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Evaluation of surge-transferred overvoltages in distribution transformers

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Abstract

The paper presents an analysis of very fast-transient overvoltages that occur because of the capacitive surge transfer from the high-voltage (HV) transformer winding to the low-voltage (LV) transformer winding.

The study is done on a 6.6 kV single-phase test transformer. By applying a pulse with a short rise time at the HV terminal, the voltage at the LV side is measured and calculated. The voltage distribution along the LV winding is calculated by applying the transmission line theory, so that the foils of the LV winding are represented as transmission lines. For the studied transformer with a nominal transformer ratio of 95.6, a maximum voltage ratio of 3.3 was measured during the rate of rise of the applied impulse. The present paper also shows that in some specific cases, the mutual inductance between the primary and the secondary side can be ignored during determination of the transients along the secondary winding. The computation and measurement of the voltage at the LV side is validated by making use of the vector fitting method.
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1. Introduction

Nowadays there are reports of transformer and motor failures during switching with vacuum circuit breakers (VCB) or gas insulating switchgears (GIS). There have been a number of studies done to determine the origin of the failure and in the recent years such progress has been made by studying the propagation of surges inside transformer and motor windings.

There are various reasons for the insulation failure. The insulation can suffer because of the high amplitude of the voltage, the high rate of rise or both. Very often the utilities ask not only to provide a proper protection but also to find the reason for the occurrence of these failures. For example in Ref. [1], it was reported that the amplitude of the inter-turn voltage can reach 0.25 times the applied sinusoidal voltage at resonance frequency.

It is known that during switching off and switching on highly inductive loads, because of the ability of the VCB to clear high-frequency currents, multiple reignitions can take place. Multiple reignitions contain oscillations with a broad frequency range. When they enter the transformer, a resonance might occur when the frequency of the oscillation matches one of the resonance frequencies of the transformer.

In Ref. [2], a transformer failure was reported during energizing a high power transformer. The reason was an external resonance between the feeder cable and the transformer that resulted in very high overvoltages on the LV transformer side.

So far there was significant research done on the investigation of transients in transformers [3–8]. In Refs. [3,4], the lumped parameter analysis was used for transformer modelling, and [5,6] deal with the modelling of transformer based on the well-known Rabins method. It was also shown that transformer can be modelled by considering the windings or group of windings as transmission lines [7,8]. Furthermore, Wilcox et al. [9] proposed a model that can be generally applied for multi-phase multi-winding transformers. Recent research performed by Gustavsen [10,11] resulted in a transformer model based on the measured admittance matrix of the transformer. In this way, a general representation of the transformer in a wide frequency range can be done. This is called vector fitting and it can be used to validate the measured results with full success.

Lightning surge studies are based on the observation of the surge transfer from the HV to the LV transformer side. For exam-

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ple, surge-transferred overvoltages in single-phase installations caused by lightning were investigated by Dugan and Smith [12]. In Ref. [13], it was shown that sometimes, simple models that can be implemented into EMTP can be used to simulate the surge-transferred overvoltages more accurately.

The present paper describes a fundamental study of surge-transferred overvoltages in a distribution transformer. For this purpose a single-phase transformer under no-load with a transformer ratio 6600/69 (V/V) is used [14].

According to the IEC standard 60076-3, transferred overvoltages have capacitive and inductive character [15]. The capacitive transfer depends on the surge capacitance. The steeper the slope of the applied surge, the higher the effect of the surge capacitance. The inductive transfer of the surge voltage depends on the flow of surge current in the HV winding, and it is less sensitive on the rate of rise of the applied voltage. However in Refs. [16,17], it is shown that depending on the transformer ratio, the inductive-transferred voltages are not much smaller than the capacitive-transferred voltages.

In the present case, the applied pulse at the HV side is with a 50 ns rise time and an amplitude of 50 V. The recorded current in the HV terminal is with an amplitude of 0.25 A, and it is damped in less than 1 μs after applying the pulse. A preliminary EMTP study on the same transformer has shown that when ignoring the surge capacitance, the voltage in the LV winding follows the transformer ratio and it is approximately 100 times lower than the applied voltage.

However, the recorded voltage at the LV terminal is much higher than that determined by the transformer transfer ratio. Therefore, in this work, the full analysis is performed. The primary and the secondary transformer side are modelled by transmission lines. For the particular transformer, it is shown that the inductive-transferred voltages are not high and can be neglected. The voltages along the LV winding are calculated by representing the turns as short transmission lines [14]. The computations and measurements are verified by applying the vector fitting method [10,11].

2. Transformer model based on transmission line analysis

For determination of the voltage along the winding, the transmission line modelling (TLM) has been applied. According to this theory, transformer turns or a group of turns can be represented by transmission lines. If N is the number of lines, and $\underline{Z}$ and $\underline{Y}$ are the impedance and the admittance matrix of the lines, respectively, the relation between voltages and currents in the lines is expressed through N voltage and N current equations:

$$\frac{d^2\underline{V}}{dx^2} = -\underline{Z}\underline{Y}\underline{V}, \qquad \frac{d^2\underline{I}}{dx^2} = -\underline{Y}\underline{Z}\underline{I} \tag{1}$$

Applying the modal theory [18], the relation between the currents and the voltages can be represented by Eq. (2):

$$\begin{bmatrix} \underline{I}_S \\ \underline{I}_R \end{bmatrix} = \begin{bmatrix} A & -B \\ -B & A \end{bmatrix} \begin{bmatrix} \underline{V}_S \\ \underline{V}_R \end{bmatrix} \tag{2}$$

where

$$A = \underline{Y}\underline{S}\underline{\gamma}^{-1}\coth(\underline{\gamma}l)\underline{S}^{-1}, \qquad B = \underline{Y}\underline{S}\underline{\gamma}^{-1}\operatorname{cosech}(\underline{\gamma}l)\underline{S}^{-1} \tag{3}$$

where $\underline{I}_S$, $\underline{I}_R$ are current vectors at the sending and the receiving end of the line, $\underline{V}_S$, $\underline{V}_R$ the voltage vectors at the sending and the receiving end of the line, $\underline{S}$ the matrix of eigenvectors of the matrix $\underline{Z}\underline{Y}$, $\underline{\gamma}^2$ the eigenvalues of the matrix $\underline{Z}\underline{Y}$ and l is the length of the line.

All parameters in (3) except l are frequency-dependent. In this way, the general telegraphers' equations, which are differential time-dependent equations, can be solved as ordinary frequency-dependent equations. The representation of the TLM for transformer modelling is represented in Fig. 1.

Applying the equality between the voltage and the current at the receiving end of a specific line, and the voltage and the current at the sending end of the next line the following matrix equation can be derived:

$$\begin{bmatrix} \underline{I}_{S1} \\ \mathbf{0} \end{bmatrix} = [\mathbf{F}] \begin{bmatrix} \underline{\mathbf{V}}_{Si} \\ \underline{V}_{Rn} \end{bmatrix}, \quad i = 1, 2, \ldots, n \tag{4}$$

where n is the total number of lines. In the present case $n = N_1 + N_2$. Since, the transformer winding is grounded, $\underline{V}_{Rn} = 0$. To eliminate the divergence, the computations are done with a small impedance $Z = 10^{-9}\ \Omega$ connected to the ground. Eliminating the current $\underline{I}_{S1}$, the voltages in all lines can be calculated by

$$[\underline{\mathbf{V}}_{Si}] = [\,\mathbf{H}_{i-1} \quad \mathbf{H}_{\chi}\,] \begin{bmatrix} \underline{V}_{S1} \\ \mathbf{0} \end{bmatrix} \tag{5}$$

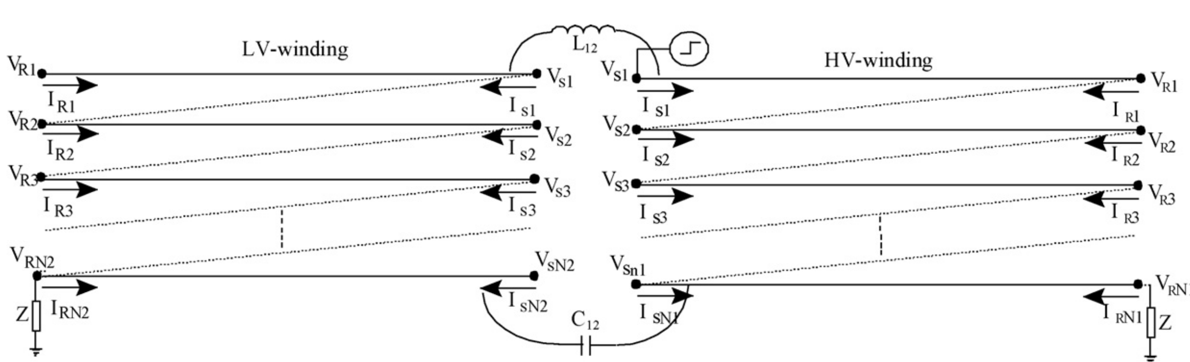

Fig. 1. Representing the transformer by transmission lines.

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