Model and experimental research of the transient process for the improvement of the traveling wave fault location

Rustem Khuziashev [1]*, *Iskander* Tukhfatullin[1], *Danil* Smirnov[1], *Iluza* Irkagalieva[1]

[1] Kazan State Power Engineering University, 51 Krasnoselskaya str., Kazan, Russia

Abstract. The results of modeling of transient signals in a single-wire line are considered. The parameters of voltage and current signals are compared. Signal oscillation's amplitude and period are given attention. The algorithm for determining the transient signal's onset time (TSOT) under the conditions of noise and oscillations of the signal's leading edge is presented. The results of experimentally recorded signals' analyses are given.

1 Introduction

The task of fault location in electric grids does not cease to be relevant due to the constant development of computing and communication technology, which allows to develop and implement more and more advanced algorithms for processing the recorded information.

Traveling wave fault location suite (TWFL) implements the measurement of TSOT, which is performed with an error of no more than 1 μs in the satellite-based navigational time scale. In homogeneous networks of a high voltage class, TWFL complexes determine the fault location in lines several hundred kilometers long [1]. For inhomogeneous networks of medium voltage class, the fault location is limited to line lengths of several tens of kilometers [2], which is due to the dispersion's destructive effect in a highly inhomogeneous line.

According to the TS parameters, in [3, 4] it is proposed to determine the correlation between the period of free oscillations and the distance to the fault location. When implementing the TWFL complex in distribution networks, it is important to increase the information value of the recorded signals and reduce the cost of the complex development, the dominant part of which is their software.

1.1 Model research of TS shaping by boundary inhomogeneities

TWFL hardware-software suite determines the place of TS occurrence. The structure of multimodal TS oscillations carries information about both the place of their occurrence and their cause. Without modelling of these processes, it is impossible to understand the mechanisms of TS shaping. The results of TS modeling were obtained with the PSCAD software package [5] in the simplest models of the electric network.

Fig. 1 shows the model of single-wire line with a return earth wire and concentrated capacitance; a source of alternating electromotive force with a 50 Hz frequency at the beginning. At the source of EMF with a phase voltage of 10 kV zero internal resistance is chosen in order to simplify the TS shaping's analysis. The line, 10 km long, is represented by 8 identical segments with distributed parameters of 1.25 km length. Line's wave impedance is 600 ohms.

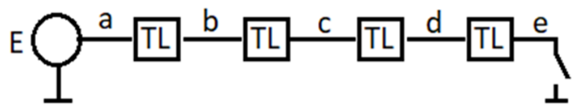

Fig. 1. Model of a homogeneous single-wire line.

Fig. 2 shows a voltage TS recorded in different parts of the line with a time sampling interval of 0.1 μs. At the end of the line a travelling wave (TW) is generated in the form of a voltage step equal to the instantaneous voltage amplitude at the moment of commutation. The TW propagates to the beginning of the line. At the beginning and at the end of the line, the voltage step's TW is reflected with reflection coefficient "-1", which corresponds to the boundary conditions of zero equality of falling and reflected waves' summed amplitudes. The superimposition of a multitude of reflected TW forms a standing voltage wave with nodes at the ends of the line.

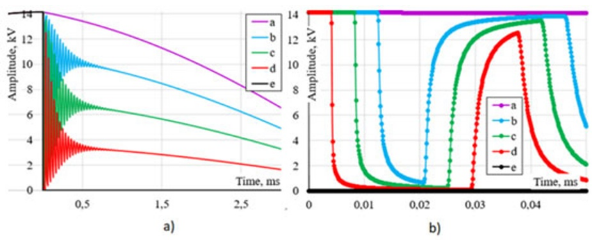

Fig. 2. Voltage TS with large- (a) and small-time scales (b) at different sections of the line. The sampling interval is 0.1 μs.

The oscillation's amplitude spread at TSOT (fig. 2) is equal to the amplitude of the phase voltage at the moment of breaker closure. As the TS amplitude

* Corresponding author: 142892@mail.ru

decreases, the voltage curve tends to become a steady-state emergency oscillation of industrial frequency of 50 Hz. The voltage oscillation amplitude's attenuation constant is 0.3 ms. The shape of voltage TW's leading edge illustrates an increase in its duration by about 1 µs for each kilometre travelled, in accordance with the dispersion effect on the TW voltage step's shape. The oscillation period of 36.2 µs corresponds to travelling twice the length of the line at a speed of 276 m/µs. This speed corresponds to the TW propagation in the ground or zero mode channel in a three-phase line.

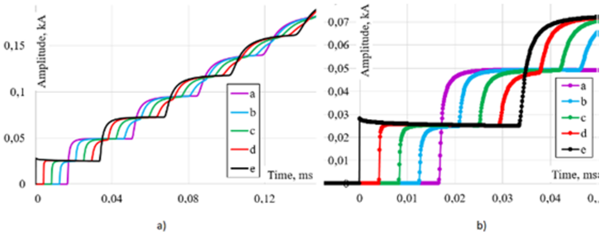

Fig. 3. Current TS with large- (a) and small-time scales (b) at different sections of the line. The sampling interval is 0.1 µs.

Fig. 3 shows a similar current TS. TW in the form of a current step is generated at the switching point and propagates to the beginning of the line. At the beginning and at the end of the line the current step's TW is reflected with reflection coefficient "+1", which corresponds to the boundary conditions of zero equality of falling and reflected waves' summed amplitudes. The superimposition of a multitude of reflected TW forms a rising standing current wave, which reaches a maximum value of 2 kA in 3 ms after the breaker closure. Current oscillation amplitude step spread for the line shown in fig. 1 on TSOT is equal to the ratio of the phase voltage to the value of line's wave resistance and is numerically equal to the value of 25 A.

It is the current TW's initial step that determines its onset time. Comparison with the voltage's initial step (fig. 2) indicates the advantage of voltage signals relative to current signals at the simplest threshold algorithms for determining the TSOT. This is due to the significantly leading edge's larger amplitude spread of the voltage signal compared to the current signal.

The TS shaping's research on the segment between the breaker's location and the end of the line is carried out (fig. 4).

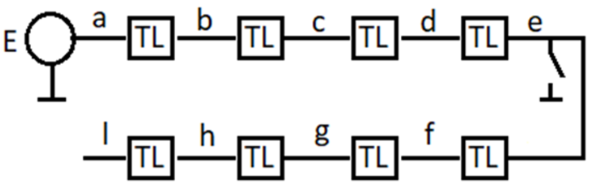

Fig. 4. Model of a single-wire line with a closing breaker in the middle of the line.

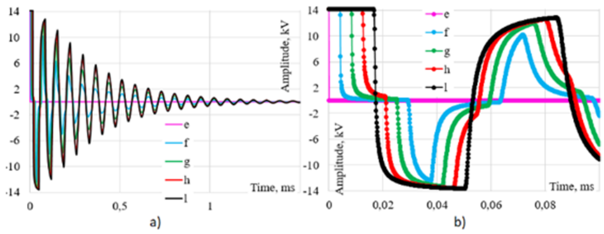

Fig. 5. Voltage TS with large (a) and small time scales (b) at different sections of the line.

The TS caused by breaker closure starts at the zero moment of time and causes zeroing of the voltage in node "e" (fig. 4, fig. 5). In this node a travelling wave (TW1) of negative polarity is formed with amplitude equal to the pre-fault value, propagating to the both line's ends (fig. 5b blue line - node "f", green line - node "g", red line - node "h", black line - node "l"). Upon reaching the end of the line with high impedance, TW1 is reflected with the coefficient "+1" and forms a reflected wave (RW1) of the same polarity, propagating to the short-circuit point. At the place of reflection, the amplitude spread of falling and reflected waves' sum is doubled. The further process of travelling and reflected waves' shaping is similar to the previously discussed one in fig. 3. The TS formed as a result of reflected waves' superimposition has free oscillations' period twice as long as the analogue period from fig. 1 for the signal to the left of the short-circuit location.

1.2 Model research of TS shaping by intermediate inhomogeneities

Equivalent circuit of all electric power facilities includes a parallel connection of complex impedances with a significant active component and a capacitor between their terminal leads having a non-zero area. According to the parameters used in the calculation models, the parasitic capacitance of the equipment is estimated to be 0.3-0.6 nF, the winding capacitance of a 220 kV autotransformer is approximately 2.7 nF, the capacitance of a plate insulator is 50 pF, and the capacitance of a reference pin insulator is 1-5 pF [6].

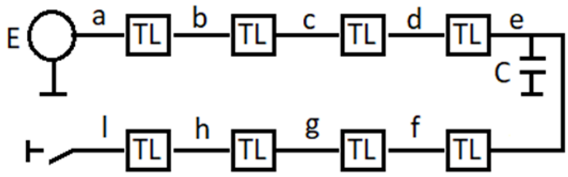

Fig. 6. Model of a single-wire line with concentrated inhomogeneity in the middle of the line.

At the initial moment of time the reflection of voltage step's TW from the capacitor occurs as from an inhomogeneity with zero resistance. This is due to the large charge current drawn by the capacitor at the initial moment of time. As the capacitor is charged, its resistance tends to infinity. Fig. 6 shows a diagram of a 10-kilometre single-wire line in the middle of which a capacitor with a variable capacitance is installed.

Fig. 7 shows the oscillogram of the voltage step's TW at node "f". TW has travelled the distance from node "l" to node "f" equal to 3.75 km in 12.4 µs, which is close to the speed of light. The wave reflected from the capacitance is registered at node "f" in 20.7-12.3 =8.4 µs, which corresponds to running a double distance from node "f" to node "e" and back from node "e" to node "f". The reflection coefficient is "-1", and the polarity of the reflected signal is similar to the situation illustrated in fig. 2.

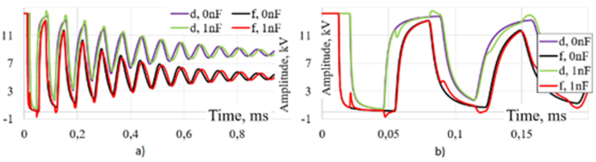

Fig. 7. Voltage TS with large- (a) and small-time scales (b) at different line sections with capacitor type inhomogeneity.

After 45.8-20.9=24.9 µs, a small wave was registered, which ran a distance of 1.25*6=7.5 km (from "f" to "l" and from "l" to "f") with a speed of 7.5/24.9=0.309 km/µs, and only after 52.3-12.3=40 µs, the main wave was registered, which ran 12.5 km (corresponding to the double running time from "f" to "a"). The decreasing distance between the TS registration point and the subsequent inhomogeneity is able to generate an oscillatory process at the TW's leading edge. This feature can be used in the machine analysis of the registered oscillograms, to determine the place of commutation inside or outside the area controlled by the TWFL complex. The decrease in TS amplitude even for a single inhomogeneity in the form of capacitance can be clearly seen. Increasing the number of inhomogeneity nodes will cause a proportional weakening of TS. The presence of an inhomogeneity in the form of a capacitor with a capacitance of 1 nF causes the appearance of high-frequency mode oscillations at the beginning of TS and a decrease in the frequency of low-frequency mode oscillations by about 1.5%.

Fig. 8 shows a diagram of a single 10-kilometre line with a branch of varying length connected to the middle of the line.

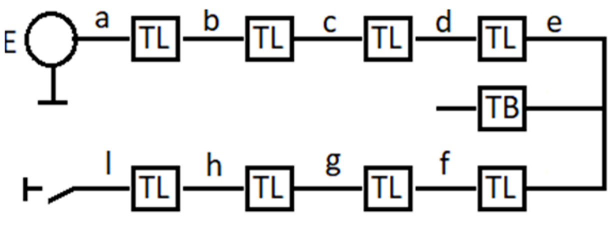

Fig. 8. Model of a simple single-wire line with a branch in the middle of the line.

Fig. 9 shows the TS oscillograms with large- and small-time scales, which clearly depict the effect of the branch on the parameters of the generated TS in comparison to its absence. A branch of any length causes the formation of high-frequency mode oscillations at the beginning of TS and an increase in the period of the dominant low-frequency mode oscillations throughout the TS's duration. The increase in period duration is 1.5 per cent for a 0.1 km branch, 10 per cent for a 1 km branch, and 100 per cent for a 10 km branch. The presence of a branch causes TS amplitude overvoltage relative to the normal phase voltage. Overvoltage's value depends on the ratio of branch length, line length and fault location.

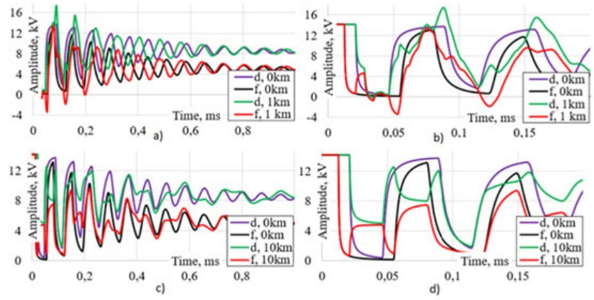

Fig. 9. Voltage TS with large- (a) and small-time scales (b) at different line sections with inhomogeneity of branching type with length of 1; 10 km.

2 Algorithm for determining the onset time of experimentally recorded TS

Fig. 10 shows typical shapes of experimentally recorded voltage TS's leading edge. The presence of oscillations with different polar amplitudes on the TS's leading edge, as shown in the previous sections, is explained by the inhomogeneous structure of the voltage step's TW propagation channel. These oscillations increase the error in determining the TSOT by threshold methods [7], two threshold methods with linear approximation to zero [8,9] and statistical methods based on high-order central moments [10, 11, 12]. Under conditions of lightning overvoltage, the amplitude of noise oscillations caused by streamer formation increases, which increases the error in determining the TSOT.

To illustrate the occurrence of the error in determining the TSOT by the statistical method based on the kurtosis function [11, 12], fig. 11a shows TS normalized to the maximum amplitude (fig. 10c, d) and calculated dispersion and kurtosis functions on the time window from the beginning of the oscillogram to the current value of the time series. We can see that statistical method for determining the TSOT requires the use of a non-zero threshold, the value of which decreases as the order of the central moment increases. The value of the threshold depends on the TS's noise value (fig. 10a, c), which is comparable to the amplitude of oscillations. Significant value of statistical method's threshold applied to the original TS causes an error in the determination of the TSOT (fig. 11a).

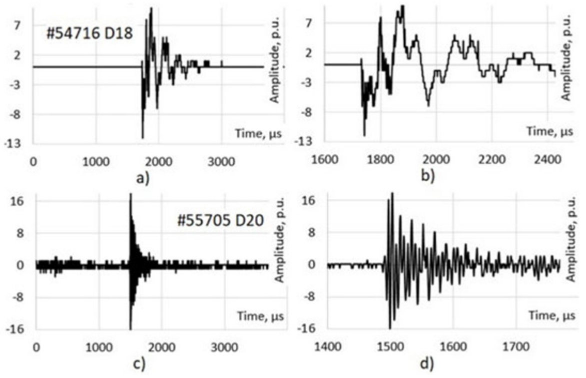

Fig. 10. Experimentally recorded TS with different shapes of leading edges. TS are depicted with large- (a, c) and small-time (b, d) scales.

In order to reduce the error of TSOT determination, an algorithm of TS's envelope construction was developed on the basis of replacement of instantaneous amplitudes by its modules, smoothing of emissions and dips of instantaneous amplitude without changing their polarity, smoothing of dips caused by oscillatory change of instantaneous amplitudes' polarity. This allowed us to approximate the TS's leading edge by a monotonic dependence and to reduce the number of noise emissions (fig. 11b).

The statistical functions of the second- and fourth-order central moments and the second-order initial moment were applied to the obtained envelope. The application of a zero threshold to the increments of these functions indicates the advantage of using the second-order initial moment from the TS envelope. The error of TSOT determination by competing functions is equal to 2 µs.

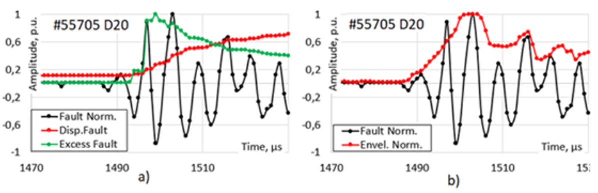

Fig. 11. Illustration of the algorithm for determining the TSOT based on the calculation of its envelope when the leading edge oscillates in the presence of noise.

When the number of noises is small (fig. 10 a-b), the second-order advantage of the initial moment vanishes, and all competing functions show the correct TSOT definition.

3 Conclusion

Medium voltage class distribution networks are significantly inhomogeneous. TS is shaped by superimposition of many reflected TW. All reflected TW in electrical network are formed by large and small inhomogeneities. Large inhomogeneities include the end and the beginning of the line. Small inhomogeneities include capacitances of substitution schemes of concentrated elements of electric power facilities (insulators, transformers) and nodes of branch connections. A three-phase electric line has three mode channels of TW propagation. Therefore, at TS registration point there is a superimposition of TW propagating in different mode channels, which greatly complicates the analysis. The paper demonstrated the mechanisms of TS shaping in a simple single-wire line, which is a substitution scheme of the ground mode channel of a three-phase line.

Model results indicate that the maximum voltage TS's spike is equal to or greater than the normal phase voltage of the line. The maximum current TS's spike is much smaller than the load current spike. This indicates the advantage of voltage TS's recording. Since standard voltage transformers have a smaller frequency bandwidth than standard current transformers, it is recommended to use input circuits based on capacitive dividers for TS recording.

This reduces the value of fault location methods based on TS period measurement.

The modelled TS shapes in the presence of a concentrated inhomogeneity indicate the occurrence of high-frequency mode oscillations at the beginning of the TS and an increase in the period of low-frequency mode oscillations proportional to the magnitude of the capacitance of the concentrated inhomogeneity or the length of the branch.

In order to reduce the error of TSOT calculation under the oscillatory nature of its leading edge and in the presence of noise, an algorithm based on TS envelope determination was developed.

References

1. Lvov A, Pinchukov P. Optimisation of search for fault locations of 220 kV overhead power lines located in the territory of the Republic of Sakha (Yakutia) using wave TWFL. // Electricity. Transmission and Distribution, **№S1(28)**, 2023, P.44-48.
2. Feoktistov A. V. Technical solutions for determination of the damage places in the distribution networks 6-35 kV. // Electricity. Transmission and Distribution, **№6(69)**, 2021, P. 94-95.
3. Kachesov, V.E. Method for determining the single-phase fault zone in distribution networks under operating voltage. // Electricity. 2005. **№ 6**. P. 9-18.
4. Shuin V.A., Filatova G.A. et al., Information parameters of electrical transient values for determining the ground fault location in distribution cable networks with voltage 6-10 kV. // Bulletin of ISPEU. **№2**, 2017, P.34-42.
5. PSCAD [Electronic resource] // URL: https://www.pscad.com (date of address: 10.09.23).
6. PAO "ROSSETI" STO 56947007-33.060.40.052-2010. Guidelines for the calculation of parameters and the selection of high-frequency carrier circuits for AC power lines of 35-750 kV. 2010. p. 143.
7. Dichev N.V. et al., Method for determining the time position of a slow-increasing echo impulse. // Bulletin of TPU. **№4**, 2010, C.146-149.
8. Soldatov A.I., Sorokin P.V., Makarov V.S., Determination of the temporal position of the acous-

tic pulse by approximation of the signal envelope. // Bulletin of SFedU. - Technical Sciences, **№ 10**, 2010, P. 178-184.

9. Schweitzer E.O., et al. Locating faults by the traveling waves they launch. // Proc. 67th annual conference for protective relay engineers. March 2014, P. 95-110.
10. Patent 2660403 Russian Federation, (06.07.18). Method of thresholdless automatic intellectual registration of acoustic emission signals by a nondestructive testing device. / Barat V.A., Shimansky A.G.
11. Lachugin, V.F.; Panfilov, D.I.; Smirnov, A.N. Implementation of the traveling wave fault location on power transmission lines using statistical methods of data analysis // Izvestia RAN. Energetika. **№ 6**, 2013, P.137-146.
12. Podshivalin, A.N. Research of kurtosis coefficient's properties for the purpose of the traveling wave fault location in transmission lines. // Relay protection and automation. №1, 2023, P.51-57.