Fault Location with Increased Reliability for Overhead Transmission Lines

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Abstract. The double-ended traveling wave (TW) method is a promising tool for fault location on transmission lines. It implies that high-frequency transients during fault inception are recorded in specific devices, which identify the precise time, when a front of an electromagnetic traveling wave reaches the corresponding end of the transmission line. The principles of operation, methods of calculations and test data of the developed traveling wave FL (TWFL) system are presented. The results of field tests and experience of operation of the TWFL system on the double-circuit 220 kV Tommot-Maya transmission line including short-circuit faults caused by lightning strikes are discussed.

1 Introduction

Accurate localization of a fault on a transmission line is may significantly reduce the time spent for restoration of a line after an emergency outage. There are various methods of fault location, but the traveling wave method based on measurements of the time of electromagnetic wave propagation along the overhead line from the fault location to each of the ends of the transmission line is known for the highest accuracy.

This method differs from the other methods by the fact that it uses information from the waves originating at the fault location on the transmission line, not yet distorted by the waves reflected from the node points of the network. The distance l from the fault location to one of the line ends (line length L) when using the TWFL method of double-ended measurements is determined by the expression [1]

$$l = \frac{L}{2} - \frac{t_2 - t_1}{2}v = \frac{L}{2} - \frac{\Delta t}{2}v \,,$$

where t_1 and t_2 are the timestamps of arrival of the electromagnetic wave front to each end of the transmission line, respectively, v is the propagation velocity of the electromagnetic wave.

2 TWFL Principles, Calculation Methods and Laboratory Tests

In the proposed method, time-synchronized (using a satellite global navigation system) instantaneous values of transmission line voltages or currents in a system of independent modal channels are processed [2]. To fix the time of wave front arrival, the method of mathematical statistics is used, which allows calculating the coefficients of excess [3] for electromagnetic wave signals in interphase modal channels of a damaged transmission line by the expression

$$K_E = \frac{\mu_4}{\sigma^4} - 3 \,,$$

where μ_4 and σ are the fourth and second central moments of the statistical distribution, respectively, defined as

$$\mu_4 = \frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^4 \,,$$

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2 \,,$$

where x_i is the signal under study, and $\bar{x}$ is the arithmetic mean value, n is the number of signal

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samples, chosen in accordance with [6] and actually accepted equal to 800.

In the absence of a transient (before the appearance of the wave front), the controlled signal (e.g. voltage drop of the incident wave, in relative units) is close to a normal distribution, so the value of the kurtosis coefficient will be at the level of zero. In the presence of a transient process, in particular caused by the occurrence of a short-circuit, the kurtosis increases sharply. This allows to determine quite accurately the fact of the wave front appearance in the points of its control [4-6] and to provide tuning of the TWFL system from interference [7]. Fig. 1 shows the dependencies characterising the change in the kurtosis coefficient for a single-phase earth fault that occurred on a 220 kV power line at a distance of 40 km from the control point.
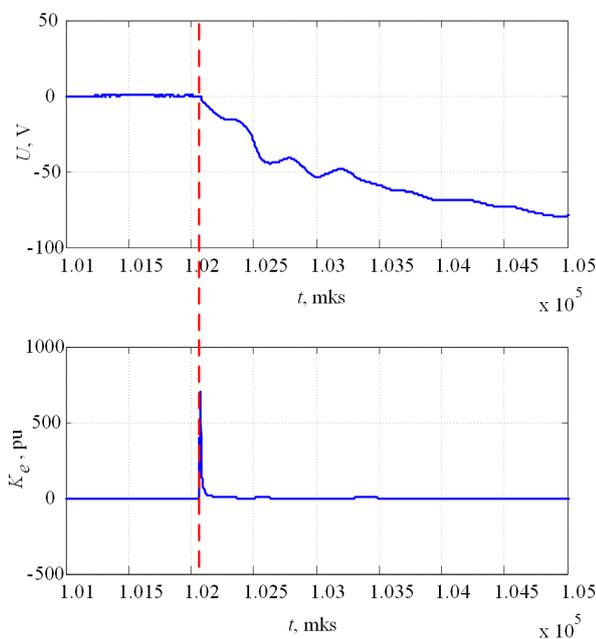

Fig. 1. Determining the timestamp of a wavefront using the kurtosis coefficient

On the basis of the proposed method, a TWFL system [8] was designed for FL on 110-750 kV overhead lines. It implements the transition from the devices used individually for each line, responding to the wave transient currents in each overhead line, to a system of devices in which the measurement of the wave voltage on the busbar system of the switchgear with a possibility to locate a fault on any transmission line of this busbar system [7]. In this regard, one TWFL device controls not one, but all lines connected to this busbar system, which leads to a significant reduction in the total number of devices used in the electrical network, and reduces the cost of transmission

companies spent for installation and operation of a TWFL system.

In the developed algorithm of the TWFL system, the superimposed values of interphase voltage components on the switchgear busbars are identified, the time of arrival of the front of these components at each line end is synchronously recorded, and the process of calculating the distance to the fault location is started only on the damaged transmission line after the operation of its selective protection. The use of interphase wave voltage allows increasing the accuracy of the TWFL system, since the degree of deformation of the wave front in the inter-phase channel [2] when propagating from the location of a short-circuit to the point of installation of the TWFL device is significantly lower than that of the phase and zero components.

To study the efficiency of the TWFL system, a model of the electrical network was created, taking into account the presence of elements directly affecting fast transients during short-circuit (transmission lines, voltage transformers, coupling capacitors and high-frequency barriers) [9]. During the calculations, the distance to the fault location, the types of faults and the value of the transient resistance at the fault location were varied. The busbar systems with the largest number of overhead lines, where the wave voltage is minimal, were considered as the design ones.

For the laboratory tests of the TWFL system, a test bench [9] was developed, including a computer and a generator of arbitrary waveform signals, simulating the transient voltage during short-circuit faults on transmission lines. The computer was loaded with a database of files of calculated test signals containing arrays of instantaneous values of voltages at the locations of the TWFL devices for different types and locations of short-circuit faults. During the tests, the terminals of the TWFL system communicated within a local network and synchronized to a satellite navigation system independently. The type of fault, place of short-circuit, instantaneous values of the voltage preceding the short-circuit, as well as the values of transient resistances in the location of a short-circuit were varied. The tests showed that in the case of a fault on 330 kV overhead line, the error of the TWFL system did not exceed 0.3 km, being within the span length of the power line.

3 Results of Field Tests and Operating Experience

A two-circuit 220 kV Tommot-Maya transmission line located in the Republic of Sakha (Yakutia) was

selected as the object of field tests. The devices of the TWFL system were connected to inductive voltage transformer (VT) installed on the 220 kV busbar of Tommot and Maya substations. The length of the double-circuit 220 kV line Tommot - Maya [9] is 434.7 km. In the course of field tests, two experiments of single-phase earth faults were performed - through a metal support and in the middle of the span between the supports of the first circuit (through a specially cut down pine tree installed under the first circuit), while maintaining transit on the second circuit. In the first experiment the error of the TWFL system on the side of the Tommot substation was 570 m and on the side of the 220 kV Maya substation - 626 m, and in the second experiment - 268 m and 314 m, respectively. At the same time, the error of the TWFL devices operating on this transmission line, reacting to the parameters of the industrial frequency, reached several kilometers.

After completion of field tests, the TWFL system was put into pilot operation on both circuits of 220 kV Tommot-Maya transmission line. During operation, several short-circuits caused by lightning overlaps of the transmission line suspension insulators were recorded, which was confirmed by the data of the transmission line bypass. The high probability of lightning outages is consistent with the general statistics of outages in this region [10]. The short-circuit outages occurred without significant damage, with traces of overlaps visible only upon close inspection. Inspection of all insulators on 1287 poles of the Tommot-Maya 220 kV transmission line is very difficult, so an accurate solution of the TWFL problem is highly relevant.

Table 1 presents the performance of the TWFL system for short-circuit faults on the Tommot-Maya transmission line. They show a significantly higher accuracy of the TWFL system [11] compared to the phasor based devices [12] installed on the same transmission line.

According to the operational data [10], the time of fault location search on this transmission line after installation of the developed TWFL system was reduced from one week to one day. This indicates the significant contribution of the TWFL system in improving the reliability of power supply to consumers by reducing the time of restoration of the 220 kV power network in conditions of difficult climatic conditions and undeveloped transport infrastructure. All short-circuits presented in the table occurred during thunderstorms. Therefore, it was important to assess the noise immunity of the TWFL system in these modes.

In the No. 1 case there was no increase in the level of interference immediately before the short-circuit in the recording, as well as during the field tests, in contrast to the No. 2 - 4 cases. At the same time, the duration of interference preceding the short-circuit counted from several hundreds of microseconds to several milliseconds. In particular, on the basis of the analysis of the data in Fig. 2, corresponding to the No. 4 case, it was determined that the value of the excess coefficient at the beginning of the flashover effect is not more than 15.1, and then increases to 117.3 after the short circuit occured, which is quite sufficient to ensure reliable selftuning of the TWFL system from the interference of a lightning and ensure high sensitivity to the wave front caused by a short circuit. Similar results were obtained when analysing the disturbances corresponding to other cases of short-circuit faults under consideration.

Table 1. Operation results of a TWFL system for short-circuits on a transmission line

No	Date, time	Actual distance to fault, km	FL by phasors, km	TWFL, km	TWFL error, km	Interference
1	22.05.2022 17:50:06	61,8	57,9	61,0	0,8	No
2	03.07.2022 18:41:44	314,4	335,9	314,1	0,3	Yes
3	03.07.2022 21:41:35	210,9	212,1	208,2	2,7	Yes
4	03.08.2022 12:36:34	181,5	182,4	181,3	0,2	Yes

Consequently, the TWFL system retains its functional reliability under lightning disturbances, not caused by the fact of a short-circuit, providing the calculation of the distance to the fault location only after the formation of the short-circuit channel.
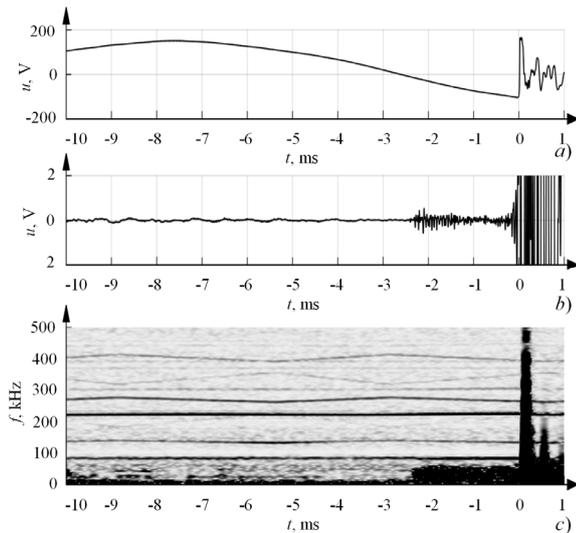
Fig 2. Development of the transient process before the short-circuit accompanied by lightning disturbances: *a)* - voltage signal measured by the VT; *b)* - voltage signal after filtering of the fundamental frequency component; *c)* – spectrogram of the voltage signal

4 Conclusions

1. The transition to a double-end TWFL system with terminals connected to the busbar VT reduces the total number of WFL devices in the electrical network and their maintenance costs.

2. The results of tests and operating experience on 220 kV Tommot-Maya transmission line, including thunderstorm disturbances, confirmed the high accuracy and reliability of the developed TWFL system. The algorithm determines the distance to the fault location on the basis of statistical method, adjusted for the impact of interference, not associated with the occurrence of short-circuit.

3.The developed TWFL system provides the increase of operational reliability of the high-voltage power network by reducing the mean time spent for the search of the actual fault location on long transmission lines from one week to one day.

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