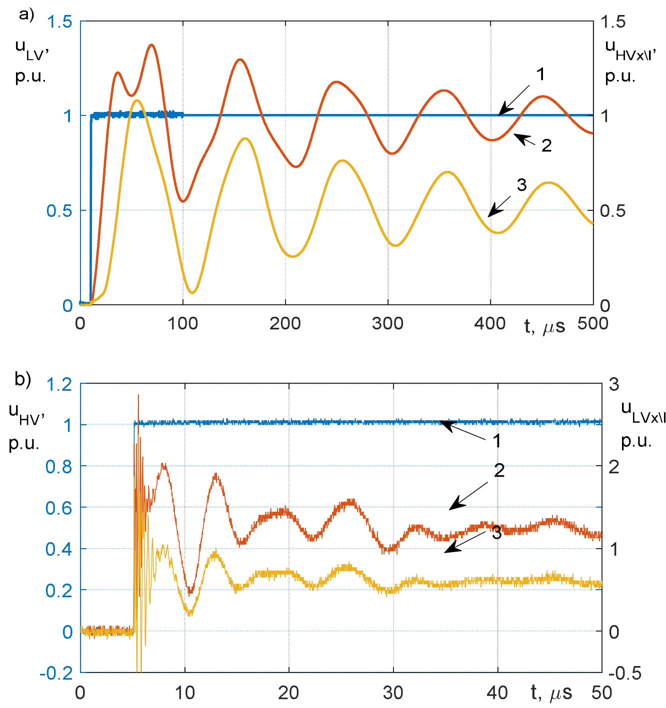

Fig. 2. Transferred overvoltages through transformer windings measured at full and in the middle of 20 kVA transformer winding, during acting of rectangular surge at full winding: 1 – source overvoltage at full winding, 2 – measured transferred overvoltage at full winding, 3 – measured transferred overvoltage in the middle of winding, a – overvoltages transferred from LV to HV, b – overvoltages transferred from HV to LV.

B. Overvoltage Frequency Characteristics Measurement

In order to analyze response of 20 kVA transformer windings to oscillation overvoltages, frequency characteristics were measured. Laboratory stand for measurement of frequency characteristics consisted of waveform generator and oscilloscope. Sweep Frequency Response (SFR) Method was used [8,9,15]. Measurements were performed in frequency range from 1kHz to 1 MHz. Measurements were normalized to source voltage.

Characteristics of internal overvoltages measured while feeding the same winding are presented in Fig. 3. Analysis of results show that oscillation components can produce high maximum value overvoltages in the middle of winding. For HV winding overvoltages can reach $u_{HV0.5}$ = 1.43 for resonant frequency f_{rHV} = 14.4 kHz. This overvoltage exceed almost 3 times nominal voltage level. For LV winding characteristic is flat in whole analyzed spectrum, one resonant frequency seen in characteristic is f_{rLV} = 26 kHz. Frequency characteristic results are comparable to measurement results from Fig. 1.

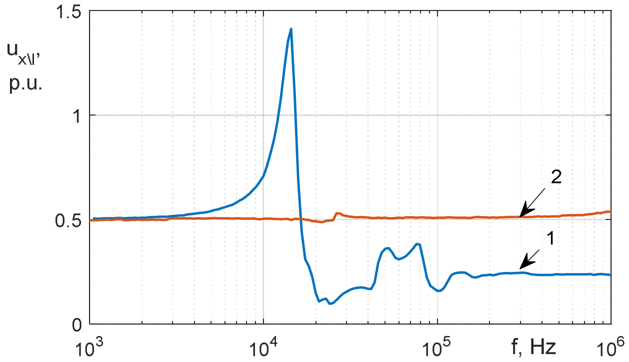

Fig. 3. Frequency characteristics of internal overvoltages measured in the middle of winding: 1 – HV winding, 2 – LV winding

Frequency characteristics of transferred overvoltages to coupled windings at full and in the middle of winding are presented in Fig. 4. Characteristics reveal resonance frequencies related to maximum overvoltages. This frequencies corresponds to frequencies analyzed in transient measurements section III.A. Additionally can be seen resonant frequency f_{tHV} = 26 kHz which is hidden in measured waveforms (Fig. 2A) and second resonant frequency in overvoltages transferred to LV windings f_{tLV} = 160 kHz, which is imposed in waveforms measurement on f_{tLV} = 205 kHz carrier. Maximal values of resonant frequencies overvoltages exceeds values from transient measurements because energy spectrum of rectangular source voltage in higher frequencies decrease and cannot stimulate resonant frequency with energy similar to sinusoidal wave like in frequency characteristics measurement.

Maximal values of transferred overvoltages in HV winding can exceed 4.5 times nominal voltage level and in the middle of HV winding at resonant frequency almost 11 times. At LV side overvoltages measured with resonance frequency reach 6 p.u. at full winding and are also 6 times higher in the middle than from voltage ratio.

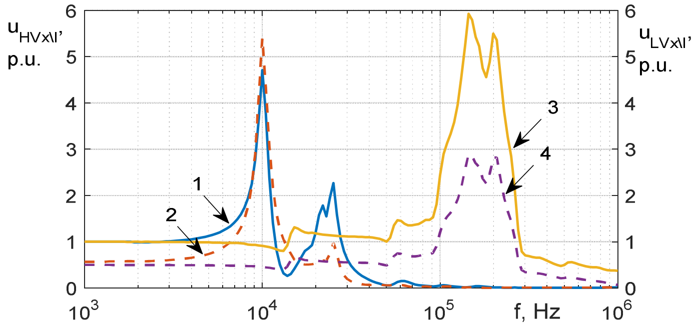

Fig. 4. Frequency characteristics of transferred overvoltages measured at the full and in the middle of winding: 1,3 – full winding, 2,4 – in the middle, 1,2 – overvoltages transferred from LV to HV, 3,4 – overvoltages transferred from HV to LV

Comparative analysis of transient overvoltages measurement excited with rectangular surge voltage with sweep frequency characteristic measurement shows similarities in obtained results. Frequency characteristics are comparable. Maximal values of overvoltage are different due to different stimulus properties. Transferred overvoltages at full winding exceed nominal voltage values, overvoltages in the middle of winding are higher than nominal voltages occurring in this point of winding.

IV. Identification of Overvoltages Resonant Frequencies

With the aim to identify potentially resonance frequencies at which internal overvoltages and overvoltages transferred to coupled windings reach maximal values, winding admittance frequency characteristics measurements were done. Measurements were performed in SFR laboratory stand [9,15] in frequency range 1 kHz to 1 MHz. Stand was equipped with current probe, PC computer analyzed measured signals-especially amplitude of primary harmonic and phase shift between source voltage and winding current. Admittance was measured as a ratio of current amplitude to voltage at measured object.

Measurements were performed on HV and LV winding separately in two cases:1 – with short-circuited coupled winding and 2 – with open windings. Short-circuit of coupled winding cause to omit magnetic coupling between windings and only properties of analyzed winding are affecting frequency characteristics shapes. Measurements of admittances of HV winding are presented in Fig. 5, and for LV winding in Fig. 6. Resonant frequencies and frequency characteristics of particular overvoltages were marked.

The analysis based on comparison of admittance measurements with overvoltage characteristics unravel correlation between resonant frequencies seen in voltage transients and frequency characteristics with resonances seen in admittance characteristics. Minimum of HV winding admittance is correlated with maximum internal overvoltages in the middle of winding (Fig. 1). For resonant frequency f_{rHV}, resonant frequencies in open LV winding configuration doesn't provide strong correlation. Most of common have resonance frequencies seen in admittance of LV side measured with open

HV winding (Fig. 6) local extremum occurring between 10 kHz and 26 kHz corresponds to both frequencies of transferred overvoltages to HV f_{tHV} (10 kHz and 16 kHz) (Fig. 4) and to internal resonance frequency of HV winding f_{rHV} = 14.4 kHz (Fig. 1). Resonance frequency at maximum of admittance is comparable to internal resonance frequency of LV winding f_{rLV} = 26 kHz (Fig. 1). Minimum of admittance occurs at 205 kHz which corresponds to maximum of transferred overvoltages to LV winding (f_{tLV} = 205 kHz) seen in voltage transient measurements.

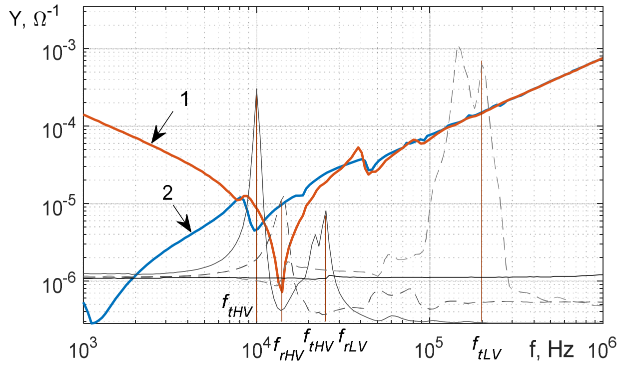

Fig. 5. Frequency characteristics of internal and transferred overvoltages and frequency characteristics of admitances for HV winding: 1 – LV winding short circuted, 2 – LV winding open, f_{tHV}, f_{tLV} – frequency characteristics of transferred overvoltages in to HV and LV winding, f_{rHV}, f_{rLV}, - resonant frequencies of internal overvoltages,

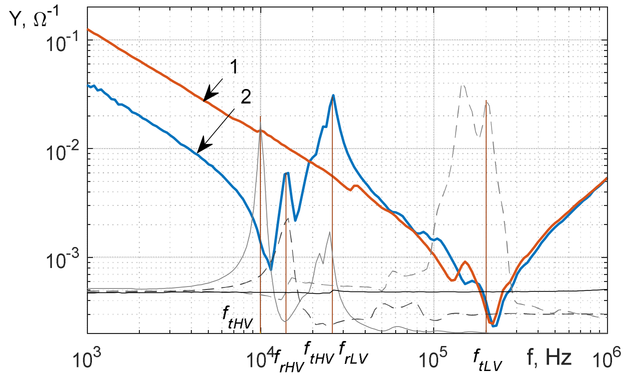

Fig. 6. Frequency characteristics of self and transferred overvoltages and frequency characteristics of admitances for LV winding: 1 – HV winding short circuted, 2 – HV winding open, f_{tHV}, f_{tLV} – frequency characteristics of transferred overvoltages in to HV and LV winding, f_{rHV}, f_{rLV}, - resonant frequencies of self overvoltages

V. Summary

Investigation of internal overvoltages and transferred overvoltages between windings in distribution transformer show that maximal values exceed nominal voltage values which should appear at this point of winding at steady state. Maximal value of overvoltage is related to resonance frequency oscillation carrier which is different due to analyzed winding and case. Measured transferred overvoltages in the middle of winding have few times higher overvoltage factor than at full winding. Measurement of frequency characteristics of overvoltages reveals resonant frequencies for which transient voltages are magnified and take maximum values, overvoltage with oscillation component equal to this resonant frequency can increase risk of winding insulation damage. Determination of this frequencies can be performed with overvoltages characteristics measurement or with winding admittance measurement in configuration with open and short-circuited coupled winding.

References

[1] Y. Shibuya, S. Fujita, T. Shimomura, "Effects of very fast transient overvoltages on transformer," IEEE Proc. Gener. Transf. Distr., Vol. 146, No. 4, July 1999, pp. 459 – 464.

[2] Y. Shibuya, S. Fujita, T., N. Hosokawa, "Analysis of very fast transient overvoltages in transformer winding," IEE Proc. Gener. Transf. Distr. Vol. 144, No. 5, Sept. 1997, pp. 461 – 468.

[3] H. Rodrigo, H. Q. S. Dang, "Behaviour of transformer windings under surge voltages," High Volt. Engin. Symp., 22 - 27 Aug. 1999, paper No. 1.287. P 6.

[4] S. Fujita, N. Hosokawa, Y. Shibuya, "Experimental investigations of high frequency oscillation in transformer windings," IEEE on Trans. Pow. Deliv., 13, 4, 1998, pp. 1201 – 1207.

[5] C. A. Banda, J. M. Van Coller, "Resonant overvoltages in wind turbine transformers," 2015 IEEE Eindhoven PowerTech, Eindhoven, 2015, pp. 1-6.

[6] M. Florkowski, J. Furgał, "High frequency methods for condition assessment of transformers and electrical machines," Pub. AGH, Kraków, ISBN 978–83–7464–614–7, 2013.

[7] IEC 60071-1:2006, Insulation co-ordination - Part 1: Definitions, principles and rules.

[8] M. Florkowski, J. Furgał and M. Kuniewski, "Propagation of overvoltages transferred through distribution transformers in electric networks," IET Gen. Trans. & Distr., vol. 10, no. 10, pp. 2531-2537, 2016.

[9] M. Florkowski, J. Furgał and M. Kuniewski, "Propagation of overvoltages in distribution transformers with silicon steel and amorphous cores," IET Gen. Trans. & Distr., vol. 9, no. 16, pp. 2736-2742, 2015.

[10] M. Popov, L. van der Sluis, R. P. P. Smeets, "Evaluation of surge-transferred overvoltages in distribution transformers," Elec. Pow. Syst. Res., Vol. 78, 3, March 2008, pp. 441 – 449.

[11] G. Zamanillo, J. Gomez, D. Tourn, E. Floren, "Experimental study of the transfer of overvoltage surges through distribution transformers," 18th Int. Conf. on Electr. Distrib., ICGRED 2005, Session no. 2, Turin, 6 - 9 June, 2005, pp. 1 – 6.

[12] P. F.Obase, F. Romero, J. M. Janiszewski, A. Piantini, A. S. Neto, T. O. Carvalho, A. Araújo Filho, "Lightning surges transferred to the secondary of distribution transformers due to direct strikes on mv lines, considering different LV line configurations," X Int. Symp. on Light. Protection, 9th - 13th Nov., 2009, Curitiba (Brazil), pp. 581 - 586

[13] J. R. Cogo, H. W. Dommel, "Voltage surges induced in transformer secondaries with loads characterized by sensitive electronic equipment," X Int. Symp. on Light. Protection, 9th-13th Nov., 2009, Curitiba (Brazil), pp. 1 - 6

[14] A. Borghetti, A. Morched, F. Napolitano, C. A. Nucci, M. Paolone, "Lightning-induced overvoltages transferred through distribution power transformers," IEEE Trans. on Pow. Deliv., Vol. 24, No. 1, Jan. 2009, pp. 360 - 372

[15] M. Florkowski, J. Furgał, "Detection of transformers winding deformation based on transfer function - measurement and simulations," Meas. Sci. and Tech., No. 14, 2003, pp. 1986 – 1992.

[16] D. J. Wilcox, W. G. Hurley, M. Conlon, "Calculation of self and mutual impedances between sections of transformer windings," IEE Proc. 136, 1989, pp. 308 – 314