Modeling transient signals in power lines

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Abstract: *Modeling in PSCAD / EMTDS of traveling waves in a single-wire power transmission line is considered. Traveling waves of the terrestrial mode are generated at the beginning and in the middle of the line in different ways. The effects of dispersion, which lead to the dependence of the recording time of a traveling wave on the value of the registration threshold and on the distance traveled, are considered. The term of instantaneous and average speed is introduced. The values of the instantaneous speed with multiple runs of the line length drop to 250 m / μs. The average speed of a traveling wave with a single run of the line decreases by 4-6% relative to the speed of light for real thresholds of signal registration.*

Keywords*: TRAVELING WAVES, DISPERSION, INTERFERENCE, STANDING WAVE, TRANSITION SIGNAL*

1. Introduction

Emergency modes in power lines are caused by switching processes. Commutations cause the appearance of traveling waves propagating in all directions along the line. Registration of traveling waves forms the basis of the traveling wave fault location method [1]. The propagation mechanisms of traveling waves are determined by the structure of the line and are observed at different points of the line in the form of a transient signal. The most important parameter of a transient signal is its start time. The mode composition of the oscillations of the transient signal carries information about the type of commutation and the electrical parameters of the line.

The study of the propagation mechanisms of traveling waves and their practical application for high-speed protection of lines and determination of the location of fault is an urgent direction of research. Dispersion is the dominant mechanism in the propagation of traveling waves. It is expressed in a decrease in the speed of propagation of harmonic oscillations with a decrease in frequency and an increase in damping with an increase in frequency [2-4]. A method for determining the location of fauly based on the change in the shape of the leading front of a traveling wave with an increase in the distance traveled is proposed in [3].

Traveling wave fault location methods are based on determining the moment of time when a traveling wave appears in the registration place. Using the sequential application of digital filters of low and high frequency, the time instant corresponding to the maximum steepness of the leading edge of the traveling wave is determinated in [1].

2. Propagation of a voltage step caused by a switched-on power line

Connecting the line to an open-ended voltage source causes the voltage step to propagate along the length of the line. The voltage step propagation will be called the propagation of a traveling wave. The signal recorded at any point of the line is caused by the superposition of traveling waves re-reflected from inhomogeneities in the line, including its ends, and is called a transient signal (TS).

The simplest model of the formation of a transient process signal with a period equal to four times the travel time of the line length, taking into account only the reflection coefficient from the ends of the line, is considered in [5]. Oscillograms of such a signal, calculated in the PsCad package for the simplest model of a line with a length of 100 km (Fig. 1), are shown in Fig. 2 and consist of one mode vibration. The effective lifetime of the transient signal is less than the power frequency period. Therefore, the model uses a constant voltage source.

The black line in Fig. 2 depicts the trajectory of the displacement of the initial amplitude of the traveling wave of the voltage jump. At the time interval from mark 0 to mark 1, the traveling wave propagates along the line under the influence of dispersion. This is due to an increase in the frequency-dependent argument of the exponential dependence of the attenuation coefficient of the high-frequency component of the spectrum of the voltage jump signal [2]. Visually manifests itself in an increase in the duration of the leading edge of the signal. At the end of the line labeled 1, the discontinuity is reflected as a line break with a reflection coefficient of "+1" [5]. The superposition of the incident and reflected traveling waves causes an increase in the amplitude of TS, which is the result of the interference of the incident and reflected traveling voltage waves.

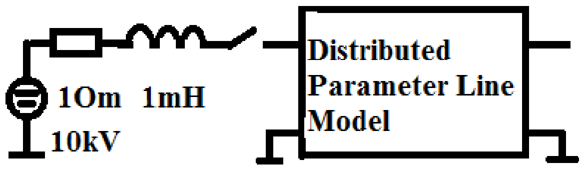

Fig. 1 *Signal "Voltage step"generation circuit at the beginning of the line***.**

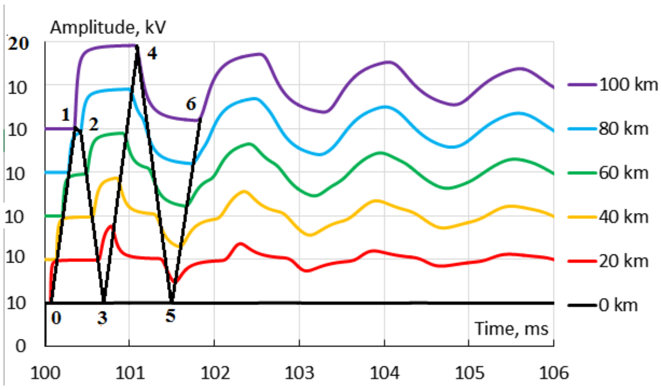

Fig. 2 *Transient signals at different distances from the beginning of the line.*

In the time interval from mark 1 to mark 2 and further to mark 3, the traveling voltage wave adds up (interferes) with the continuation of the traveling wave propagating towards the end of the line. The traveling voltage wave having reached the beginning of the line (mark 3) is reflected with the coefficient "-1" [Ionke], as from an inhomogeneity with a low transverse resistance. Visually, the traveling wave at the beginning of the line is not recorded. This is due to the presence at the beginning of the line of a powerful voltage source with a low internal resistance, which is not disturbed by the lower power of the traveling wave.

A traveling wave of negative polarity re-reflected from the beginning of the line is superimposed on its continuing tails. The propagation of this traveling wave is clearly visible in the resulting signal of the transient process from mark 3 to mark 4 (Fig. 2). At the end of the line, a traveling wave of a voltage jump of negative polarity is reflected for the second time with a reflection coefficient of "+1". Its propagation continues from mark 4 to mark 5 to the beginning of the line. At mark 5, one period of oscillations ends, recorded at all points of the line.

A traveling wave of a voltage jump is influenced by all mechanisms affecting the propagation of waves in lines - dispersion, reflection from transverse inhomogeneity, interference of re-reflected signals. The form of oscillations asymptotically, with an increase in the lifetime of the SPP and the multiplicity of the path length of the line, tend to sinusoidal.

The leading edge of a traveling wave is subject to dispersion, which visually manifests itself in a decrease in its steepness. The steepness of the leading edge is a determining factor in the accuracy of the waveform OMP method. Table 1 shows the space-time characteristics of the leading edge.

Table 1: Space-temporal characteristics of the leading edge.

Parameter \Distance, km	20	40	60	80	100
Trun[µs]	67	133	199	265	331
Aini [kV]	7,4*E-4	5,5*E-8	4*E-12	3*E-16	4,5*E-20
Vini[km/µs]	0,298507	0,300752	0,301508	0,301887	0,302115
T_A1% [µs]	68	138	208	279	350
T_A5% [µs]	69	139	210	282	354
T_A10% [µs]	70	141	212	285	358
T_A90% [µs]	94	192	296	403	516
V_A1% [km/µs]	0,29411	0,28985	0,28846	0,28673	0,28571
V_A5% [km/µs]	0,28985	0,28777	0,28571	0,28368	0,28248
V_A10% [km/µs]	0,28571	0,28368	0,28301	0,28070	0,27933
Slope [µs/km]	1,2	1,275	1,4	1,48	1,58

The Trun time is the duration of the propagation of the initial high-frequency precursor of the traveling wave corresponds to the speed of light Vini with the calculation error in the Pscad package (Table 1). The initial high-frequency traveling wave precursor has an extremely small amplitude Aini. An increase in the duration of the leading edge at levels of 10% -90% of the maximum signal amplitude from the distance traveled corresponds to a decrease in the slope at Slope = 1.2-1.6 µs for each km traveled. The duration of the leading edge of the traveling wave is 158 µs when the line passes 100 km.

The time T_A1% of the first run of the traveling voltage wave from the beginning to the end of the line, which can be recorded by hardware methods, taking into account the real signal-to-noise ratio of 40 dB, is 350 µs (Table 1). This corresponds to the apparent speed V_A1% of propagation of a traveling wave of 286 m / µs, which is 5% less than the speed of light (Fig. 3). A similar value of the propagation speed of a traveling wave at 20 km is 294 m / µs, or 2% less than the speed of light. Accordingly, when using the average experimentally determined value of the signal propagation velocity, the error in determining the location of the signal origin is several percent of the line length.

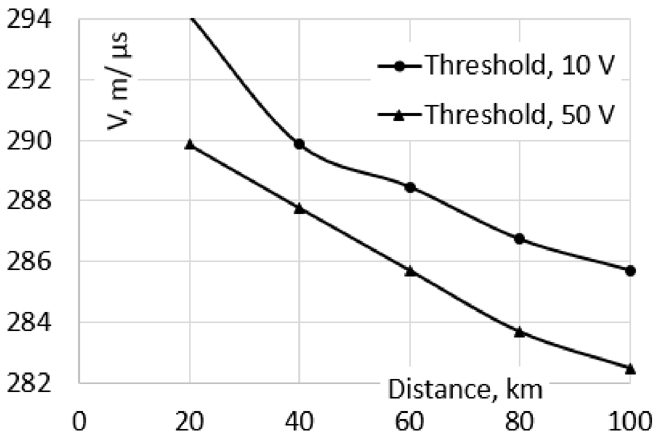

Fig. 3 *The recorded average velocity of propagation of the traveling voltage wave of the terrestrial mode at different distances from the beginning of the line.*

The half-period of the formed free oscillations is calculated from the time of intersection of the instantaneous amplitudes of the signals of the steady-state voltage of 10 kV (Fig. 2). The half-period of oscillations asymptotically, with an increase in the number of multiple reflections of the traveling wave from the ends of the line, tend to the steady-state value of 795 µs (Fig. 4). The steady-state half-cycle is set faster at the far end of the line. The steady-state oscillations are in phase with each other at any point of the line. We assume that the period of free oscillations is due to the fourfold run of the line length.

The single line wave contains only the ground wave, which corresponds to the zero mode for the three phase line. The speed of propagation of oscillations is calculated as 200 km / 795 µs = 252 m / µs. The speed corresponds to a fixed frequency of 629 Hz of steady free harmonic oscillations for the earth wave in [Smirnov] [KhRG]. This fixed speed is much lower than the average and instantaneous speeds on the first 100 km of the line (Fig. 3), which correspond to the higher frequency components of the earth wave. Thus, a standing wave mode is formed in the line in Fig. 1 at a frequency for which the line represents a quarter-wave segment. The beginning of the line corresponds to the node of the standing wave, and the end of the line corresponds to the antinode.

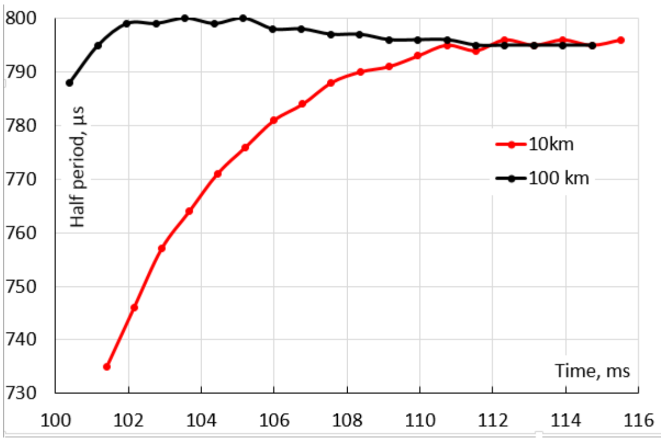

Fig. 4 *Dependence of the duration of half-periods of damped oscillations of the signal of the transient process on the time of its existence at different distances from the beginning of the line.*

3. Voltage step propagation when half line is turned on

Let's move the switching key to the middle of the line (Fig. 5). Signal oscillograms are shown in Fig. 2 and fig. 3. The generated voltage surges of different polarity propagate in opposite directions with the paths marked in Fig. 3. The number of mode oscillations in the first half of the line is two. The number of mode vibrations in the second half of the line is one. This fact can be used for additional identification of the switching point.

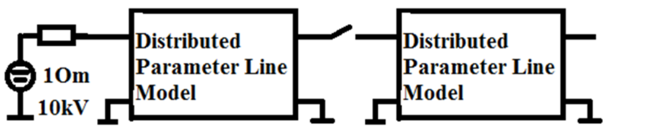

Fig. 4 *Signal "Voltage step" generation circuit in the middle of the line.*

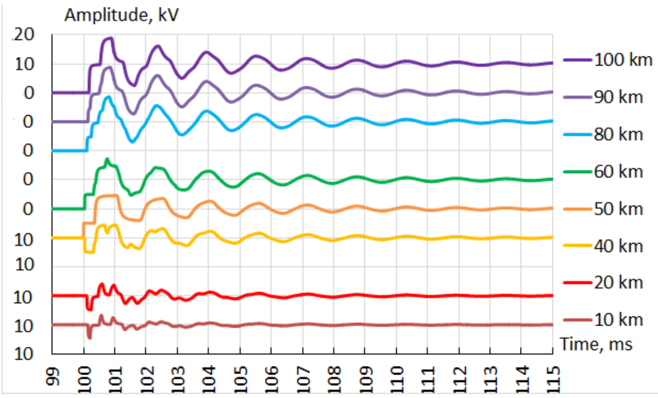

Fig. 5 *Transient signals at different distances from the beginning of the line.*

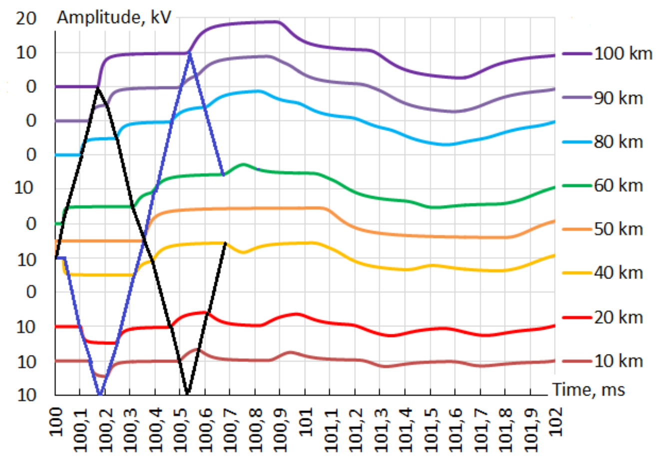

Fig. 6 *The trajectory of a traveling wave at different distances from the beginning of the line.*

4. Propagation of a voltage pulse caused by a charge capacitance

The mechanism of voltage jump propagation along the line considered in the previous section is registered experimentally. Consider the propagation of a voltage pulse generated in the line model when a capacitor is connected (Fig. 7). This circuit is the simplest model for a single-phase earth fault (SPEF) in isolated neutral distribution networks. Figure 8 shows the oscillograms of the TS recorded at different points of the line. The multimode nature of SPEF is well manifested. There are low-frequency oscillations in phase at all points of the line and high-frequency oscillations of different frequency in the first and second half of the line. The decay time constant of high-frequency modes is significantly less than the analogous value for the low-frequency mode.

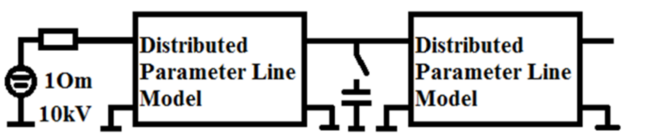

Fig. 7 *Signal "Soliton" generation circuit in the middle of the line.*

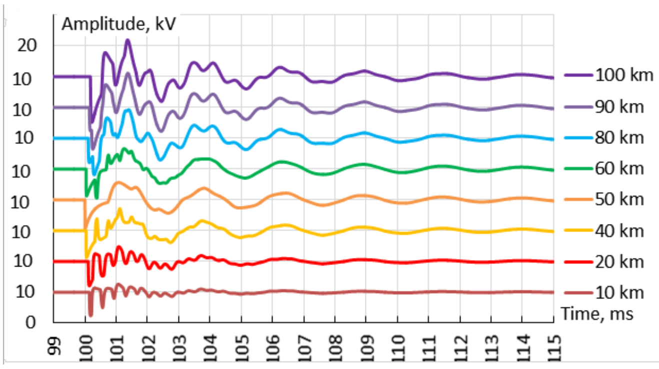

Fig. 8 *Transient signals for "Soliton" generation circuit in the middle of the line.*

Let us consider the mechanisms affecting the propagation of the leading front of the traveling wave according to Fig. 9. A traveling wave arises at the point marked with the mark 0 due to the closure of its electrical potential to ground through an uncharged capacitor. This causes a large jump in the capacitor charging current and a corresponding jump in the voltage dip. The traveling wave of a voltage dip surge propagates in opposite directions to the beginning and to the end of the line. Upon reaching the beginning of the line at the point marked 1, the traveling wave is reflected with a reflection coefficient of "-1". The reflected traveling wave is superimposed on the continuation of the traveling wave and generates the first burst of the emerging high-frequency TS mode.

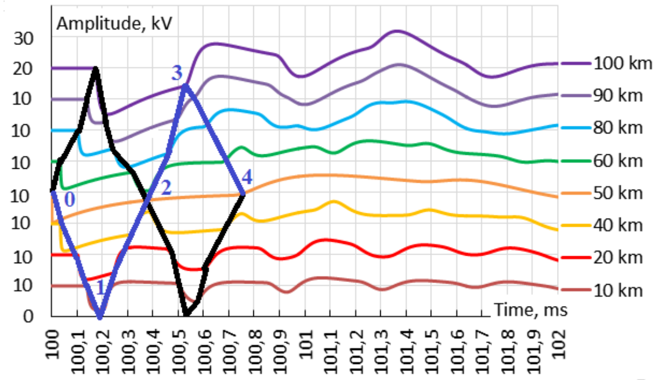

Fig. 9 *The trajectory of a traveling wave at different distances from the beginning of the line.*

A similar traveling wave propagating to the end of the line is reflected from its open end with a reflection coefficient of "+1". The traveling wave reflected from the end is in phase superimposed on the continuation of the traveling wave. A distorted rise front of the first burst of the emerging high-frequency TS mode is formed, the instantaneous amplitude of which goes over to the negative half-plane.

At the point marked 2, the traveling waves of antiphase polarities of the traveling waves are mutually eliminated both in amplitude and in synchronous time position. At the point marked 2, the unperturbed process of charging the capacitor continues according to the exponential law. At the point marked 3, the traveling wave is reflected with the reflection coefficient "+1" and is superimposed on the continuation of the traveling wave. The trailing edge of the first pulse of the emerging high-frequency TS mode is formed. At the point marked 4, the signals of the slowly changing process of charging the capacitor in the middle of the line and the one reflected from the beginning and end of the line are superimposed.

The period of steady-state free harmonic oscillations in the presence of inhomogeneity (Fig. 8) is higher than in a homogeneous line (Fig. 2 and Fig. 5). The inhomogeneity in the form of a transverse container increases the effective line length. Fig. 5 and

Fig. 6 well illustrate the twofold difference between the periods of oscillations of high-frequency modes on the two halves of the line. This fact can be used to further identify the location of damage.

5. Conclusions

Based on the results of modeling the propagation of traveling waves of the terrestrial voltage mode, it is shown that the dispersion of the leading edge of the traveling voltage wave leads to an underestimation of the recorded propagation velocity of traveling waves. The amount of underestimation is proportional to the distance traveled, depends on the registration threshold and is 0.07% of the speed of light for each km traveled for a uniform line. With the propagation of a traveling wave in an inhomogeneous line, the value of the velocity underestimation increases. Accordingly, when using the average experimentally determined value of the signal propagation velocity, the error in determining the location of the signal origin is several percent of the line length. The interference of traveling waves re-reflected from the ends of the line forms a standing wave of free oscillations at a quarter-wavelength of the line. The simulated waveforms of the transient process illustrate the possibility of determining both the type of switching and its location outside or inside the observed zone of the wave method complex for determining the fault location.

6. References

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