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Influence of temperature on overvoltages in transformer windings

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Abstract

Transformers operating in power grids or industrial environment may be subjected to transients or stimulus with different wave fronts. In industrial networks distribution transformers are exposed to many switching operations which often generate overvoltages. Overvoltages usually have oscillatory components. These components can be sources of resonance inside overvoltages in transformers. If the spectrum of incoming surge voltage matches that of the winding, a corresponding winding resonance will be excited. Therefore external transients occurring in power systems can trigger internal overvoltages with large maximum values in the transformer windings. Analysis of the influence of oil temperature on frequency characteristics of the voltage in transformer windings is very important from a practical point of view. The impact of oil and temperature on the frequency characteristics of internal voltages are presented in this paper. Time domain step response signals of transient voltages in windings, generated for a given step voltage with a selected rise time, are also presented. The paper presents investigation results for disc and layer model transformer windings. The presented results might be used both in the design and optimization of transformers windings.

Keywords: transformar windings, overvoltages, influence of temperature.

Wpływ temperatury na przepięcia w uzwojeniach transformatorów

Streszczenie

Transformatory pracujące w sieciach elektrycznych lub w środowisku przemysłowym mogą być poddawane działaniu przepięć o zróżnicowanych przebiegach. W sieciach przemysłowych transformatory rozdzielcze są poddawane działaniu częstych przepięć łączeniowych. Przepięcia zawierają zwykle składowe oscylacyjne. Mogą być one źródłem zjawisk rezonansowych. Przepięcia generowane w sieciach elektrycznych mogą więc być źródłem przepięć o dużych wartościach maksymalnych wewnątrz uzwojeń transformatorów. Analiza wpływu temperatury na przepięcia w transformatorach ma duże znaczenie praktyczne. W artykule przedstawiono wpływ temperatury oleju na charakterystyki częstotliwościowe przepięć wewnętrznych w uzwojeniach. Zamieszczono także przebiegi napięć przejściowych generowanych wewnątrz uzwojeń podczas działania udarów napięciowych prostokątnych o różnych czasach narastania do wartości maksymalnej. Badania wykonano dla uzwojenia modelowego dyskowego i warstwowego. Przedstawione wyniki mogą znaleźć zastosowanie w projektowaniu i optymalizacji uzwojeń transformatorów.

Słowa kluczowe: uzwojenia transformatorów, przepięcia, wpływ temperatury.

1. Introduction

Power transformer insulation systems are subjected to many stresses during operation due to lightning and switching. The crest values of overvoltages appearing at the transformer terminals are limited by protective devices like surge arresters to a level determined by the insulation coordination. Those values are usually higher than the maximum nominal voltage levels. Transients having lower amplitude than the protection level of the surge arresters arrive at the transformer input practically without changes in either the amplitude or the waveform. Overvoltages usually contain oscillatory components which may cause resonance overvoltages in transformers. The overvoltages containing the oscillating components may be generated, for example, during the switching operations in SF_6 based gas insulated substations (GIS), during power making or breaking in lines supplying the transformers, or by ground faults. If the spectrum of the incoming surge voltage matches that of the winding, the corresponding resonance will be excited. Therefore, external transients occurring in power systems might trigger internal overvoltages with large maximum values in the transformer windings. Overvoltages having such a character have been the root cause of many power transformer failures [1-5].

Therefore, analyses of the influence of exploitation conditions of transformers, such as oil properties and temperature, on the frequency characteristics of internal overvoltages in transformer windings of different construction are very important.

In this paper there are presented measurements of the frequency response of the winding and the time domain responses of transient voltages in the windings, generated for step voltages with selected rise times. Since dielectric properties are also strongly temperature dependent, the influence of temperature on the frequency characteristics of overvoltages was analyzed.

2. Theory

A resonance requires two components, namely a passive structure of inductance and capacitance forming excitations. The first one is related to transformer windings and the latter one may be represented by various sources occurring in electric systems. The transformer windings can be represented as a complex network of resistive, inductive and capacitive elements being an equivalent of disks, layers, turns as well as inductive and capacitive couplings and frequency-dependent resistances, representing various sources of losses in the transformer. In such a structure there are many potential modes of local resonances. If the incoming transient on a line terminal has an oscillating component, the frequency of which matches the local resonance frequency of the winding, then an internal resonance oscillation will be triggered. The amplitude of the overvoltage depends on attenuation conditions and the duration of the oscillating components. The dielectric parameters of the insulation material have an impact on both propagation and distribution of the voltage along the winding and the resonance frequency. Frequency dependent dielectric properties of materials are described by the complex frequency-dependent permittivity ε^*:

$$\varepsilon^* = \varepsilon'(\omega) - \mathrm{j}\varepsilon''(\omega) = \varepsilon'(\omega)(1 - \mathrm{j}\,\mathrm{tg}\delta) \qquad (1)$$

where dissipation factor $\mathrm{tg}\delta$ is defined as a ratio between the real and imaginary part of the permittivity:

$$\mathrm{tg}\delta = \varepsilon''(\omega)/\varepsilon'(\omega) \qquad (2)$$

In addition, dielectric spectrum is highly temperature dependent, shifting the spectra toward higher frequencies, while increasing the temperature [e.g. 6-9]. These effects can be analyzed either in frequency or in time domain as a dielectric response, and have been carefully investigated over the years [e.g. 7-14].

3. Model windings

The experiments presented in this paper were carried out on two model layer windings, composed of a paper-oil insulation system. The cross sections of the windings are presented in Fig. 1.

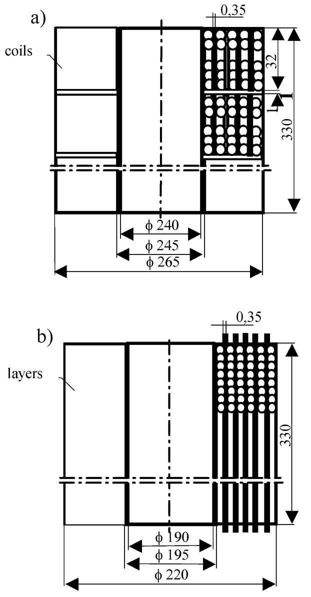

Fig. 1. Cross sections of the model windings: a - disk type model winding, b - layer type model winding

Rys. 1. Przekroje poprzeczne uzwojeń modelowych: a - uzwojenie typu dyskowego, b - uzwojenie typu warstwowego

The first winding is a disc type winding, whilst the second winding is of the layer type. The disc type winding consists of ten coils, 100 turns in each coil. The second winding is layer type. It consists of 6 layers, 200 turns in each layer. The diameter of the wire of both windings is ϕ 1,6 mm. The insulation paper was used for the inter layer and coil insulation. The oil moisture was at the level of 1 % at 25°C.

The frequency dependencies of the permittivity and the power dissipation coefficient of dry insulation paper at 25°C and oil immersed paper at 25°C, 50°C and 70°C are presented in Fig. 2. The measurements were made with a Solatron frequency impedance analyzer.

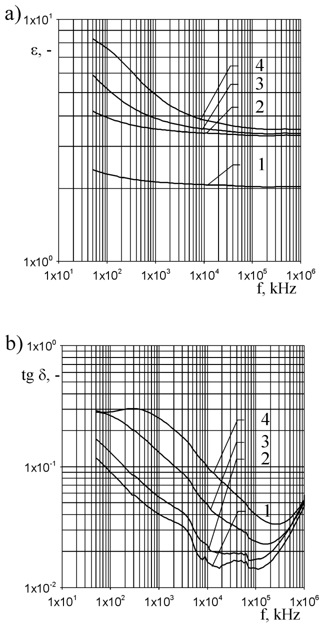

Fig. 2. Frequency dependencies of the permittivity magnitude and the power dissipation coefficient of dielectric materials in the experimental windings: a - $\varepsilon = g(f)$; b - $tg\ \delta = g(f)$, 1 - dry paper at 25°C, 2 - paper with oil at 25°C, 3 - paper with oil at 50°C, 4 - paper with oil at 70°C

Rys. 2. Zależności częstotliwościowe przenikalności elektrycznej i współczynnika strat dielektrycznych materiałów izolacyjnych w uzwojeniach eksperymentalnych: a - $\varepsilon = g(f)$; b - $tg\ \delta = g(f)$, 1 - papier suchy w temperaturze 25°C, 2 - papier nasycony olejem w temperaturze 25°C, 3 - papier nasycony olejem w temperaturze 50°C, 4 - papier nasycony olejem w temperaturze 70°C

4. Instrumentation

Investigations of the overvoltages at sinusoidal excitations with wide range of frequency were conducted with use of a digital oscilloscope 100 MHz, 1Gs/s connected to the host computer by GPIB-PCMCIA interface [15] and a software module consisting of a programmable function generator. The software module, processing and analysis were implemented in LabView™ from National Instruments.

The sinusoidal supply voltage with stepwise variable frequency was applied to the terminals of the transformer windings. The maximal values of to-ground at selected windings taps for selected frequencies were recorded. The investigation was carried out using a low voltage excitation, with an amplitude of 10 V, and tunable frequency in the range 20 Hz up to 200 kHz. The measurements of transient voltages inside the windings at different stimulus were made on the model windings using a programmable step function generator, with the variable rise time range 5-1000 ns, and output voltage 10 V. The waveforms were recorded at the winding tabs using a Tektronix TDS 3054. The test tank was equipped with a temperature regulator, which allowed the temperature in the tank to be stabilized during the experiment.

5. Results of investigations

Frequency response of the windings

The experiments were performed on both dry air and oil immersed windings. The windings were subjected to a sinusoidal voltage with frequency ranging from 20 Hz to 2 MHz. In the case of the oil immersed winding, the measurements of frequency characteristics were taken at a number of different temperatures. The oil temperature was controlled in the tank by a digitally controlled heater. After increasing the temperature and prior to performing any measurements, a period of stabilization was allowed, to ensure that the temperature of interest was consistent throughout the measurement period. The frequency dependencies of voltage at selected tabs were recorded. The measurement results for the disc are illustrated in Fig. 3 and for the layer winding in Fig. 4. Analysis of the frequency response was performed. The measurements were made on the dry windings at 25°C and on the oil immersed windings, at 25°C, 50°C and 70°C.

For the dry winding the main resonance frequency for the disc winding was 70 kHz and for the layer winding it was equal to 570 kHz. The relative resonance peak value for the disc winding appear in the case of the dry winding, and for the point $x/l = 0.8$ it was equal to 1.35. Immersing the windings in oil resulted in a shift of resonance frequencies to about 60 kHz.

The relative resonance peak magnitude for the oil disc winding in the point $x/l = 0.8$ was reduced from 1.25 at 25°C, through 1.23 at 50°C, to 1.21 at 70°C (Fig. 3, 5). The resonance peak value for the layer winding at point $x/l = 0.83$ was about 1.26. Immersing the windings in oil resulted in a shift of resonance frequencies to 500 kHz (Fig. 4, 6). The relative resonance peak magnitude for the oil layer winding in the point $x/l = 0.83$ was reduced from 1.25 at 25°C, through 1.21 at 50°C, to 1.19 at 70°C. The temperature rise from 25°C up to 70°C did not significantly influence the resonance frequency, however it did impact the relative magnitude, which was changed by 14 % within the temperature range. This effect can be explained by a change of the conductivity, as paper and oil conductivity have an exponential increase with temperature [8, 9].

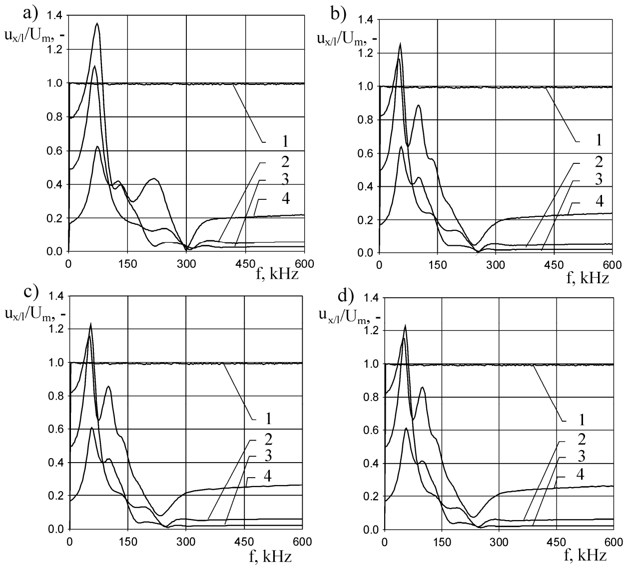

Fig. 3. Frequency characteristics of voltage distribution at selected taps x/l in dry (a) and oil model disc winding at temperatures rise: a - dry winding at 25°C, b - oil immersed winding 25°C, c - oil winding at 50°C, d - oil winding at 70°C: 1 - $x/l = 1.0$; 2 - $x/l = 0.8$; 3 - $x/l = 0.5$; 4 - $x/l = 0.2$

Rys. 3. Charakterystyki częstotliwościowe rozkładu napięcia doziemnego w wybranych punktach x/l w uzwojeniu cewkowym suchym i zanurzonym w oleju dla różnych temperaturach: a - uzwojenie suche w temperaturze 25°C, b - uzwojenie olejowe w temperaturze 25°C, c - uzwojenie olejowe w temperaturze 50°C, d - uzwojenie olejowe w temperaturze 70°C: 1 - $x/l = 1.0$; 2 - $x/l = 0.8$; 3 - $x/l = 0.5$; 4 - $x/l = 0.2$

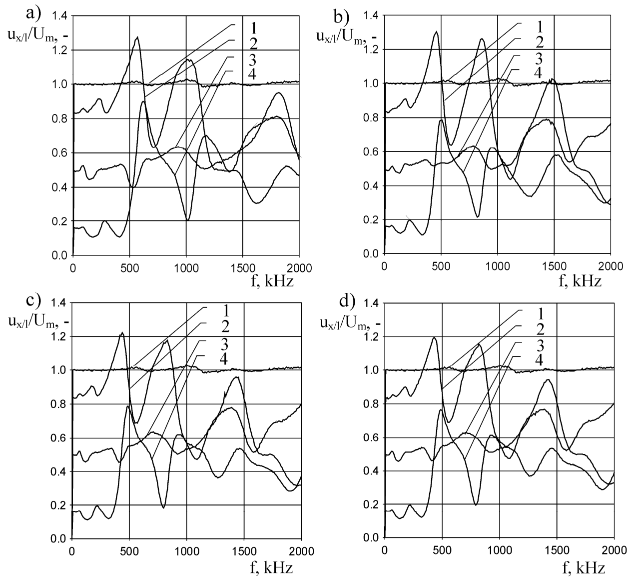

Fig. 4. Frequency characteristics of voltage distribution at selected taps x/l in dry and oil model layer winding at temperatures rise: a - dry winding at 25°C, b - oil immersed winding 25°C, c - oil winding at 50°C, d - oil winding at 70°C: 1 - $x/l = 1.0$; 2 - $x/l = 0.83$; 3 - $x/l = 0.5$; 4 - $x/l = 0.17$

Rys. 4. Charakterystyki częstotliwościowe rozkładu napięcia doziemnego w wybranych punktach x/l w uzwojeniu warstwowym suchym i zanurzonym w oleju dla różnych temperaturach: a - uzwojenie suche w temperaturze 25°C, b - uzwojenie olejowe w temperaturze 25°C, c - uzwojenie olejowe w temperaturze 50°C, d - uzwojenie olejowe w temperaturze 70°C: 1 - $x/l = 1.0$; 2 - $x/l = 0.8$; 3 - $x/l = 0.5$; 4 - $x/l = 0.17$

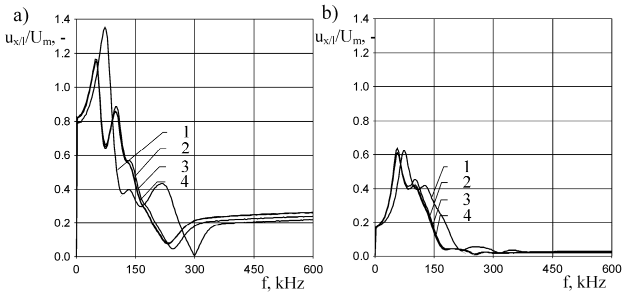

Fig. 5. Frequency characteristics of voltage distribution at selected taps x/l in dry and oil model disc winding at temperatures rise: a - $x/l = 0.8$; b - $x/l = 0.2$: 1 - dry winding at 25°C, 2 - oil immersed winding 25°C, 3 - oil winding at 50°C, 4 - oil winding at 70°C

Rys. 5. Charakterystyki częstotliwościowe rozkładu napięcia doziemnego w wybranych punktach x/l w uzwojeniu cewkowym: a - $x/l = 0.8$; b - $x/l = 0.2$: 1 - uzwojenie suche w temperaturze 25°C, 2 - uzwojenie olejowe w temperaturze 25°C, 3 - uzwojenie olejowe w temperaturze 50°C, 4 - uzwojenie olejowe w temperaturze 70°C

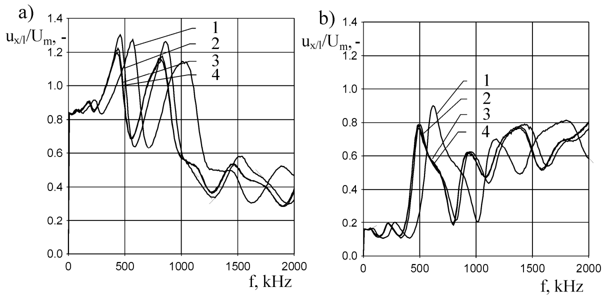

Fig. 6. Frequency characteristics of voltage distribution at selected taps x/l in dry and oil model layer winding at temperatures rise: a - $x/l = 0.83$; b - $x/l = 0.17$: 1 - dry winding at 25°C, 2 - oil immersed winding 25°C, 3 - oil winding at 50°C, 4 - oil winding at 70°C

Rys. 6. Charakterystyki częstotliwościowe rozkładu napięcia doziemnego w wybranych punktach x/l w uzwojeniu warstwowym: a - $x/l = 0.83$; b - $x/l = 0.17$: 1 - uzwojenie suche w temperaturze 25°C, 2 - uzwojenie olejowe w temperaturze 25°C, 3 - uzwojenie olejowe w temperaturze 50°C, 4 - uzwojenie olejowe w temperaturze 70°C

Controlled rise time step response

The modeled windings were also subjected to a rise time controlled step voltage. The investigations were conducted in order to analyze the influence of temperature and oil on the time domain responses of overvoltages inside the windings.

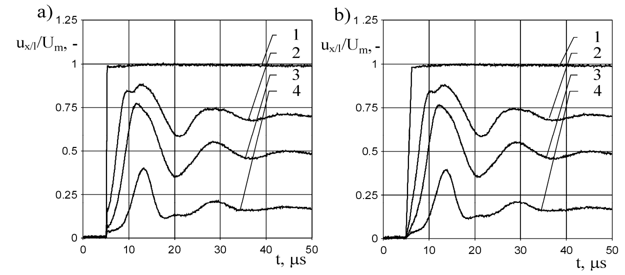

Fig. 7. The voltage distribution at selected taps x/l in dry disc winding subjected to step voltage with controlled rise time: a - 5 ns, b - 1000 ns; 1- x/l = 1.0; 2 - x/l = 0.8; 3 - x/l = 0.5; 4 - x/l = 0.2

Rys. 7. Rozkład napięcia doziemnego w wybranych punktach x/l uzwojenia dyskowego suchego poddanego działaniu udaru prostokątnego z kontrolowanym czasem narastania czoła: a - 5 ns, b - 1000 ns; 1- x/l = 1.0; 2 - x/l = 0.8; 3 - x/l = 0.5; 4 - x/l = 0.2

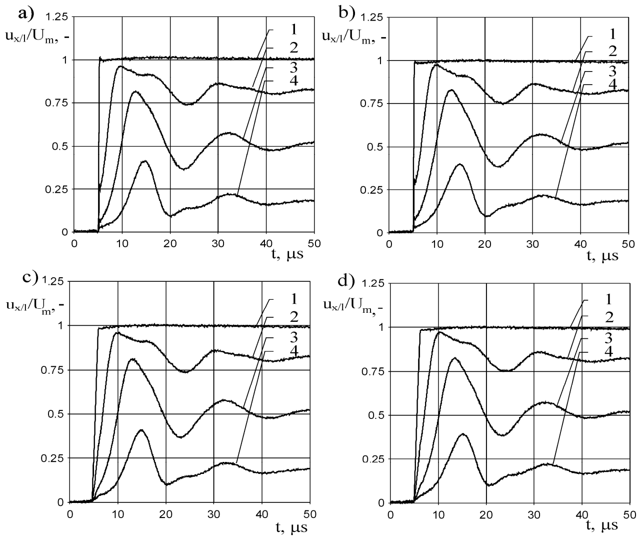

Fig. 8. The voltage distribution at selected taps x/l in oil disc winding at temperatures 25°C (left) and 70°C (right) subjected to step voltage with controlled rise time: a,b - 5 ns; c,d – 1000 ns: 1 - x/l = 1.0; 2 - x/l = 0.8; 3 - x/l = 0.5; 4 - x/l = 0.2

Rys. 8. Rozkład napięcia doziemnego w wybranych punktach x/l uzwojenia dyskowego olejowego w temperaturze 25°C (strona lewa) i 70°C (strona prawa) poddanego działaniu udaru prostokątnego z kontrolowanym czasem narastania czoła: a,b - 5 ns, c,d - 1000 ns; 1- x/l = 1.0; 2 - x/l = 0.8; 3 - x/l = 0.5; 4 - x/l = 0.2

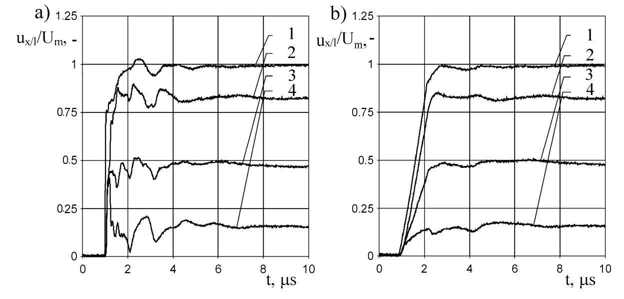

Fig. 9. The voltage distribution at selected taps x/l in dry layer winding subjected to step voltage with controlled rise time: a - 5 ns, b – 1000 ns; 1 - x/l = 1.0; 2 - x/l = 0.83; 3 - x/l = 0.5; 4 - x/l = 0.17

Rys. 9. Rozkład napięcia doziemnego w wybranych punktach x/l uzwojenia warstwowego suchego poddanego działaniu udaru prostokątnego z kontrolowanym czasem narastania czoła: a - 5 ns, b - 1000 ns; 1- x/l = 1.0; 2 - x/l = 0.83; 3 - x/l = 0.5; 4 - x/l = 0.17

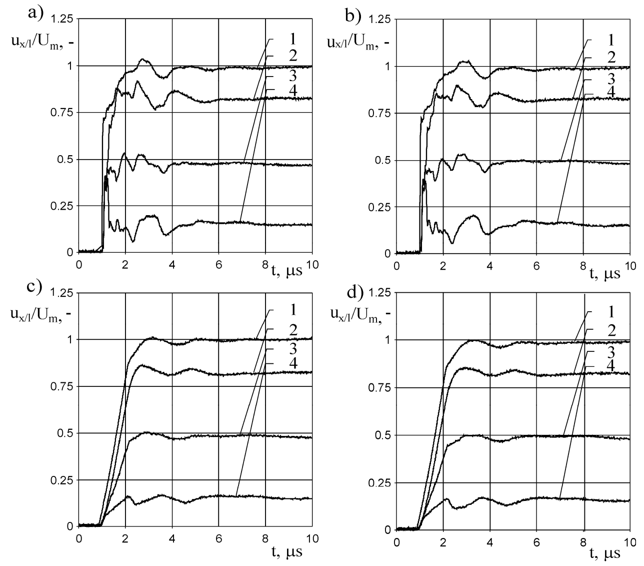

Fig. 10. The voltage distribution at selected taps x/l in oil layer winding at three temperatures 25°C (left) and 70°C (right) subjected to step voltage with controlled rise time: a,b - 5 ns, c,d - 1000 ns; 1 - x/l = 1.0; 2 - x/l = 0.83; 3 - x/l = 0.5; 4 - x/l = 0.17

Rys. 10. Rozkład napięcia doziemnego w wybranych punktach x/l uzwojenia warstwowego olejowego w temperaturze 25°C (strona lewa) i 70°C (strona prawa) poddanego działaniu udaru prostokątnego z kontrolowanym czasem narastania czoła: a,b - 5 ns, c,d - 1000 ns; 1- x/l = 1.0; 2 - x/l = 0.83; 3 - x/l = 0.5; 4 - x/l = 0.17

The voltage distributions at selected tabs of the dry disc model winding recorded for the rise time 5 ns and 1000 ns is shown in Fig. 7. In the case of the oil immersed winding, the measurements of the step response were taken at various temperatures. After increasing the temperature, prior to making measurements, the stabilization period was in place. The voltage distributions at selected tabs were recorded. The measurement results for temperature 25°C and 70°C are illustrated in Fig. 8. For slopes with a fast rise time (5 ns) the temperature was observed to have little impact on the voltage distribution. However, for a longer rise time (1000 ns), the increased temperature led to slight attenuation of du/dt.

Whilst performing measurements on the model layer winding with rise time controlled stimulus, the act of immersing the winding in the oil and increasing the temperature was observed to produce several other effects. The dielectric properties of the insulation system influence the propagation properties. Putting a dry winding into oil results in the prolonged propagation of the pulse front. Additionally, this effect can be observed, while increasing the oil temperature, especially for a longer rise time (1000 ns) (Fig. 9, 10). From the time courses of overvoltages in the transformer it can be seen that the resonance frequency of the windings is equal to the frequency of the transient components of internal overvoltages. The character of changes of these frequencies under different working conditions of the windings is the same as it can be observed in the frequency dependencies of overvoltages.

6. Conclusions

This paper presents the frequency response of dry and oil immersed disc and layer model windings subjected to sinusoidal voltage excitation with frequency from 20 Hz to 2 MHz and a pulse voltage with different rise time. The frequency domain voltage distributions at various temperatures were obtained at selected winding tabs. The resonance frequency of the winding was shifted after immersing both model windings in oil. The temperature rise resulted in reduction of the resonance peak magnitude in the windings of different construction.

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