Transients in Transformer Windings

T. Hasman
High Voltage Laboratory
Czech Technical University in Prague
166 27 Prague, Technicka 2, Czech Republic
hasman@feld.cvut.cz

Abstract – The paper deals with electromagnetic transients in power transformers. It describes measurement on the transformer winding and relates parameters detected on transformer terminals with voltage distribution along transformer windings.

I. INTRODUCTION

Power transformers are the key components of power systems not only from the viewpoint of electrical power transmission, but also from the viewpoint of electromagnetic transients caused by lightning or switching operations in power systems. Although in principal simple, power transformers are quite complicated equipment with properties depending on their loading (transformers are non-linear elements) and on voltage frequency (properties of transformers are frequency dependant). Non-linearity of transformers behaviour has its origin mainly in properties of magnetic core. As the penetration of magnetic flux into the magnetic core decreases with increasing frequency, the non-linearity of power transformers behaviour can be regarded as negligible for frequencies higher than about several kilohertz. The influence of frequency on transformer properties is caused by electromagnetic coupling between windings and grounded parts of transformers, between primary and secondary windings and between particular winding turns. This dependence on frequency is the cause of quite complicated responses of transformers to electromagnetic transients.

There are two reasons for study of transformers behaviour during electromagnetic transients. The first one results from the necessity to anticipate electrical stresses on the main and inter-turn insulation of transformers windings. The second reason is set up by the need to represent transformers in transients analyses of circuits with transformers. Transient studies of transformers usually deal either with transients in transformer windings (internal modelling of transformers), or with influence of transformers on transients in electrical circuits (terminal modelling of transformers). The aim of this paper is to show connection between "internal" and "terminal" behaviour of transformer during electromagnetic transients. The paper is based on measurement on a two-winding transformer.

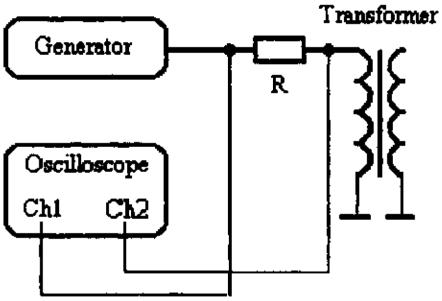


Fig. 1. Circuit layout for measurement of input impedance of transformer

II. DESCRIBTION OF TRANSFORMER

The transformer used for measurement is two-winding transformer with the magnetic core and uniform primary and secondary windings. The number of turns of both primary and secondary windings is the same (1700 turns) and there are taps on every tenth of windings length for measurement of the voltage distribution along the windings. The ends of the windings are grounded.

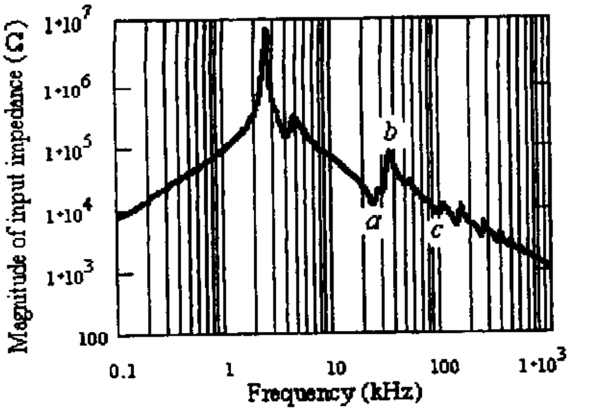
III. MEASUREMENT OF TERMINAL PROPERTIES

Behaviour of a no-loaded transformer is fully described by its input impedance Z_{in}, which is defined by the following expression (V_1 is the primary voltage, I_1 and I_2 are primary and secondary currents):

$$Z_{in} = \frac{V_1}{I_1} \, |I_2 = 0$$

The frequency dependence of the magnitude and the phase of input impedance of the transformer model was measured according to circuit layout in Fig. 1, results of the measurement for frequencies from 100 Hz to 1 MHz are plotted in Fig. 2. For frequencies up to 2.5 kHz the magnitude of the input impedance increases and the phase corresponds to inductive character of the impedance. For higher frequencies the impedance magnitude decreases except of several short frequency intervals. From the frequency 2.5 kHz the impedance has a capacity character. There are some changes of the phase for frequencies which enclose intervals of increasing impedance magnitude.

Some points of the dependence in Fig. 2 are marked by letters. The reason will be explain later.



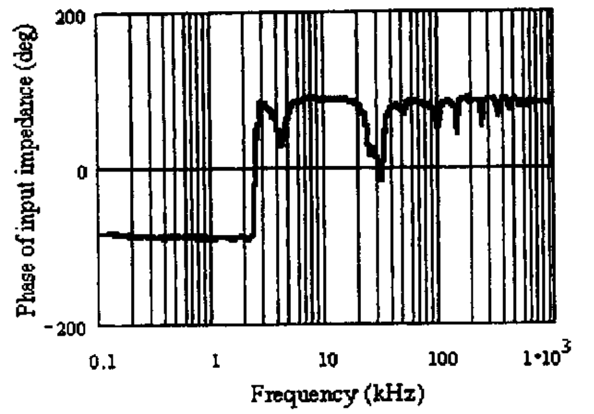


Fig. 2. Magnitude and phase of input impedance

IV. INTERNAL MEASUREMENT ON WINDINGS

The aim of this measurement was to find connection between changes of the frequency dependence of the input impedance and the voltage distribution along windings. The voltage distribution of both primary and secondary

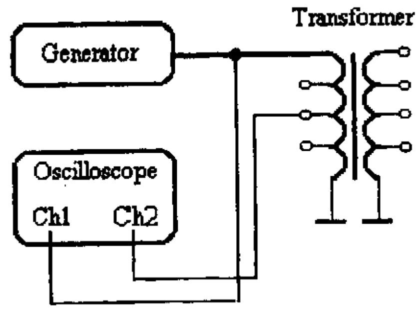


Fig. 3. Circuit layout for measurement of voltage distribution along winding

windings was measured in both frequency and time domain according to circuit layout in Fig. 3. The magnitude and the phase of voltages along windings were measured in frequency domain, responses to the rectangular voltage impulse were measured in time domain. Results of the measurement on the primary winding are plotted in Fig. 4 and 5.

It can be seen in Fig. 4 that the voltage in the primary winding is quite uniformly distributed for frequencies up to about 10 kHz, for higher frequencies there are big peaks and deep valleys in the voltage distribution. The frequency of the first peak of voltage distribution is 23 kHz. The same frequency is related to the point *a* of the frequency dependence of the input impedance in Fig. 2. Similarly, the point *b* in Fig. 2 is related to the highest peak in the voltage distribution of the secondary winding (31 kHz), at the frequency of the point *c* (87 kHz) there is another peak in the voltage distribution of the secondary winding. The voltage distributions related to points *a*, *b* and *c* are plotted in Fig. 6. The curves in this figure evoke distributions of standing waves, but phases of the voltages on particular taps are not the same. The frequency 23 kHz is the

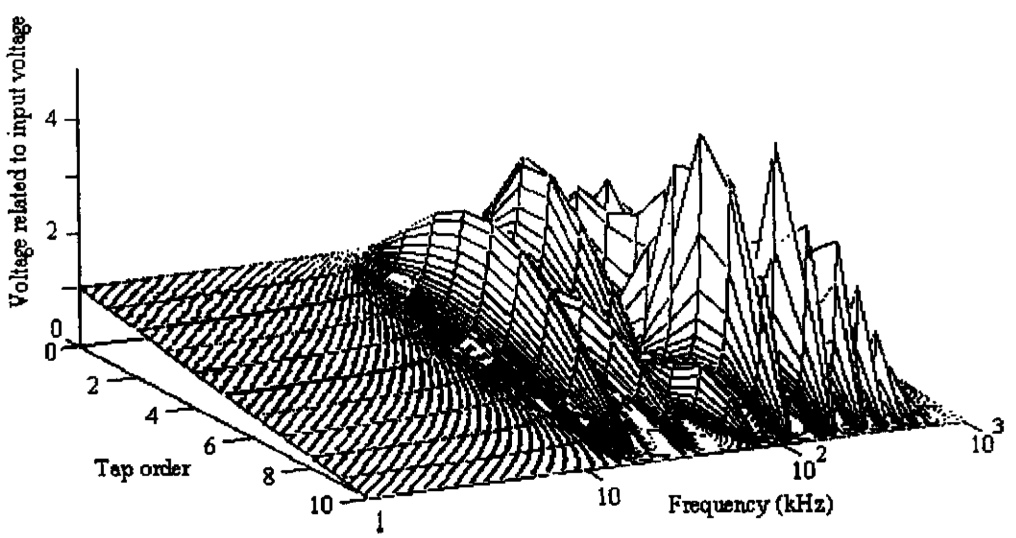


Fig. 4. Distribution of voltages measured on taps of the primary winding in frequency domain

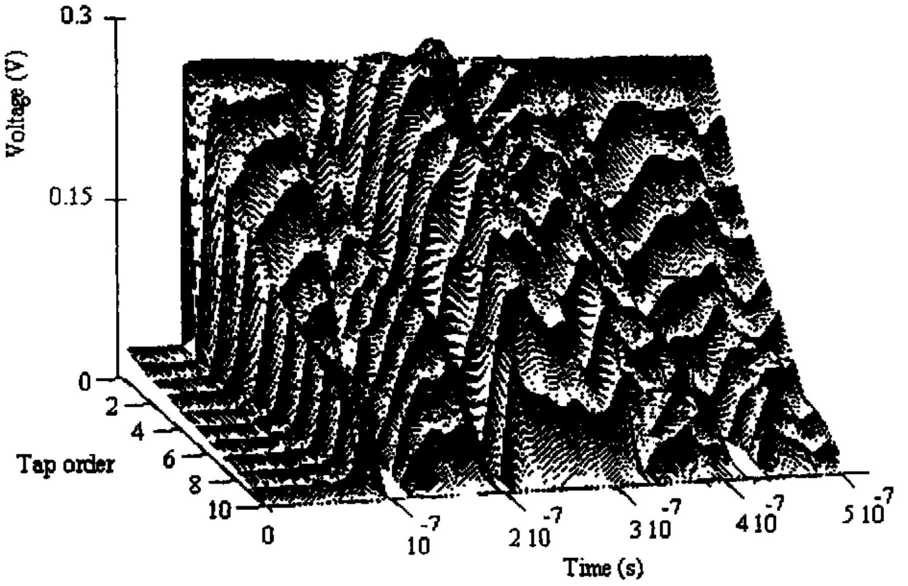


Fig. 5. Distribution of voltages measured on taps of primary winding in time domain

frequency of the natural oscillation of the primary winding, similarly frequencies 31 and 87 kHz are frequencies of natural oscillations of the secondary winding.

The relation between results of measurement in frequency and time domain is evident from Fig. 7. The voltage responses to two types of rectangular impulses were measured in the middle (the 5th tap) of the primary winding. The rectangular impulses differ in their width. The impulse in Fig. 7a) takes 0.1 ms, the impulse in Fig. 7b) takes 0.025 ms. The main frequency of the oscillations of both responses is the same as the natural frequency of the winding.

The response in Fig. 7a) reaches higher magnitude than the response to the shorter impulse, although the

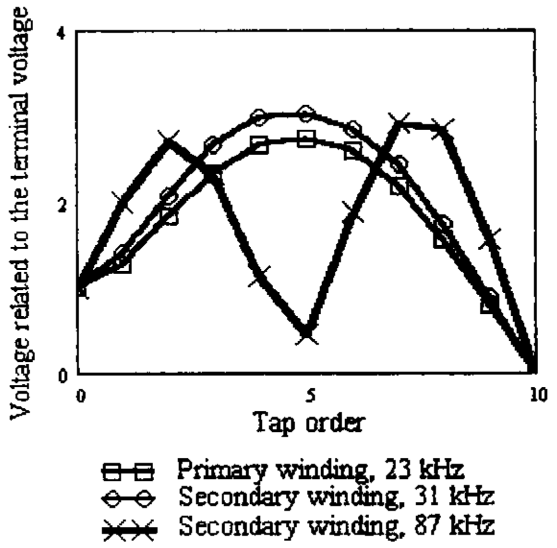


Fig. 6. Voltage distribution along windings for frequencies 23 kHz, 31 kHz and 87 kHz

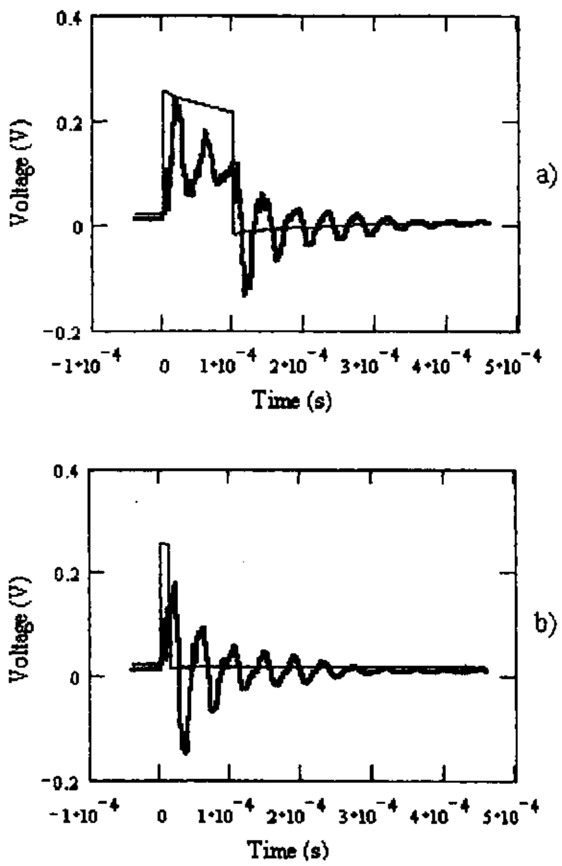


Fig. 7. Voltage responses in the middle of the primary winding to two different rectangular impulses.

magnitude of both impulses is the same. This difference is caused by the different relation between the first harmonic frequencies of the impulses and the natural frequency of the winding. The first harmonic frequency of the first impulse is lower than 23 kHz (the natural frequency of the primary winding), in the case of the second impulse the first harmonic is higher than this frequency.

The distribution of voltages along the primary and secondary winding measured in time domain is plotted in Fig. 8. The steepest voltage distribution occurs near the input terminal of the primary winding in the time of impulse arrival, the highest voltage was measured on the terminal of the secondary winding.

V. CONCLUSIONS

The paper describes measurement on the two-winding transformer. The frequency dependence of the input impedance was measured as well as the voltage distribution in the primary and secondary transformer windings.

The results of measurement can be summarise as follows:

1) The voltage distribution in both primary and secondary windings is uniform for frequencies rather lower than the first natural frequency of a winding (in the case of the measured transformer the lowest natural frequency was 23 kHz). Therefore the highest peak of the input impedance magnitude at frequency 2.5 kHz (Fig. 2) is not caused by oscillations in windings.
2) The changes of the course of the input impedance frequency dependence (Fig. 2) at frequencies equal to or higher than the first natural frequency of a winding are connected with special cases of voltage distribution not only in primary, but also in secondary winding (Fig. 6).
3) The magnitude of the voltage response of windings to a voltage impulse depends on the relation between the first harmonic frequency of the impulse and a natural frequency of the winding. If the first harmonic is lower than the natural frequency, the magnitude of the voltage response is higher and vice versa (Fig. 7).
4) The voltage distribution after impact of a voltage impulse is steeper in the primary winding than in the secondary winding, but magnitudes of the voltage can be higher in the secondary winding (Fig. 8).

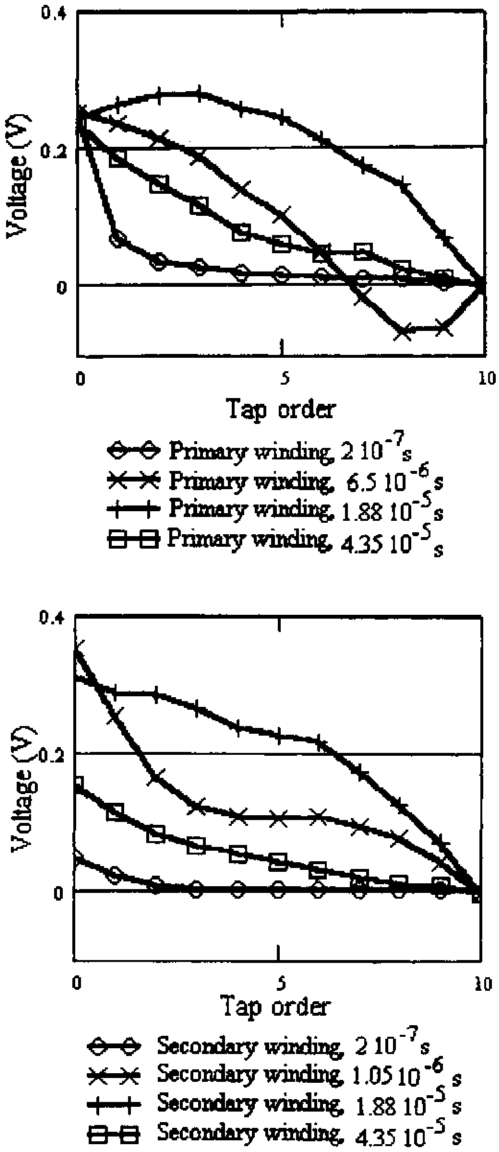


Fig. 8. Voltage distribution in the primary and secondary winding in time domain

VI. REFERENCES

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