Diagnostic Signs of Transient Signals in Power Lines

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Rustem Khuziashev ; Igor Kuzmin ; Iluza Ircagalieva All Authors

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I. Introduction

Practical implementation of the traveling wave fault location in power lines in networks of different voltage classes is an urgent task for the electric power industry [1]. The correct determination of the fault location in tree-like networks is often complicated by many reasons. The accumulated experimental os[…] signals show a wide variety of their shapes, which is associated with different causes and con[…]chanisms of dispersion, re-reflection and

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Rustem Khuziashev
Kazan state power engineering university
Kazan, Russia
142892@mail.ru

Igor Kuzmin
Kazan state power engineering university
Kazan, Russia
to_kigor@list.ru

Iluza Ircagalieva
Kazan state power engineering university
Kazan, Russia
irkagalieva2001@mail.ru

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Keywords—transient process, equivalent circuit, lumped parameters, distributed parameters, diagnostic signs, modeling

I. INTRODUCTION

Practical implementation of the traveling wave fault location in power lines in networks of different voltage classes is an urgent task for the electric power industry [1]. The correct determination of the fault location in tree-like networks is often complicated by many reasons. The accumulated experimental oscillograms of the transient process signals show a wide variety of their shapes, which is associated with different causes and conditions of their occurrence. The mechanisms of dispersion, re-reflection and interference during propagation of traveling waves distort the leading edge and waveform. This makes it difficult to develop a fully automated complex that excludes visual analysis of waveforms.

In the literature, various algorithms for determining the onset of a signal are considered [2,3]. To correctly determine the place of origin of the signal, it is necessary to take into account the forms of the recorded oscillograms. The study of simulated transient signals is important in the analysis of experimental observations. When analyzing the waveform of the transient process, its diagnostic features are calculated. Modal analysis decomposes the transient signal into oscillations of different frequencies, each of which is modulated in amplitude, frequency and phase [4,5]. The paper discusses the results of modeling the signals of the transient process. A sequence of determining the diagnostic signs of a transient signal that has a physical meaning is proposed. The relevance of research in this direction is confirmed by the works [6,7], in which algorithms for determining the onset of the transient process signal are considered.

A. SIMPLEST LINE MODEL WITH LUMPED PARAMETERS

The transient signal is generated in the electrical network due to planned or emergency switching of any kind. The electrical distribution network is characterized by the presence of a large number of closed contours. RLC parameters of each contour form independent damped oscillations. According to [8], in an electrical network with an isolated neutral at the beginning of the line, damped oscillations of two frequencies dominate in amplitude. Low-frequency oscillations occur in a contour containing a large inductance of the internal resistance of the power source. High frequency oscillations occur in a contour containing a low inductance power line.

Let's consider a model of a line (Fig. 1) with lumped parameters in a single-phase earth fault (SPEF) mode. Identical internal resistances of phase sources, longitudinal and transverse elements of phase lines are assumed. The resistances of the phase values of the loads are assumed to be infinitely large. We will carry out two stages of simplification of the original scheme.

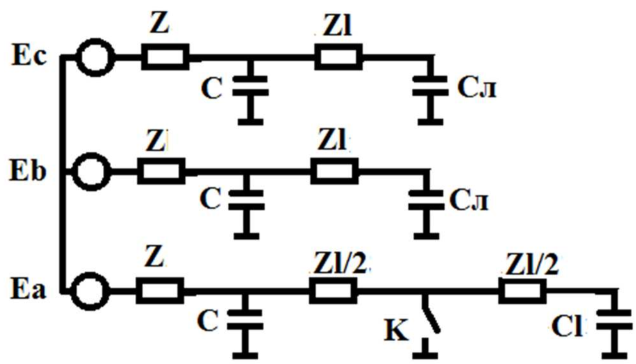

Fig. 1. Line model in SPEF mode

At the first stage, we discard one intact phase line together with its source (Fig. 2). At the second stage, we discard the lumped elements of the second unfault phase line (Fig. 3). The model was created in the PSCAD software package. To measure the currents in the branches, add active resistances of 1 Ohm at the bottom of each branch. The complex resistance Z is formed by an inductance of 1 mH. Complex resistance Zl is formed by an inductance of 0.1 mH. The sectional capacitance C, formed by other lines, is equal to 1 μF. The phase capacitance Cl is 0.1 μF.

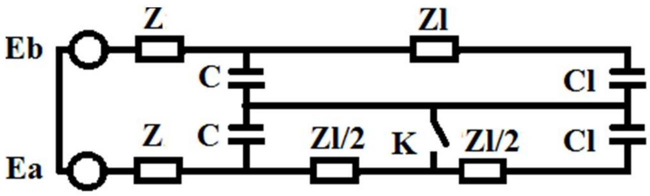

Fig. 2. Line model in SPEF mode without one unfault phase line

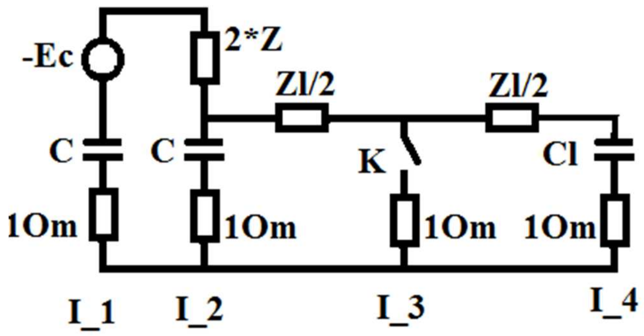

Fig. 3. The simplest three-contour line model in the SPEF mode

Table 1 shows the distribution of the values of the oscillation periods along the branches I1-I4.

TABLE I. DISTRIBUTION OF VALUES OF OSCILATION PERIODS

Branch no.	Oscillation period, µs		
	200	*43*	*14*
I_1	V		
I_2		V	
I_3	V	V	V
I_4			V

The circuit in Fig. 3 consists of 4 parallel branches, one of which (branch 3) has almost zero resistance and is a low-resistance shunt that forms three independent RLC circuits with different free oscillations.

On the buses of the unfault phase, there are oscillations, the period of which is determined by the inductance of the internal resistance of the source and the value of the phase sectional capacitance (Table 1). On the buses of the fault phase, there are oscillations, the period of which is determined by the inductance of the fault section of the line and the value of the phase section capacitance. At the end of the fault phase, there are oscillations, the period of which is determined by the inductance of the damaged fault of the line and the value of the phase capacitance of the line. The earth fault current contains a superposition of all three values of the periods of free oscillation.

The obtained regularity of the distribution of oscillation periods confirms the fulfillment of the principle of superposition of signals of transient processes in a multi-contour circuit. Probably, a necessary condition of this principle is a low resistance of one branch in a multicontour circuit consisting of parallel branches. The maximum amplitude of current fluctuations in the branch is determined [9] by dividing the magnitude of the voltage perturbation by the characteristic impedance of the circuit. The value of the wave impedance is equal to the root of the ratio of the inductance value to the capacitance value of the contour under consideration.

The obtained model results indicate the value of diagnostic information contained in the value of the period of free oscillations.

II. SIMPEST LINE MODEL WITH DISTRIBUTED PARAMETERS

Let us investigate the temporal and spatial forms of the transient process signals in the model of an overhead line with a voltage of 10 kV. The model was created in the PSCAD software package.

The line model consists of ten single-phase distributed line blocks. Each block consists of an AC-95/16 wire 10 km long. After 10 km, starting from kilometer zero, recording voltmeters were installed. The end of the line is unloaded. The signal is calculated with a time interval of 1 µs.

Consider two ways to generate switching signals.

A. Signal type "Voltage step"

Short-circuit and single-phase ground fault modes generate signals of the "voltage step" type. Consider this method of generating a transient signal (Fig. 4). The line model is connected to the source with a switching key on 100-th ms. As an source, a 10 kV constant voltage source with an internal resistance of 1 Ohm and an inductance of 1 mH was used. Figure 5 shows the time oscillograms of voltage signals at 0. 10. 50 and 100 km.

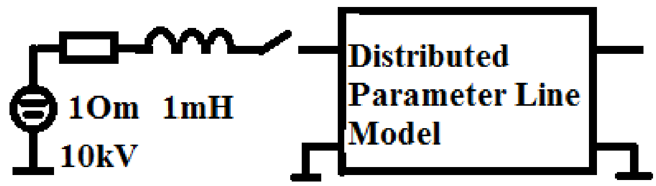

Fig. 4. Signal "Voltage step" generation circuit

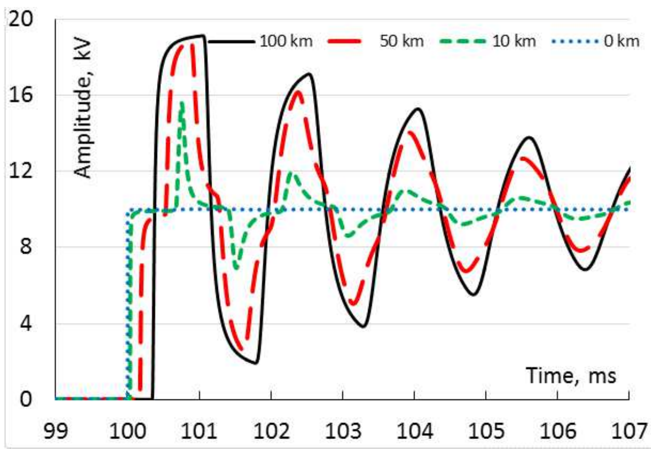

Fig. 5. Oscillograms of the resulting signals at different distances from the beginning of the line during the generation of "Voltage step"

The mechanisms of dispersion, reflection from the end and beginning of the line, and interference of re-reflected waves are clearly manifested. The reflection coefficient of the incident wave from the idle end of the line is +1, and from the beginning of the line -1 [9]. The combined action of these mechanisms leads to the establishment of damped harmonic oscillations in the signal line. The fourfold run at the speed of light of the length of the line by the "voltage step" signal forms an oscillation period close to 1.333 msec.

The resulting signal on Fig.5 is well described by a quasi-sinusoidal shape. The shape of the resulting signal at different distances is the same up to phase shift, despite the different times of its start.

Let us estimate the change in the duration of the leading edge of the "Voltage step" signal at different distances from the beginning of the line between the levels of 90%, 80% and, accordingly, 20%, 10% of the steady-state signal values (Table 1).

TABLE II. LEADING EDGE DURATION IN MICROSECONDS

Levels,%\Distance,km	0	10	50	100
10%-90%	0	11	68	163
20%-80%	0	4,5	30,5	65

Reflection of a "Voltage step" from the end of the line with a coefficient of "+1" doubles the amplitude of the resulting signal (Fig.5). This causes overvoltage phenomena that are dangerous for the insulation. In the first period of the resulting signal, the maximum amplitude at 100 km is 1.5 times greater than the same value at 10 km. Starting from the 3rd period, the maximum amplitude for 100 km is 5 times more than for 10 km.

The time dependence of the maximum amplitudes over the period of the resulting signal on time (Fig. 5), regardless of the distance from the beginning of the line, is described by a quasi-exponential dependence.

The presented characteristics of the signals do not depend on the presence or absence of an inductance of 1 mH, as a constituent element of the internal resistance of the EMF source.

B. Signal of the "Dumped oscillation" type

In the electric power industry, all sources (generators and transformers) have an internal inductive resistance due to their design. With a decrease in the voltage class, the source power decreases and the inductance value of the source internal resistance increases. Consider a circuit (Fig. 6) Containing inductance in the source internal resistance.

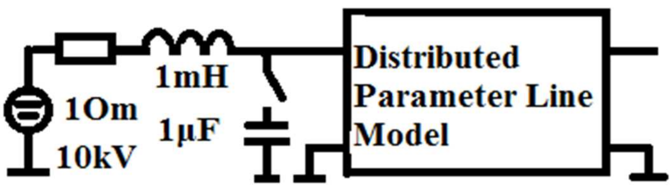

Fig. 6. Signal "Damped Oscillations" generation circuit

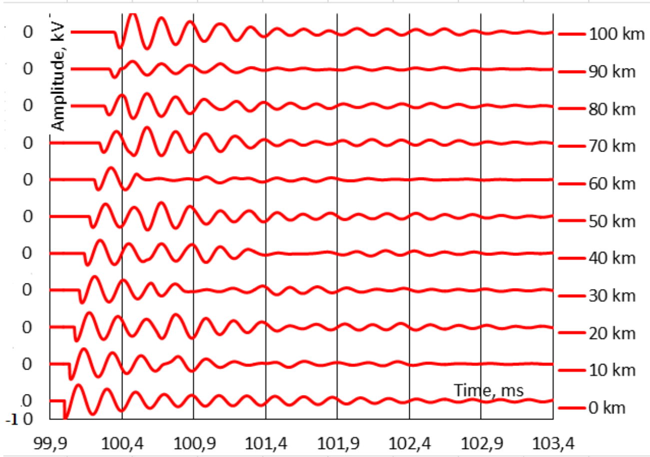

Fig. 7. Oscillograms of the resulting signals at different distances from the beginning of the line during the generation of "Damped Oscillations

Closing the key at 100 ms generates damped harmonic current oscillations in the RLC circuit. The time constant of damped oscillations [9] is 2 * L / R = 2ms. The duration of the generated signal exceeds four times the travel time of the line length. A traveling wave of voltage fluctuations propagates along the line, is reflected from its end with a coefficient of +1. The wave is reflected from the beginning of the line with a negative coefficient close to -1. All reflected waves interfere with each other. Oscillograms of the resulting signals are shown in Fig. 7.

III. HALF PERIOD METHOD

Analysis of the recorded oscillograms of transient processes in a 10 kV electrical tree-like distribution network (Fig. 8) [10] makes it possible to formulate an algorithm for calculating diagnostic signs.

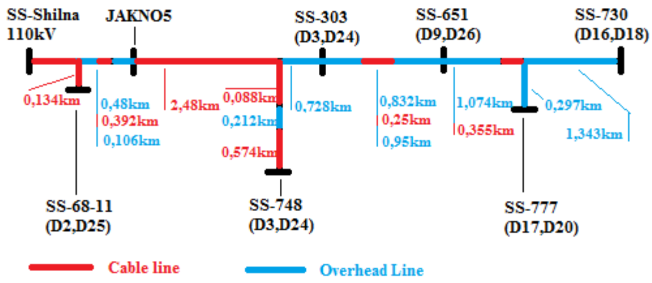

Fig. 8. Diagram of a tree-like electrical network

Fig. 9 shows an example of a transient signal recorded at different distances from the place of its occurrence during its propagation in a 10 kV electrical tree distribution network (Fig. 8). In the signal recorded closest to the place of its occurrence, multi-pulse of the signal or numerous commutations caused by bouncing of contacts of a high-voltage switch are well manifested.

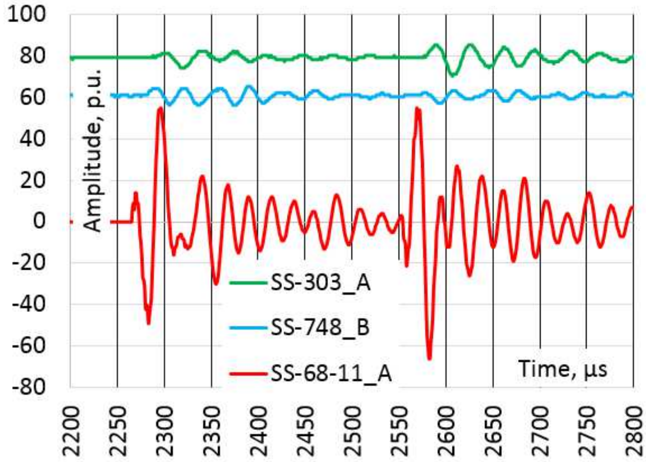

Fig. 9. Synchronous waveforms at different points in the network

Figure 10 shows three phase signals of the transient process recorded at substation SS-303 (Fig. 8). In case of bounce-related re-commutations, the in-phase / anti-phase of the phase signals changes. The presented graphs illustrate the diagnostic value of information about the period and phase of oscillations in the transient signal.

For the purposes of further signal analysis, a simplified modal analysis method or a half-period method is proposed, which determines its main diagnostic signs of transient signals. Let us consider the main stages of the proposed method using the example of an oscillogram of a high-intensity transient signal recorded most close to the place of planned switching in the form of connecting a feeder under load (Fig. 9). The original signal will be called S0.

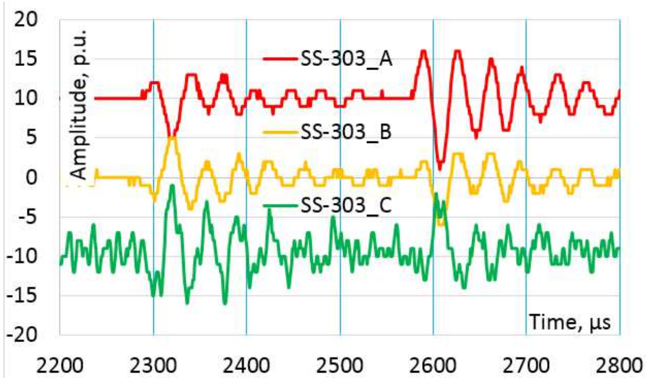

Fig. 10. Synchronous oscillograms in different phases of the line

At operating voltages and overvoltages caused by planned and emergency switching in the elements of the weakened high-voltage insulation of the line, partial discharges (PD) occur. The duration of the overwhelming majority of PDs is much less than the sampling interval of the oscillograms. Due to their short duration, PD quickly decay and propagate no further than a few meters from the place of their origin. On the recorded oscillograms, PDs appear in the form of single bursts, the amplitude of which is small, comparable to or greater than the amplitude of the transient process signals. PDs are recorded both before and during the registration of the transient signal.

A diagnostic sign of PD or single noise spikes is the constancy of the time trend of the signal amplitude before and after a single amplitude spike. This allows you to programmatically remove single peaks from the signal oscillogram. The number of remote surges and their amplitude before and after the start of the transient signal is diagnostic feature No. 1. We receive signal S1.

The duration of the recorded oscillogram is 6 ms, recorded with a sampling interval of 1 µs. The beginning of the transient process signal recorded by the sensor of the complex by the differential algorithm is located in the time interval from the beginning of the third to the end of the fourth millisecond. Most likely, the time interval in the first millisecond does not contain a transient signal. The arithmetic mean of instantaneous amplitudes in this interval carries information about the magnitude of the constant component in the amplitude of the transient process signal. This constitutes the content of the diagnostic feature No. 2. By subtracting the dc component from all instantaneous samples of signal S1, we obtain signal S2.

Find the standard deviation A of instantaneous amplitudes in the interval of the first millisecond of signal S2. We find the modulus B of the maximum displacement of the instantaneous amplitude in the interval of the first millisecond of the signal S2. This constitutes the content of the diagnostic feature No. 3.

We build the upper and lower signal envelopes over the entire time interval of the signal. Piecewise linear envelopes should touch only those points of the signal that are local maxima and minima of positive and negative signal half-periods. We build the resulting signal envelope as the difference between the upper and lower envelopes (Fig. 11).

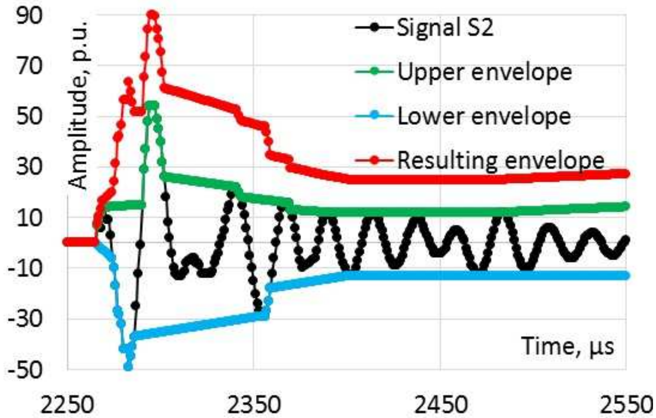

Fig. 11. Signal envelopes

The resulting envelope allows you to determine the number of pulses and their effective duration in the transient signal at the level of 0.33 of the maximum value of the resulting envelope. This constitutes the content of the diagnostic feature No. 4. This feature plays a decisive role in determining the cause of the formation of a transient signal.

The resulting envelope allows you to determine the beginning of the transient signal according to the following algorithm. We iterate over the instantaneous amplitudes of the S2 signal in the direction from left to right from the end of the first millisecond to the end of the oscillogram. We remember the first three points in time at which the inequality $|S2(i)| >= P$, if $|S2(i-1)| < P$ or $|S2(i)| < P$, if $|S2(i-1)| >$

= P. We denote the smallest time T (1). If T (3) -T (1) <50μs, then the time T (1) is used to determine the location of the signal. In the opposite case, the time T (3) is used. This constitutes the content of the diagnostic feature No. 5.

The half-sum of the upper and lower envelopes of the PSD carries information about the variation of the constant component in the PSD, caused by various physical mechanisms. By subtracting this half-sum from the signal S2, we obtain the signal S3. This allows the periods of all transient signal modes to be arranged more symmetrically relative to the zero line.

In the time interval from T (1/3) to the end of the first pulse, the moments of the change in the sign of the amplitudes of the signal S3 are determined. The maximum and minimum values of the amplitudes in each half-period are determined. For the purpose of symmetrical arrangement of the amplitudes of the half-periods in the interval between the heteropolar extemums, the arithmetic mean of the instantaneous amplitudes is considered. Each instantaneous amplitude is reduced by the calculated arithmetic mean value in its interval. We receive signal S4.

For the signal S4, we determine the numerical sequence of the times of the transition of instantaneous amplitudes through zero, the duration of half periods, the maximum and minimum values of the amplitudes in each half period, the mean value of the half period determined by the least squares method (LSM), the slope of the approximating line in the LSM (Fig. 8). This constitutes the content of the diagnostic feature No. 6.

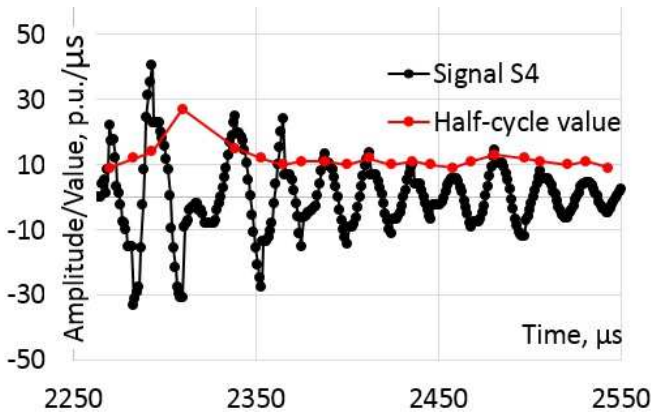

Fig. 12. Time dependence of the value of the half-period of oscillations

Conclusion

The paper analyzes the characteristic patterns of oscillations of the transient process signal in power lines observed experimentally and simulated by the PSCAD simulation tool. It is shown that the transient signal is formed by both lumped and distributed line elements. The recorded transient signal is formed by the mechanisms of dispersion, reflection and interference of signals.

The simplest three-contour equivalent circuit with lumped parameters of the single-phase earth fault mode demonstrates the multimode nature of the transient signal. The mode with the lowest frequency is formed on the buses of the intact phase. A medium frequency mode is formed on the buses of the damaged phase. The mode with the maximum frequency is formed near the damage site.

The simplest switching equivalent circuit in a distributed line demonstrates that the generated transient signals have a duration exceeding the travel time of the entire line length. The maximum signal amplitudes recorded at different points of the line increase from the beginning to the end of the line. The location of the maximum signal amplitude shifts from the beginning of the signal to its middle when the place of their registration is shifted towards the end of the line. This is due to the interference mechanism of incident and reflected waves from the end of the line.

Model calculations of signal measurements at different points of the line illustrate their synchronism with an accuracy of half a period, despite the different start times. This confirms the participation of the entire line in the formation of the transient signal.

Experimental measurements of signals at different points of the line indicate an increase in the duration of half-periods of oscillations with distance from the beginning of the line. This is probably due to multiple reflections from line irregularities.

The proposed method of half-periods is the simplest implementation of modal analysis and is aimed at identifying different modes of oscillations both during one signal and at comparing their parameters for signals recorded at different points of the line.

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