Overvoltage Propagation from Transmission Line into Transformer Winding

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Abstract. *The paper deals with very fast transient phenomena in a system consisting of two parts: a cable line and a transformer winding. In this case an adequate model should be considered as a circuit with distributed parameters. Its description is given by a system of partial differential equations of hyperbolic type. Our approach is based on a numerical solution in the time domain and the method FDTD has been used. It allows obtaining results in a form of time-space voltage and current wave distribution along the cable line and the transformer winding. This distribution is depending on many factors some of them were studied in this paper.*

Keywords

Overvoltage on transmission line, transients in transformer winding.

1. Introduction

It is a common practice to connect a transformer in a substation to the incoming line through a cable. A surge overvoltage wave induced by switching-on and switching-off processes travels not only along the cable but it propagates into the transformer winding. These processes can cause transformer failures and can be very dangerous for its isolation system. Moreover, the shape of the travelling wave is strongly depending on parameters of both parts. Due to different surge impedances of both, the cable and the transformer winding, reflections appear at the transformer winding input. Because of these reflections the voltage or current peak value can reach higher values than it was considered in the design of the isolation and protection systems. The other factors which have a similar impact on the surge wave shape are the manner of transformer winding output and the cable length.

Many authors have been interested in the analysis of very fast transients in a transformer winding and they used various methods. Some of them utilized a simulation in EMTP or ATP software [1], [2]. Other authors used transmission line model solved in the frequency domain [3], [4]. In [5] the numerical analysis based on FDTD method in the time domain was presented. Very important role in transients analysis play the parameters of winding, those problems were discussed in [4], [6], [7]. Simulation of various switching conditions has shown that severe internal overvoltage can arise between adjacent coils of the high voltage windings, while the terminal voltage of the transformer remains below the guaranteed basic insulation level [7]. In such cases surge arrester cannot provide a sufficient protection since high frequency oscillations may cause partial winding resonance. All authors of these papers analysed only transients in a transformer winding.

According to practical experiences the distribution of voltage and current wave in a transformer winding depends not only on transformer parameters but also on the shape of a travelling surge wave which is propagating from the transmission line connected to the transformer. In this case is also necessary to study an influence of line parameters. For such a complex analysis it is important to consider the whole system consisting of a transmission line (cable-line) and a transformer winding.

In this paper an algorithm for a complex analysis is presented. Our approach published in [8] is based on modelling of the system consisting of a transmission line and a transformer winding as a circuit with distributed parameters. A general basic line element has been introduced it allows to formulate one common mathematical model for both parts. The obtained equations can be very simply modified for the line and the transformer winding. This approach allows a formulation of a common algorithm for numerical computation.

1.1. Mathematical Model

A general basic element respecting a transmission line element and a transformer winding element is depicted in the Fig. 1, all parameters are per unit length.

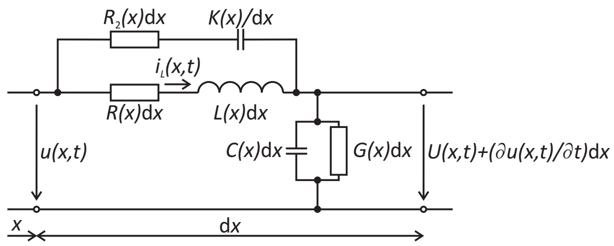

Fig. 1: Basic element at distance x from the line beginning.

In the proposal circuit element inductance $L(x)$ involves self-inductance and in the case of a transformer winding also mutual inductances turn to turn.

Capacitance $K(x)$ respects turn to turn capacitances and it is involved only in the transformer winding part. Capacitance $C(x)$ respects a capacitance to the earth. Resistance $R(x)$ corresponds to Joule's losses and resistance $R_2(x)$ interrupts a redundant capacitance loop.

The element on the Fig. 1 can be described with following equations:

$$-\frac{\partial u}{\partial x} = L(x)\frac{\partial i_L}{\partial t} + R(x)i_L, \quad (1)$$

$$-\frac{\partial i_L}{\partial x} = C(x)\frac{\partial u}{\partial t} + K(x)\frac{\partial^2 u_K}{\partial x \partial t} + G(x)u, \quad (2)$$

$$-u_K = \frac{\partial u}{\partial x} + R_2(x)K(x)\frac{\partial u_K}{\partial t}. \quad (3)$$

The Eq. (1), Eq. (2) and Eq. (3) overcome to the known transmission line equations in the case that $R_2 \to \infty$ and K=0. To find the solution of these partial differential equations the knowledge of initial and boundary conditions is needed. The computation starts from the zero initial condition, boundary conditions describe the relationship at the input of the line and the way of transformer winding end.

1.2. Algorithm for Numerical Solution

To derive a system of difference equations for the partial differential equations Eq. (1), Eq. (2) and Eq. (3) the stable implicit Wendroff's formula [9] was utilized. The first order derivatives have been replaced by the following differences:

$$\left.\frac{\partial v(x,t)}{\partial t}\right|_{k,l} = \frac{1}{2}\left(\frac{v_k^l - v_k^{l-1}}{\Delta t} + \frac{v_{k+1}^l - v_{k+1}^{l-1}}{\Delta t}\right), \quad (4)$$

$$\left.\frac{\partial v(x,t)}{\partial t}\right|_{k,l} = \frac{1}{2}\left(\frac{v_k^l - v_{k+1}^l}{\Delta t} + \frac{v_k^{l-1} - v_{k+1}^{l-1}}{\Delta t}\right), \quad (5)$$
$$k = 1, 2, ..., N.$$

A difference scheme for the second order derivative in Eq. (2) was evaluated in the form:

$$\left.\frac{\partial v^2(x,t)}{\partial x \partial t}\right|_k^l \cong \frac{\left.\frac{\partial v(x,t)}{\partial t}\right|_{k+1}^l - \left.\frac{\partial v(x,t)}{\partial t}\right|_k^l}{\Delta x} = \frac{1}{\Delta x}\left(\frac{v_{k+1}^l - v_{k+1}^{l-1}}{\Delta t} - \frac{v_k^l - v_k^{l-1}}{\Delta t}\right). \quad (6)$$

Supposing that the length of the cable line and the transformer winding is divided into N length elements and applying these difference approximations to Eq. (1), Eq. (2) and Eq. (3) we receive a system of algebraic equations for nodal values of currents i_{Lk} in inductance L, voltages u_k across capacitance C and voltages u_{Kk} across capacitance K at the time l-th level. These discrete nodal values are arranged in the vector $\mathbf{v}^{(l)} = [\{i_{Lk}\}, \{u_k\}, \{u_{Kk}\}]$. This system of algebraic equations is than supplemented by boundary conditions at the input and output of the system according to Fig. 2. It results into $3N + 3$ equations in a matrix form:

$$\mathbf{A} \cdot \mathbf{v}^{(l)} = \mathbf{B} \cdot \mathbf{v}^{(l-1)} + \mathbf{D}. \quad (7)$$

Elements of matrix $\mathbf{A}$ and $\mathbf{B}$ depend on parameters of the cable and the transformer winding, elements of matrix $\mathbf{D}$ respect a voltage source. Matrix Eq. (7) enables to evaluate unknown discrete values of voltages and currents at l-th time level from the known values at previous (l-1)-th level, the computations were carried out in MATLAB.

2. Illustrative Examples

The proposal algorithm has been used for the analysis of very fast transient phenomena in one phase 1 MVA transformer connected to a 22 kV cable line. The unloaded HV transformer winding was considered because it is the worst case with regard to an overvoltage peak value. The influence of some important factors was studied, the results obtained for various cable length and various voltage wave shape are discussed in the next parts.

2.1. Overvoltage Induced by Step Voltage Surge Wave

At first the voltage source producing a step voltage of peak value $U_n = 22$ kV with a various slope was connected to the system on the Fig. 2. The evaluation was carried out for cable parameters: $R = 0.35$ mΩ·m^{-1}, $L = 0.529$ µH·m^{-1}, C = 218 pF·m^{-1}, the various cable length $l_C = 0$, 100, 200, 300 and 400 m was supposed.

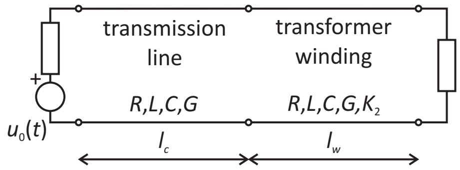

Fig. 2: System consisting of line and transformer winding supplied from voltage source.

The time space distribution of voltage and current surge wave is depicted on Fig. 3 and Fig. 4. The cable line and the transformer winding have different surge impedances for this reason the reflections at the transformer input cause the higher magnitude of voltage wave propagating into winding and opposite the current wave in the transformer winding reaches lower magnitude. The very high values of current wave at the line input are caused by a small impedance of the voltage source (near to short-circuited end).

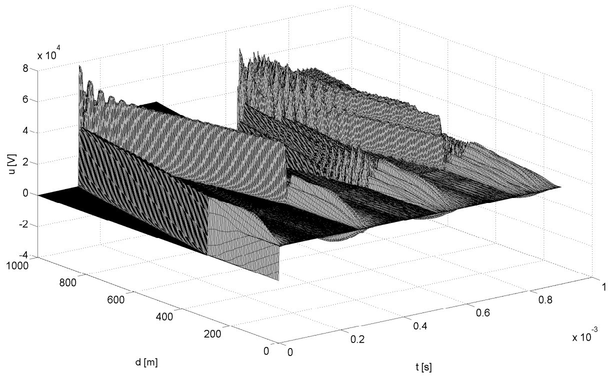

Fig. 3: Time-space voltage distribution, step voltage source.

On the Fig. 5 is shown the dependence of the output voltage in % unit on the slope of source voltage rise and on the cable length. Voltage at winding input increases due to surge wave propagation through cable for a greater rate of rise. It results in very high peak value at winding output $U_{out} > 3.2\ U_n$.

The time voltage distribution at the input and output transformer winding ($l_C = 400$ m, slope = 10 kV·µs^{-1}) is depicted on the Fig. 6. It is seen that not only the high voltage peak value but also high frequency oscillations depending on the slope value appear. For comparison the time voltage distribution at the transformer input for a smaller parameters ($l_C =$

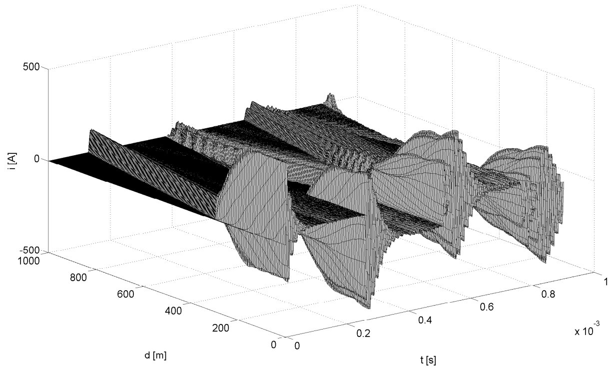

Fig. 4: Time-space current distribution, step voltage source.

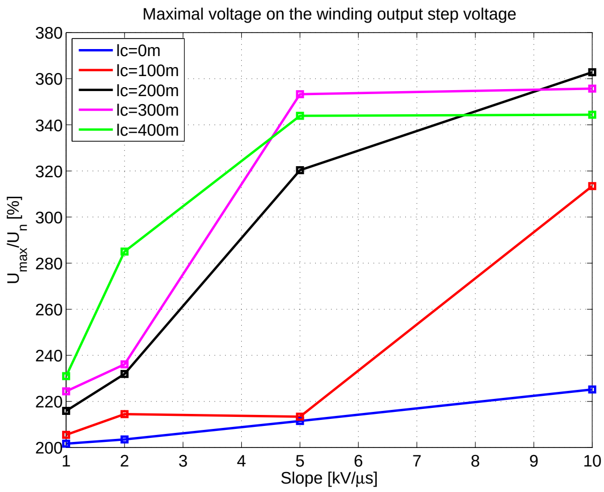

Fig. 5: Dependence of maximal voltage peak value U_{out} on cable length and step voltage slope.

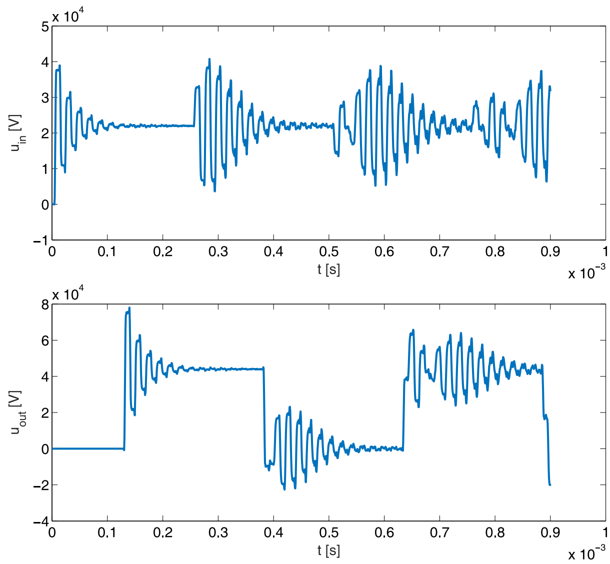

Fig. 6: Time voltage distribution for transformer winding input and output, step voltage source: slope = 10 kV·µs^{-1}, $l_C = 400$ m.

100 m, slope = 1 kV·µs^{-1}) is shown on the Fig. 7. The oscillations propagating from the cable line are much

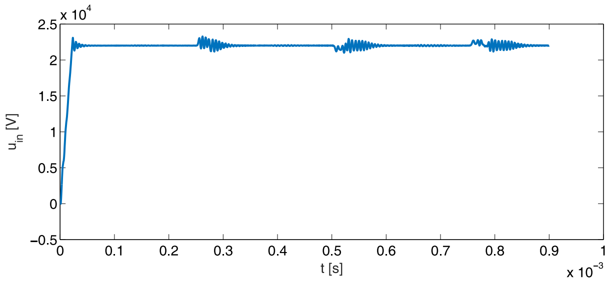

Fig. 7: Time voltage distribution at transformer winding input for step voltage source: slope = 1 kV·µs^{-1}, cable length l_C = 100 m.

lower and shorter, the peak value is near to U_n = 22 kV. In this case the impact of wave travelling along the cable is insignificant. From obtained results follows that the overvoltage in the transformer winding can reach dangerous peak value for a high rate of voltage rise and a longer cable length. This influence should be taken into account in a protection system design.

2.2. Overvoltage Induced by Voltage Surge Wave

The propagation of the surge wave 1.2/50 µs with peak value U_n = 22 kV along the cable into the transformer winding has been studied in this part. At first the surge voltage wave was applied directly at the transformer input. Secondly, the same surge wave propagating through the cable of the length 100 m and 400 m was investigated. The parameters are the same as in the previous example.

The voltage time distribution at the transformer winding input is depicted on the Fig. 8. It is seen that due to propagation of voltage surge wave along the cable high frequency oscillations occur and the peak value is nearly twice higher than U_n. It is caused by reflections at the connection point of both parts. The voltage time distribution at the transformer winding output is depicted on the Fig. 9.

Tab. 1: Voltages on the input and output for various cable lengths.

cable line	U_{in} [kV]	U_{out} [kV]
0	21.993	53.050
100	37.101	78.419
400	37.483	76.519

There is seen how long needs the wave to reach winding output and oscillations caused by reflections at the winding input and output.

Comparing the time voltage distribution on the Fig. 8 and Fig. 9 we find that it is strongly depending on the cable length. Not only the voltage peak

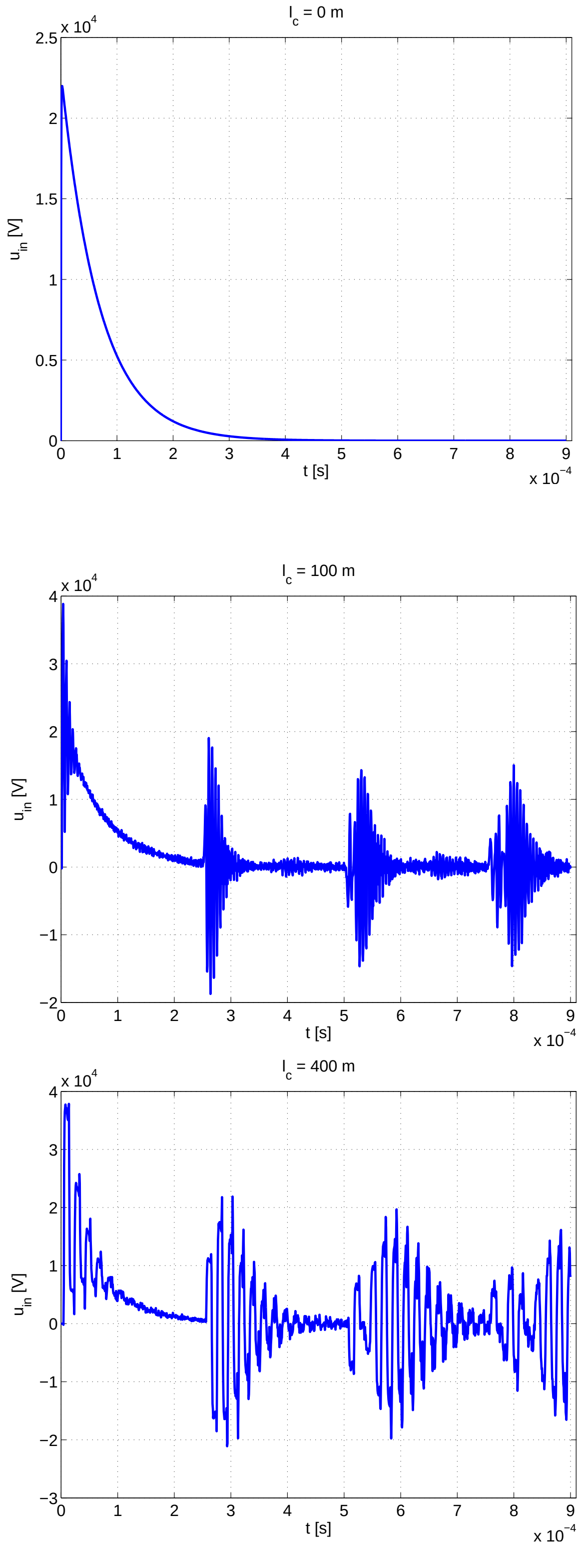

Fig. 8: Time voltage distribution at transformer winding input for surge voltage wave and cable length l_C ∈ (0, 100, 400) m.

value but also the frequency of oscillations differs for various cable lengths. The very high peak values are seen in the following Tab. 1.

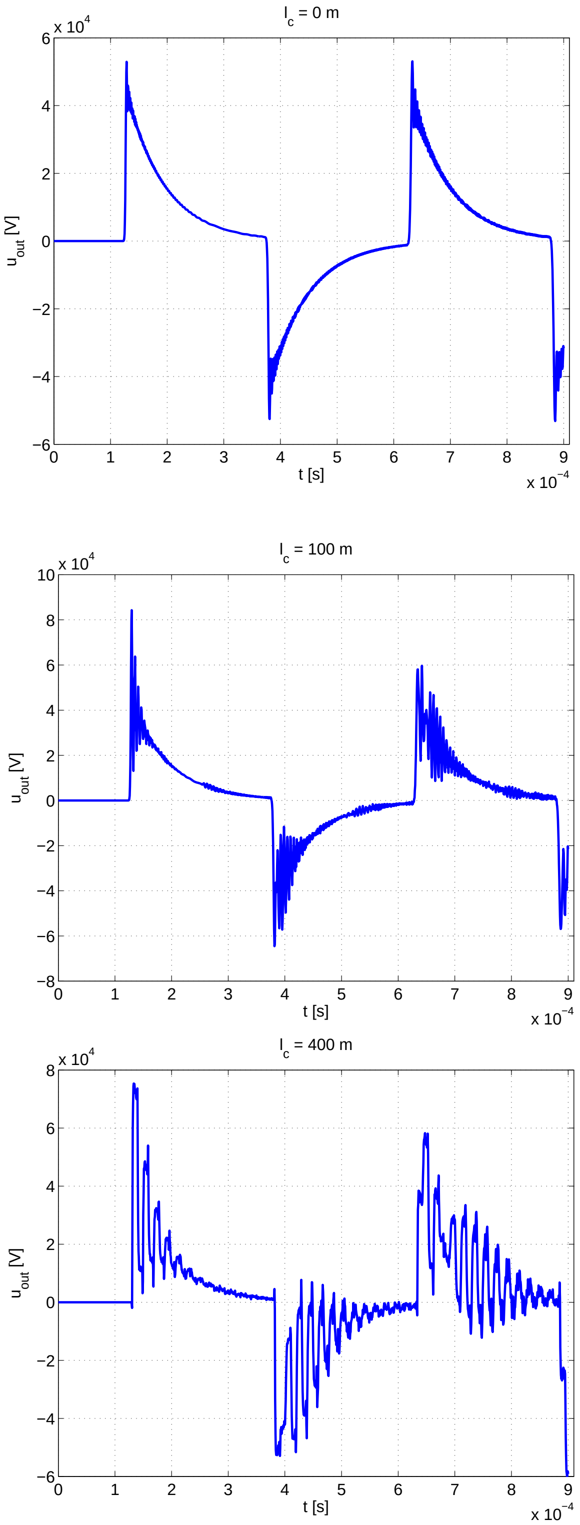

Fig. 9: Time voltage distribution at transformer winding output for surge voltage wave 1.2/50 µs and length $l_C \in (0, 100, 400)$ m.

3. Conclusion

An efficient algorithm for a numerical analysis of very fast transients in the transformer winding connected to the transmission line was introduced. It results in time-space voltage and current surge wave distribution and allows assessing of dangerous switching conditions in power systems. The influence of the shape surge wave, its slope and the line length was studied. It was found that besides the high overvoltage peak value also oscillations with very high frequency can appear. These facts are very dangerous for the isolation system and can cause damage of the transformer winding. The proposed algorithm provides a deeper view into very fast transient phenomena and can be very helpful for a correct design of the protecting and isolation system of transformer.

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Vaclav KOTLAN (was born in Pilsen in the Czech Republic (1947). She graduated from University of West Bohemia in Pilsen, Faculty of Electrical Engineering in 1970; in 1985 she received her CSc. degree Ph.D. She has worked as an Associate Professor at University of West Bohemia in Pilsen since 1994 and as a Professor since 2002. Her research interest concerns on numerical methods for electromagnetic field analysis and on theoretical problems of power electrical energy systems (transmission line parameters, numerical methods for analysis of transient phenomena on transmission lines, transformer winding and EMC). She published more than 90 papers and contributions in various scientific and conference proceedings.

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