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I. Introduction

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Influence of transmission lines inhomogeneities on transient signal

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***Abstract*—The paper compares the parameters of current and voltage transient signals in electric lines of high and medium voltage classes. The paper compares frequency dependences of their propagation coefficient. Modelling results show the destructive influence of concentrated inhomogeneities on the leading edge of the travelling voltage wave. It is shown that the small length of medium voltage class lines allows to obtain acceptable measurement errors of fault location not exceeding the similar one in high voltage class lines.**

***Keywords*—travelling wave, transient signal, inhomogeneity, MatLab, PSCAD, modal signals.**

I. Introduction

Reliable operation of power distribution networks is impossible without monitoring systems to detect pre-emergency and emergency regimes of its operation. This is necessary both in the interests of preventive maintenance of grids and for quicker detection of the fault location for its subsequent elimination. Due to the large length of cable and overhead power lines, remote methods of monitoring the condition of power grids are relevant. One of the promising monitoring methods is travelling wave fault location (TWFL) complexes.

Passive TWFL in power grids is gaining popularity. At present, its practical development is most relevant in medium-voltage class distribution networks. This is due to the reduced cost of hardware devices, the lack of alternative methods of fault location in such networks, small emergency currents in networks with isolated neutral and their treelike structure. A large number of papers are devoted to the study of transient signal (TS) registration issues, their modelling [1-5], algorithms for determining the beginning of the transient signal (BTS) [6, 7].

In treelike distribution networks TWFL complex sensors are installed in dead-end or intermediate transformer substations [8]. The transformer substation provides guaranteed power supply, weather and vandal protection. It is practically easy and cost-effective to implement the registration of voltage TS by using high-voltage insulators. Synchronous registration of TS in a unified satellite time scale in spatially separated substations of one electrical network allows to implement a multilateral TWFL algorithm [1-5]. Basically, the accuracy of fault location is determined by the error of BTS registration, which is determined by the shape of TS and, in particular, by the type and steepness of the TS leading edge. The shape of TS and the period of its oscillations contain ambiguous information about the structure of the distribution network.

TWFL complexes functioning is based on registration of TS, generated on and near the line due to various causes. Such causes are non-emergency and emergency switching, including partial discharges and lightning overvoltage. During switching operations, overvoltage of various magnitudes occurs, which lead to deformation of high-voltage line insulation elements.

TS are registered by sensors installed in substations, distributed throughout all or part of the electrical network, or at least at the ends of a line section. The use of information concerning the beginning time of TS, registered in the unified satellite time scale, and the TS shape allows to determine not only the location but also the cause of the fault. Research in this direction has been widely carried out worldwide in the last two decades. However, the last two decades demonstrate an avalanche-like increase in publications of research in this direction.

At the switching point of an electric line, step-like surges of current and voltage arise. They propagate in all directions in the form of travelling waves (TW). The TW propagation speed and their deformation caused by dispersion phenomenon is described by telegraph equations. The parameters of the telegraph equation are the impedance matrices $\overline{Z}$ and conductance matrices $\overline{Y}$ of a homogeneous transmission line. The matrices $\overline{Z}$ and $\overline{Y}$ are generally non-diagonal because each phase mode parameter (current, voltage) depends on the other phase parameters in the *n*-phase line. During research of wave TS in n-phase line, the conversion of phase currents and voltages (phase coordinates) to wave channels (modal coordinates) is applied [9,10].

The conversion matrix $\overline{T_U}$ [11] of phase currents and voltages to modal coordinatesis used. The extraction of wave channels makes it possible to obtain *n* systems of currents and voltages in an *n*-phase line independent of each other. In this case, the phase voltages and currents equal the superimposition of the modal voltages and currents. In [11], it is shown that the first modal channel or interphase channel has the highest TW propagation speed. The TW propagation speed in the zero modal channel or ground channel is smaller. Numerical studies of these phenomena are possible in the MatLab software package. The limiting case of the conversion matrix for a perfectly symmetric line is the Clark matrix [12].

Electric lines are significantly inhomogeneous, which is caused by the presence of areas of concentrated inhomogeneity. These are concentrated insulation elements, nodes of transposition and line branching, places of transition to cable inserts, substations busbars with transformers. During TW propagation in an inhomogeneous line phenomenon of reflection and refraction occur, the coefficients of which are frequency dependent and different for each modal signals. Numerical study of these phenomena is possible in PSCAD software package.

The paper's goal is to analyze the sources of measurement error and prove the possibility of TWFL practical use in medium voltage class distribution networks by using model calculations. The substantiation is based on the comparison of line and TS parameters between medium voltage class lines and high voltage class lines, where TWFL complexes proved their effectiveness. Section II presents the results of TW propagation coefficient's study as a function of electric line parameters. Section III presents the results of modelling of TS formed by the most significant inhomogeneities of the electric line.

II. Comparison of Propagation Coefficient Between High and Medium Voltage Class Lines

Numerical calculation of $\overline{Z}$ and $\overline{Y}$ matrix elements for standard sizes of 220 kV and 10 kV transmission line support traverses is performed in the MatLab software package in the "power_lineparam" program using Carson's equations. Table 1.1 shows the parameters used for the traverses and phases of 220 kV and 10 kV lines located in the horizontal plane. Paper [10] demonstrated that in the complex elements of the transformation matrix $\overline{T_U}$ the imaginary parts are at least an order of magnitude smaller than the real parts. It is also shown there that at 1-1000 kHz frequencies the change in the real parts of the transformation matrix $\overline{T_U}$ is insignificant and does not exceed 10% of their average values.

TABLE I. 10 and 220 kV lines parameters

Voltage class	Traverse parameters		
	Conductor type	*Conductor distance, m*	*Traverse height, m*
220 kV	400 mm^2	5,7	17
10 kV	50 mm^2	0,66	7,75

The conversion matrix $\overline{T_U}$, which diagonalizes the matrix $\overline{Z}\times\overline{Y}$ is calculated using the *eig* function of the MatLab package at 10 kHz.

The influence of conductor and ground resistance is amplified by the surface effect. The depth of the surface layer in aluminium conductor at frequencies greater than 10 kHz is 0.66 mm, which is at least an order of magnitude less than the radius of ACSR50, ACSR400 conductor [13]. The increased decay constant in the zero wave channel is explained by the surface effect in the conductors and to a greater extent by the ground resistance and the surface effect in it. Figure 1 shows the modal phase speed and decay constant for 10 and 220 kV line parameters with the ground resistance 100 Om*m.

Figure 1 convincingly shows the worse parameters of the 10 kV line relative to similar values of the 220 kV line, not only in the zero-mode channel, but also in the first mode channel.

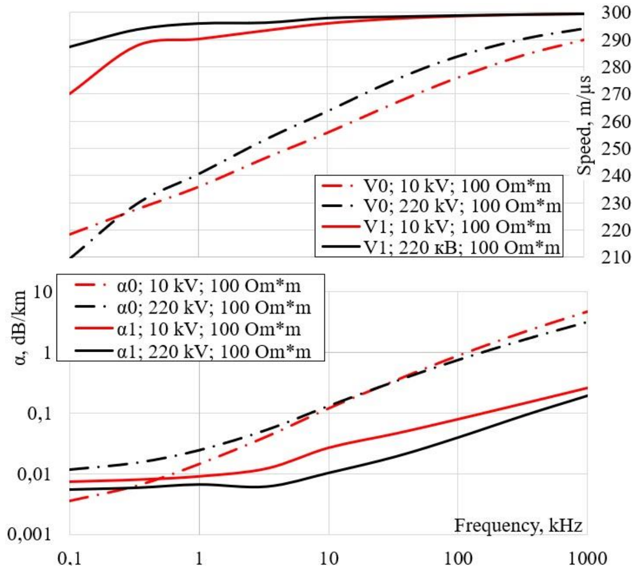

Fig. 1. Frequency dependences of modal phase speed and decay constant.

III. Research of the Influence of Concentrated Inhomogeneities of the Line on the TS Shape

To analyze the influence of line parameters on the shape of TS and its leading edge, a 10 km long line model (Fig.2) with phase-to-ground switching was created in PSCAD package to simulate the occurrence of TS in the middle of the line. The line is powered by an EMF source with zero internal resistance. The end of the line has no load. Typical parameters for 220 kV and 10 kV lines are taken, that were presented in Table 1.1.

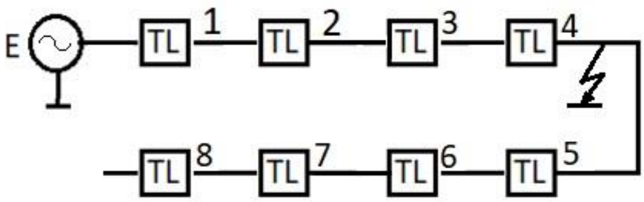

Fig. 2. Schematic of a line consisting of 8 identical sections of 1.25 km length.

Fig. 3 shows oscillograms of current and voltage TS registered at the ends of a single-phase line at 5 km from the place of its occurrence. A TW in the form of a voltage step and a current step is born in the place of transmission line fault. The voltage step spread is equal to the potential difference on the phase conductor before and after the moment of fault or emergency switching. The current step magnitude is equal to the voltage step voltage spread divided by the line impedance.

The total amplitude of current and voltage signals at the ends of a simple line is formed as a result of superimposition of travelling (incident) and reflected waves. The magnitude of the reflection coefficient of current and voltage waves is different and is determined by the ratio of the wave impedance of the line and the resistance of the inhomogeneity node according to the formula: [14]

$$k_u = -k_i = \frac{Z_H - Z_B}{Z_H + Z_B} \qquad (1)$$

The left end of the line (Fig.2) has zero resistance, the right end - infinite resistance. The form of the recorded current and voltage TS (Fig.3) is defined by the superimposition of incident current and voltage TW and current and voltage TW reflected from the ends of the line and the fault location.

The graphs of Fig.3 illustrate the dominance of information value of voltage signals over current signals. Voltage TS have an amplitude comparable to the voltage amplitude before the emergency mode. Current TS have an amplitude smaller than the current amplitude after the emergency mode.

In Fig.3, zero time corresponds to the moment of key switching in Fig.2. The beginning of the voltage and current step is deformed much stronger in the 10 kV line relative to the 220 kV line. This corresponds with the values of the propagation coefficient given in Fig.1. The beginning of current and voltage TW, corresponding to the minimum deviation from their pre-emergency value (Fig.3), is registered at both ends of the line at the moment of time 16.7 µs, corresponding to the propagation speed of 0.2995 km/µs at the travelled distance of 5 km. It is impossible to experimentally record the very beginning of TS, which is due to the finite value of the amplitude quantum of the digitized signal and the presence of noise in the measurement channel. This determines the reduction of the observed or threshold TW propagation speed.

The line model created in PSCAD package (Fig.2) allows to change the number of phases in the line, the diameter of the line conductors, the parameters of the traverse, the presence/absence of supply and load transformers at the ends of the line, 1 nF capacitances reflecting the capacitance of insulating elements on the substation busbars, the presence of adjacent feeders departing from the substation busbars. All these elements form concentrated nodes of inhomogeneities, which have a significant impact on the reflection and refraction of TW. Let us examine the modelling results.

Fig.4 shows the phase voltage TSs of a three-phase 10 kV line with different time scales: on the left - small time scale, on the right - large time scale. The left end of the line (Fig.2) is powered by a three-phase 220/10 kV transformer with apparent power of 25 MVA with star/delta windings. The right end of the line is loaded on a 10/0.4 kV transformer with apparent power of 0.025 MVA with delta/star windings and no low-voltage load.

Fig.4a shows the TS of the damaged phase "A" for a single-phase earth fault in the middle of the line (Fig.2). TS at the left and right line ends of a three-phase line ("A;beg.line" and "A;line end") are the same. This is due to the same infinite resistance between the ends of the line and the ground for the line with isolated neutral. In contrast to a single-phase line (Fig. 3), TS in a three-phase line on the damaged phase consists of in-phase superimposition of modal signals generated at the fault location and propagating through three modal channels [11]. The propagation characteristics of the zero or ground channel and the interphase channels are very different from each other (Fig. 1), which can be seen in Fig. 4.

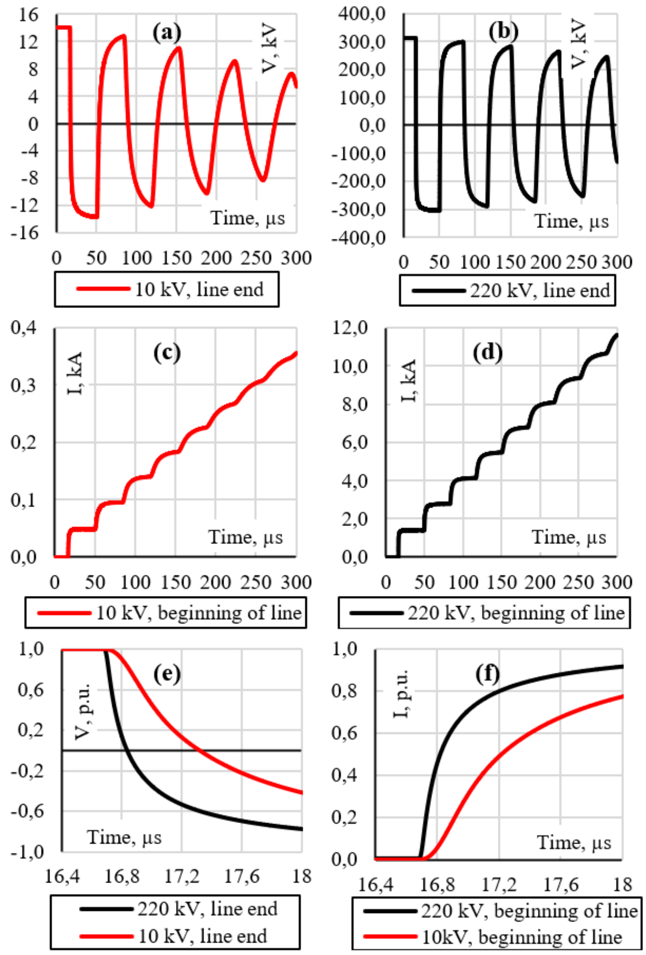

Fig. 3. Time dependences of current and voltage TS in a simple single-phase line for 10 and 220 kV line.

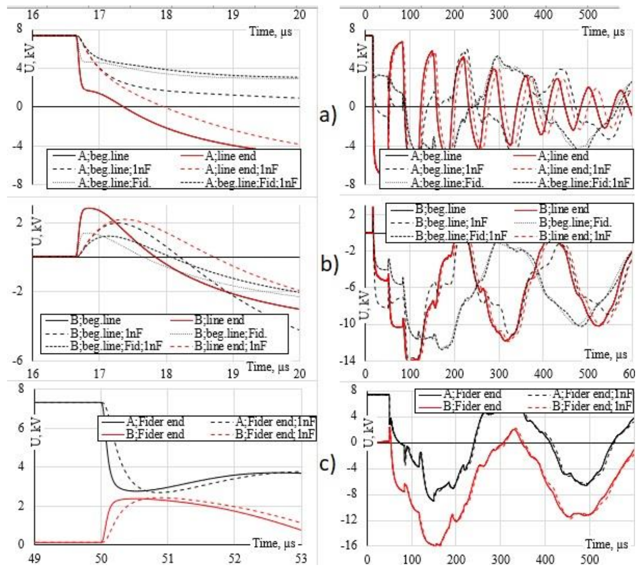

Fig. 4. Time dependences of voltage TS in a three-phase line.

The consideration of the concentrated capacitance (in Fig.4a "A;beg.line;1nF" and "A;line end;1nF") of the isolating elements on the substation busbars with the value of 1 nF leads to a significant reduction of TW leading edge's slope. This is a source of TWFL measurement errors. Consideration of the wave impedance of the adjacent feeder departing from the supply substation buses according to (2.1) leads to a decrease in the TW reflection coefficient (in

Fig. 4a "A;beg.line;Fid"). The total effect on the TW of the insulation capacitance and the adjacent feeder (in Fig.4a "A;beg.line;Fid;1nF") reduces both TW leading edge's slope and the amplitude of its interphase modal component. Fig.4a clearly shows that only the interphase modal channel is able to provide an acceptable TWFL measurement error.

TS in a three-phase line on undamaged phases (Fig. 4b) consists of an antiphase superimposition of modal signals. The amplitude spread of the interphase modal signal is two times smaller than in the damaged phase. The presence of concentrated capacitive inhomogeneities and the adjacent feeder changes the slope and magnitude of TW leading edge similarly as in the damaged phase (Fig.4a).

The amplitude range of the interphase modal signal at the end of the adjacent feeder on the damaged phase is 1.5 times greater than on the busbars of the supplying substation. This indicates the ability of TWFL to monitor all feeders coming from the substation by the complex sensors installed at their ends.

Oscillograms with a large time scale (right side of Fig. 4) illustrate different periods of TS oscillations on damaged (small period) and undamaged (large period) phases. This is explained by the impassability of the fault location node of the damaged phase for TW. This sign should be used to determine the damaged phase. The beginning of TS oscillograms at undamaged phases contains spectral components of oscillations corresponding to the damaged phase. This is due to the influence of the interphase modal signal.

Fig.5 shows the modal signals m_1 and m_0 calculated using the Clark matrix for the reference phase «A»:

$$\begin{cases} U_{m1} = \frac{2}{3}(U_a - \frac{U_b + U_c}{2}) \\ U_{m2} = \frac{1}{\sqrt{3}}(U_b - U_c) \\ U_{m0} = \frac{1}{3}(U_a + U_b + U_c) \end{cases} \quad (2)$$

Figure 5a shows the modal signals m_1 at the beginning and at the end of the line ("m1;beg.line" and "m1;line end"). We can see that the reflection coefficient of these signals is different. The resistance of the end inhomogeneity, in the form of the supplying power transformer, at the beginning of the line is frequency dependent and inductive. The resistance of the end inhomogeneity, in the form of the load power transformer, has insignificant frequency dependence, and its modulus exceeds the wave impedance of the line. Different powers of supply and load transformers determine different values of longitudinal inductance of their substitution schemes. The supply transformer has a small inductance value, the load transformer has a large inductance value. On the line side, the supply transformer with power source is a transverse inductance because the voltage source has a small resistance. The substitution diagram of the load transformer with load represents a transverse inductance with a large active load resistance connected in series, which in this case is equal to infinity.

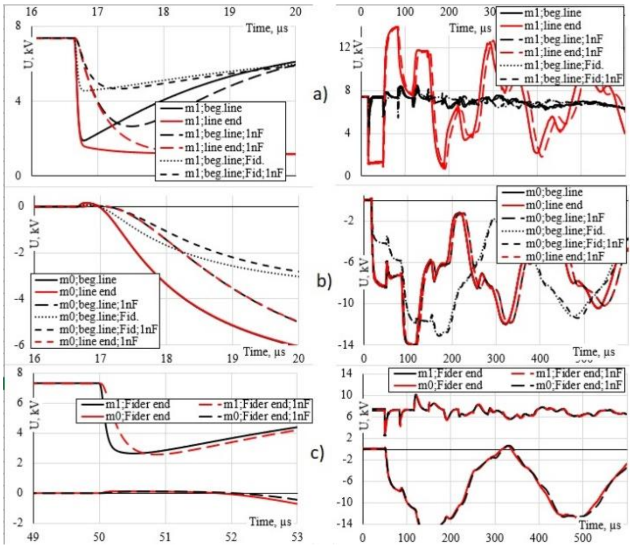

Fig. 5. Time dependencies of modal TS voltage for three-phase line.

Consideration of the insulating elements capacitance on the substation busbars leads to a significant reduction of the TW leading edge's slope in the 1st modal channel ("m1;beg.line;1nF" and "m1;line end;1nF" in Fig.5a). The combined effect of the presence of insulation capacitance and adjacent feeder ("m1;beg.line;Fid" and "m1;beg.line;Fid;1nF" in Fig.5a) on the TW reduces both the TW leading edge's slope and the amplitude spread of its interphase modal component. Fig.5a confirms the higher efficiency of registration of signals of the 1st modal channel on the busbars of load transformers, compared to their registration on the busbars of the supply substation. The pre-emergency value of the 1st modal channel signal is equal to the phase voltage value, which illustrates the fact of power transmission only in interphase channels.

Fig.5a,b,c confirm that the required accurate characteristics of TWFL complexes are guaranteed only by the use of signals of the first modal channel.

IV. Conclusion

Modelling of the current and voltage TW leading edge indicates a greater information value of voltage signals, which is determined by their large amplitude spread relative to the amplitude both before and after the emergency mode.

The experimentally registered TW propagation speed is determined by the time of its registration at a fixed threshold value, which is determined by the slope of the TW leading edge. Therefore, we may use the term "threshold speed". For lines of high voltage class, the TW leading edge slope is higher than in lines of medium voltage class. This is manifested in the frequency dependence of the propagation coefficient and the value of the threshold speed.

The shape of TS for all modelled typical structures of electrical networks is described by a decaying exponent. The period of oscillations in the damaged and undamaged phases to the left and right of the fault differs, which is due to the difference in the reflection coefficients of different modal components of the TW from inhomogeneities of different electrical network structures.

In electrical networks, the busbars of supply and load substations have a significant transverse inhomogeneity of capacitive nature. This concentrated capacitance increases the TW leading edge duration similarly to the distributed line capacitance. This is well explained by the processes of inclusion of the RC-circuit on the DC voltage of the TW step.

The wave impedance of adjacent feeders connected to the busbars of the supply substation reduces the total sum impedance relative to the value of the line wave impedance. This forms a negative value of the TW voltage reflection coefficient. At the busbars of the feeding substation the total registered voltage spread of TS leading edge decreases.

The leading edge of the first modal voltage spread at the end of an adjacent feeder is larger than the same voltage spread at the feeder busbars. This allows to monitor the whole electrical network with fewer TWFL sensors.

The maximum voltage spread of the first modal TW leading edge is registered on the damaged phase. On undamaged phases, the leading edge spread is many times smaller and appears as a spike of opposite polarity than on the damaged phase.

Simulation results show that the small linear length of medium voltage class distribution networks allows for the same time discretization of TS to provide TWFL measurement error equal or even smaller than in significantly more homogeneous lines of high voltage class.

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