Article

Research on Fault Location of Distribution Lines Based on the Standing Wave Principle

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Abstract: Aiming at the fast and accurate location of a single-phase ground fault in the distribution network, a single terminal injection signal location method, based on the standing wave principle, is proposed. Firstly, the double conductor standing wave principle formation, based on uniform transmission line theory, is analyzed, and the mathematical model of the fault distance algorithm is established. Secondly, a fault detection circuit is built by simulation, and the distribution trend of the standing wave and its relationship with unit capacitance and unit inductance are studied. By setting the source signal frequency and detection point interval and other parameters, the fault location of this method under direct grounding fault and through grounding resistance fault is simulated and studied. Finally, the fault distance is calculated and located by an experiment. The results show that the positioning accuracy is high, which verifies the effectiveness of the standing wave positioning method.

Keywords: single-phase earth fault; fault location; detecting point; accurate positioning

1. Introduction

At the end of the power system, the distribution network plays the function of transmitting electrical energy to the end-users. The network topology and load distribution of the distribution network are complex [1]. Among the fault types of distribution networks, single-phase grounding faults account for more than 80% of all faults [2]. Therefore, it is necessary to study the fault location method to locate the fault location accurately, quickly troubleshoot the fault, and improve the safety and quality of power consumption.

Previous literature [3] proposed a fault location method for distribution networks based on the active component of zero sequence current. The disadvantage of this method is that the active power component in the system is weak, which can easily lead to misjudgment.

Previous literature [4] aimed to predict the high-frequency periodic signal before the arrival of the traveling wave head, based on integrated moving average autoregressive model (ARIMA); combined with the real waveform of the arrival time of the wave head, the waveform residual was obtained; the accurate arrival time of traveling wave head was determined by the difference of residual stationarity before and after the arrival time of traveling wave head, so as to realize traveling wave fault location.

Reference [5] proposed a fault location method based on synchronous squeezed wavelet transform (SWT). SWT is used to extract the fault traveling wave wavelet ridge and generate a set of intrinsic mode-like function components (IMTS). The IMTS was transformed by the Hilbert transform to extract the fault point feature, and then, the arrival time of the first wave head was calibrated. The fault distance was calculated according to the principle of two-terminal ranging.

Reference [6] proposed a fault location scheme using network topology information and reclosure-generating traveling waves. Based on the topology, the circuit breaker...
closure-generating normal traveling waves (CNTWs) could be analyzed. The circuit breaker reclosure-generating fault traveling waves (RFTWs) contains information on fault position. The difference between the CNTWs and RFTWs, defined as reclosing superimposed traveling waves (RSTWs), was calculated. For RSTWs, their initial traveling waves are detected by wavelet transform. The time difference between the reclosing instant and the arrival instant of the reflected traveling wave of the fault point was employed to calculate the fault distance.

Reference [7] proposed a new fault location algorithm for radial distribution networks employing synchronized distributed voltage traveling wave (TW) observers. The influence of power system components on traveling wave propagation was studied, and a fault location method for a heavy branch radial distribution network was proposed.

Reference [8] proposed a novel FL scheme by utilizing the information of the time differences of arrival (TDOAs) of modal traveling waves (MTWs) asynchronously sampled in the network. The fault area was determined by searching the minimum TDOA of MTWs. By applying the fictitious fault point method in the fault area, the minimum accumulated difference was used to detect the fault line. The accurate FL was estimated by solving the objective function of the absolute distance between the FL and multiple FL candidates.

Reference [9] proposed a traveling wave-based fault location method. Before the fault occurred, an intrinsic distance difference matrix (IDDM) was established based on the characteristics of traveling wave propagation and the topology of the distribution network. After the fault, the initial fault traveling wave signals were decomposed into several intrinsic mode function (IMF) signals by variational mode decomposition (VMD), and the first IMF signal was analyzed by the Teager energy operator (TEO) to determine the arriving time of initial fault traveling waves.

Reference [10] proposed a new traveling wave fault location algorithm for hybrid lines based on the time difference method. The algorithm used the absolute time difference of traveling waves to calculate the faults in any section. Then, the traditional wave velocity normalization algorithm was extended to the mixed connection of a multi-section cable and overhead line, which was calculated by fixed wave velocity and time difference.

In reference [11], the PCA-SVM model was constructed by using principal component analysis (PCA) and a support vector machine (SVM), the curve cluster characteristics of the fault current traveling wave were extracted, and the fault section was divided and defined as a cut set. Then, the fault location function was constructed by forward and reverse voltage traveling waves, the distribution characteristics along the sudden change points of traveling waves were extracted, and the invalid sudden change points were removed according to the amplitude and polarity of the sudden change points and the relationship between time window and line length, so as to realize the accurate fault location of the radial distribution network.

Reference [12] studied the traveling wave transmission mechanism of a distribution network with a single-phase distribution branch after a single-phase grounding fault, including phase mode transformation, transmission speeds with different moduli, and transmission characteristics at the boundary of the single-phase distribution branch. On this basis, an accurate fault location method was proposed to determine whether the fault was located in a single-phase distribution branch or three-phase distribution branch, according to the transmission time difference of the line mode and zero-mode components.

Reference [13] proposed a single-ended fault traveling wave location technology based on bus disturbance signal. After a permanent single-phase grounding fault occurred, the non-fault phase bus was grounded through resistance, an effective line mode component was selected according to the traveling wave transmission principle, and the fault distance was calculated by measuring the time difference between the arrival time of the reflected traveling wave of the line mode component and the generation time of the disturbance signal.

Reference [14] proposed a technique based on synchronized measurements in distribution networks; a fault location method based on the analysis of the energy of the transient
zero-sequence current in the selected frequency band (SFB) was proposed. The equivalent impedance of the distribution network with lateral branches was studied with an equivalent network, and the phase-frequency characteristics of the equivalent impedance were analyzed. The SFB, within which the transient energy of the faulty line section is larger than that of the healthy line sections, was determined.

Reference [15] proposed a novel dc pole-to-pole short-circuit fault location algorithm for complex dc distribution networks. According to the high-frequency transient current loops, this paper constructed the high-frequency impedance equivalent models of a module multilevel converter (MMC) and dc/dc converter. High-frequency transient voltages of sparse measurement points were extracted by a wavelet transform to form the node high-frequency transient voltage equation. The node high frequency transient current sparse vector was solved to locate the fault position by the node high-frequency transient voltage equation, combined with the Bayesian compressed sensing (BCS) theory.

Reference [16] proposed a new method for fault location of medium voltage flexible DC distribution lines based on the slope of the transient current waveform. This was achieved by analyzing the transient characteristics of a unipolar grounding short-circuit fault and bipolar short-circuit fault in the time domain. For different fault types, the tangent slope of the fault transient current waveform at both ends of the line was used to solve the fault distance.

In reference [17], by further analyzing the waveform characteristics of transient zero sequence current, it was found that its concave-convex characteristics contain fault information that can be used for location. The VMD algorithm was used to extract the effective components that could characterize the concave-convex characteristics of transient zero sequence current, and a peak valley algorithm was proposed to characterize the concave-convex characteristics of effective frequency components. According to the characteristic that the number of bumps on both sides of the fault point is greatly different and the initial bumps are opposite, while the number of bumps on the same side of the fault point is roughly equal and the initial bumps are the same, a fault location criterion based on kurtosis and initial bumps was constructed.

Reference [18] proposed an adaptive convolutional neural network (ACNN)-based fault line selection method for a distribution network. This method improved the feature extraction ability of the network by improving the pooling model. On this basis, the secondary fault location was identified using the principle of two-terminal.

Reference [19] proposed a novel fault location method for HVDC transmission lines by considering the double-end unsynchronized, using the Hilbert–Huang transformation and one-dimensional convolutional neural network (1D-CNN). After the fault signal was collected at both ends, the high-frequency components of the double-terminal fault signals were connected in series to make a characteristic waveform. This waveform contained characteristics of different fault types and distances, which could be learned by the CNN. The trained CNN could then be used to identify fault location effectively.

Reference [20] proposed a deep learning approach without manual feature extraction under big data applications. To this end, in the proposed method, the attention mechanism, the Bi-GRU, and a dual structure network were applied to analyze the current data from different perspectives. Complete information for the fault features was extracted for the fault location.

Reference [21] proposed a method of fault section location by constructing a hierarchical neural network based on multi-source data in the distribution network. The inherent characteristics of various types of 10 kV distribution networks were extracted. According to the inherent characteristics of distribution networks, the fault location models of various distribution networks were obtained; the fault location condition characteristics of each section of the distribution network with a single-phase grounding short-circuit fault were inputted into the corresponding fault location model to judge the fault condition of each section and realize fault location.
Reference [22] proposed a single-phase grounding fault location method for wind farm collector lines using all phase fast Fourier transform (apFFT) spectrum correction and limit gradient lifting (XGBoost). The fundamental phasors of fault voltage and current were obtained by the apFFT spectrum correction method to construct the original feature set. The regression model of single-ended fault location was established by using the XGBoost algorithm, and the importance and ranking of fault characteristics were calculated. The XGBoost fault locator was used to locate the new input mode according to the existing model, and the accurate position of the fault point was obtained.

In the distribution network, the traveling wave method has the problem of difficulty in determining the wave head of the traveling wave, and the traveling wave method requires that the reflected wave head appears at an apparent time for accurate positioning. When it is not obvious, the positioning accuracy is significantly affected. The shortcoming of the method based on the transient signal comparison method is that the duration of the temporary signal is short, which requires the equipment to extract brief fault information quickly and accurately. Although many intelligent algorithms have been proposed, this kind of method needs to collect many samples in advance to train the neural network and has a high requirement for sample data.

At present, the new type of community distributes electricity through buried cables. After the buried cables fail, the system will switch to the backup line to maintain the regular power supply of users. At this time, it is necessary to accurately obtain the fault location through the fault location method and dig out the cable near the fault point to eliminate the fault. On the other hand, after the overhead line power distribution system fails, it will continue to supply power on the standby sideline through the ring network cabinet. The fault location method is used to perform offline processing on the faulty line to determine the location of the fault. Given the above two situations, designing fault location methods to study non-branch distribution networks has important practical significance to solve the problem of buried cables and distribution network systems.

This paper proposes a single-ended injection method based on the standing wave principle, given the above problems. Firstly, the relationship between the voltage amplitude value $|U(x)|$ at $x$ position on the transmission line and the distance $x$ from the point to the fault point is deduced theoretically. Secondly, the specific operation method of two detection points for fault location is determined. Finally, the simulation and experimental study of the proposed method are performed. The experiments show that the proposed method does not need to calculate the time difference, has strong anti-interference ability and small positioning error, and meets the engineering application.

2. Materials and Methods

There is resistance, capacitance, inductance, and conductance everywhere in the actual transmission line. When the wavelength of the working signal is much smaller than the length of the line, the actual line can be simplified or made equivalent to centralized parameter circuit processing. If the signal’s wavelength is comparable to the line length, the transmission line should be regarded as a distributed parameter circuit.

Figure 1 shows the equivalent model of a network circuit of type $\Gamma$ corresponding to a double conductor of length $dx$ [23].
The starting end of the input signal is taken as the reference zero, and a signal with a constant frequency $\omega$ is inputted at the starting point. In Figure 1, the symbol $U(x)$ represents the voltage at the transmission line $x$ relative to the reference point 0, and the unit is V. The symbol $I(x)$ means the current at the transmission line $x$. The unit is A. Divide the transmission line into many micro-segments, $dx$. The symbol $U(x) + dU(x)$ represents the voltage after $dx$ length, and the unit is V; the symbol $I(x) + dI(x)$ represents the current after $dx$ length, and the unit is A. The current and voltage on the line are harmonics with a constant frequency. The symbols $R_0$, $L_0$, $C_0$, and $G_0$ respectively represent the transmission line resistance, inductance, capacitance, and conductance per unit length.

The relationship established by Kirchhoff’s theorem is:

$$
\begin{align*}
-dU(x) &= (R_0 + j\omega L_0)I(x)dx \\
-dI(x) &= (G_0 + j\omega C_0)[dU(x) + U(x)]
\end{align*}
$$

(1)

The wave equation of the transmission line is obtained by omitting high-order small quantities and the differential and by rewriting Equation (1). The wave equation is as follows:

$$
\begin{align*}
\frac{d^2U(x)}{dx^2} &= (R_0 + j\omega L_0)(G_0 + j\omega C_0)U(x) \\
\frac{d^2I(x)}{dx^2} &= (R_0 + j\omega L_0)(G_0 + j\omega C_0)I(x)
\end{align*}
$$

(2)

To solve the second-order homogeneous linear differential equation in Equation (2), the general solution is:

$$
\begin{align*}
U(x) &= A_1e^{-\gamma x} + A_2e^{\gamma x} \\
I(x) &= A_3e^{-\gamma x} + A_4e^{\gamma x} \\
\gamma &= \sqrt{(K_0 + j\omega L_0)(G_0 + j\omega C_0)} = \alpha + j\beta
\end{align*}
$$

(3)

In the general solution, $A_1$, $A_2$, $A_3$, and $A_4$ are all constants, and their values depend on the boundary conditions of the start and end of the transmission line; the symbol $\gamma$ is the propagation constant, $\alpha$ is the attenuation constant, and $\beta$ is the phase shift constant [24].
The current $I(x)$ has the following relationship with $A_1$ and $A_2$ in the derivation process:

$$
\begin{align*}
I(x) &= \frac{A_1 e^{-\gamma x} - A_2 e^{\gamma x}}{Z_0} \\
Z_0 &= \sqrt{\frac{R_0 + j\omega L_0}{C_0 + j\omega C_0}}
\end{align*}
$$

(4)

In Equation (4), the symbol $Z_0$ represents the characteristic impedance of the transmission line. $U(x)$ and $I(x)$ in Equation (3) are decomposed into the incident wave flowing to the load end and the reflected wave flowing to the load. The characteristic impedance is defined as the ratio of the incident wave voltage to the incident wave current at any point or the ratio of the reflected wave voltage to the reflected wave current.

The lossless transmission line refers to the transmission line, with the symbol $R_0$ equal to 0, and the symbol $C_0$ equal to 0, so that the characteristic impedance, $Z_0$, under the lossless transmission line is:

$$
Z_0 = \sqrt{\frac{L_0}{C_0}}
$$

(5)

The characteristic impedance of the lossless transmission line is only related to the distributed inductance, $L_0$, and distributed capacitance, $C_0$, per unit length, which is an actual number. Taking the coaxial transmission line as an example, the calculation formula for the distribution parameter of the coaxial transmission line is:

$$
\begin{align*}
L_0 &= \frac{\mu}{2\pi} \ln \frac{b}{a} \\
C_0 &= \frac{2\pi \epsilon}{\ln \frac{b}{a}}
\end{align*}
$$

(6)

In Formula (6), the symbol $\mu$ represents the magnetic permeability; the symbol $\epsilon$ is the permittivity; the radius of the inner conductor of the coaxial line is $a$; the radius of the outer conductor is $b$. When using other types of transmission lines, the parameter calculation formula for parameter calculation must be referred to.

Combining Formulas (5) and (6) can obtain the impedance calculation formula of the coaxial transmission line, and the characteristic impedance of the lossless coaxial transmission line can be obtained by calculation.

If it is known that the starting signal voltage is $U_1$ and the current is $I_1$, then $x$ is equal to 0; $U(0) = U_1$ is equivalent to $I(0) = I_1$; through simultaneous Formulas (3) and (4), the values of $A_1$ and $A_2$ can be obtained.

$$
\begin{align*}
A_1 &= \frac{1}{2} (U_1 + Z_0 I_1) \\
A_2 &= \frac{1}{2} (U_1 - Z_0 I_1)
\end{align*}
$$

(7)

As in Formula (7), if the boundary conditions at the beginning are known, the values of $A_1$ and $A_2$ can be obtained. The voltage and current at $x$ at this time are transformed into:

$$
\begin{align*}
U(x) &= \frac{1}{2} (U_1 + Z_0 I_1) e^{-\gamma x} + \frac{1}{2} (U_1 + Z_0 I_1) e^{\gamma x} = U_i(x) + U_r(x) \\
I(x) &= \frac{1}{2Z_0} (U_1 + Z_0 I_1) e^{-\gamma x} - \frac{1}{2Z_0} (U_1 + Z_0 I_1) e^{\gamma x} = I_i(x) + I_r(x)
\end{align*}
$$

(8)

In Formula (8), $U_i(x)$ and $I_i(x)$ represent the incident voltage and incident current at position $x$, and the symbols $U_r(x)$ and $I_r(x)$ are the reflected voltage and reflected current at $x$. It can be concluded from Formula (8) that the voltage and current at any position $x$ can be decomposed into incident waves and reflected waves.

If the terminal is taken as the reference point 0, the symbol $x$ indicates the distance from the terminal. When the variable $x$ is equal to 0, it is represented as the load side. Knowing the voltage $U_0$ and current $I_0$ information of the terminal, the coefficients $A_1$ and $A_2$ can also be obtained. The current and voltage at any position $x$ can be decomposed into the incident wave and reflected wave, consistent with the above analysis.
When a short-circuit fault occurs, total reflection occurs at the terminal of the short-circuit fault, and the incident wave and the reflected wave are superimposed to form a standing wave.

To describe the reflection phenomenon quantitatively, the voltage reflection coefficient \( \Gamma(x) \) is used to express:

\[
\Gamma(x) = \frac{U_r(x)}{U_i(x)}
\]  

(9)

The symbol \( U_r(x) \) is the reflected voltage at position \( x \); the symbol \( U_i(x) \) is the incident voltage at position \( x \).

When the terminal is the reference zero point, the reflection coefficient \( \Gamma(x) \) at any point of the lossless transmission line and the terminal reflection coefficient \( \Gamma_0 \) have the following relationship:

\[
\begin{align*}
\Gamma(z) &= \frac{U_r(x)}{U_i(x)} = \Gamma_0 e^{-2j\beta z} \\
U(z) &= U_0^+ e^{j\beta z} (1 + \Gamma_0 e^{-2j\beta z})
\end{align*}
\]  

(10)

In Formula (10), the symbol \( U_0^+ \) is the terminal incident voltage. The voltage at any point \( x \) on the lossless transmission line has the above relationship with the terminal reflection coefficient, \( \Gamma_0 \).

When a direct ground fault occurs, the voltage at the fault point is 0. The incident wave and the reflected wave at the terminal are exactly opposite, and \( \Gamma_0 \) is equal to -1. The voltage value at any position \( x \) in Equation (10) can be simplified to obtain Equation (11):

\[
U(x) = 2jU_0^+ \sin \beta x
\]  

(11)

Since the conductor materials that make up the transmission line are all good conductors, the medium filled in the transmission line is also good, and generally, \( R_0 << \omega L_0 \), \( G_0 << \omega C_0 \) at this time. At this point, the voltage on the lossy transmission line can be approximated as an ideal standing wave.

When a direct ground fault occurs, the amplitude of the voltage along the line satisfies the following relationship:

\[
|U(x)| = |2U_0^+| |\sin \beta x|
\]  

(12)

In Formula (12), the voltage amplitude value at point \( x \) on the transmission line is a periodically oscillating signal with a period of \( \lambda/2 \). The symbol \( \lambda \) is the wavelength of the standing wave, and the calculation formula is as follows:

\[
\lambda = \frac{2\pi}{\beta}
\]  

(13)

The half-cycle of the periodic signal in Formula (12) is a monotonically increasing signal. Within this range, the fault distance can be located by the voltage amplitude values of the two detection points in the half-cycle of the standing wave.

The specific operation of using two detection points for fault location is as follows:

A signal of constant frequency \( \omega \) is inputted at the signal input terminal; the detection point 1 is installed at the signal input terminal; the detection point 2 is installed at a distance \( d \) from the detection point 1. The distance between detection point 1 and the fault point is \( x \), and the distance between detection point 2 and the fault point is \( x-d \). The voltage amplitude of detection point 1 is \( |U(x)| \), the voltage amplitude of detection point 2 is \( |U(x-d)| \), and the following equation is established using the ratio of the voltage amplitude of the standing wave, according to Formula (12):

\[
\begin{align*}
\frac{|U(x-d)|}{|U(x)|} &= \frac{2|U_0^+| |\sin (\beta (x-d))|}{2|U_0^+| |\sin (\beta x)|} = \frac{\sin (\beta (x-d))}{\sin (\beta x)} \\
\beta &= \omega \sqrt{L_0C_0}
\end{align*}
\]  

(14)
In Formula (14), the voltage amplitude values detected by detection point 1 and detection point 2 are known, and the interval between the two monitoring points is known. The transmission line parameters $L_0$ and $C_0$ can be calculated by Equation (6). The frequency $\omega$ of the source signal input at the beginning is known, and there is only an unknown quantity that can be solved.

The solved $x$ is the estimated value of the actual distance; the symbol $x$ represents the estimated distance from the input terminal to the fault point after calculation.

Suppose the actual situation allows only one detection point to be installed. In that case, the method of inputting multi-frequency signals through one detection point can be used to detect the fault for the purpose of achieving the fault location.

The specific operation of using only one detection point for fault location is as follows:

When a direct ground fault occurs, the input terminal provides signals with stable frequencies $f_1$ and $f_2$, respectively, and the following formula can be obtained, according to Formula (12):

$$
\frac{|U_1(x)|}{|U_2(x)|} = \frac{2U_0^+ |\sin(2\pi f_1 \sqrt{L_0C_0} x)|}{2U_0^+ |\sin(2\pi f_2 \sqrt{L_0C_0} x)|} = \frac{|\sin(2\pi f_1 \sqrt{L_0C_0} x)|}{|\sin(2\pi f_2 \sqrt{L_0C_0} x)|} \tag{15}
$$

In Equation (15), $x$ is the distance from the input terminal to the fault point. The symbol $|U_1(x)|$ represents the voltage amplitude detected at the detection point at the frequency $f_1$; the symbol $|U_2(x)|$ represents the voltage amplitude detected at the detection point at the frequency $f_2$. In Formula (15), other variables are known, and there is only one unknown quantity so that this unknown quantity can be solved.

In addition, the frequency $f$ should be adjusted to satisfy the following relationship to make half of the period of the standing wave voltage amplitude appear on the line of length $L$.

$$
f \leq \frac{1}{4L\sqrt{L_0C_0}} \tag{16}
$$

The symbol $L$ represents the total length of the cable.

When the fault is a fault with a fault resistance, part of the energy transmitted by the signal source is absorbed by the fault resistance at the terminal, and the other part is reflected back. There are both traveling-wave components and standing wave components on the transmission line. At this time, the line is in the state of a traveling standing wave, that is, the working state of partial reflection.

When a grounding resistance fault occurs, with the terminal as a reference point 0, the same conditions are set as in Equation (14). When a grounding resistance fault occurs, the voltage amplitude at $x$ on the transmission line has the following relationship with the variable $x$:

$$
|U(x)| = |U_0^+| \sqrt{1 + |\Gamma_0|^2 + 2|\Gamma_0| \cos(2\beta \times x + \phi_0)} \tag{17}
$$

In Equation (17), the symbol $|\Gamma_0|$ is the modulus of the terminal reflection coefficient. The symbol $\beta$ is the phase shift coefficient. The symbol $\phi_0$ is the phase angle, and $|U(x)|$ is the voltage amplitude corresponding to the distance $x$ from the fault point.

The same conditions as those described in Equation (14) are set. At this time, the calculation formula for the distance from the signal input terminal to the fault point, in the case of fault resistance, is as follows:

$$
\begin{align*}
\frac{|U(x-d)|}{|U(x)|} &= \sqrt{1 + |\Gamma_0|^2 + 2|\Gamma_0| \cos(2\beta \times (x-d) + \phi_0)} \\
\beta &= 2\pi f \sqrt{L_0C_0} \\
|\Gamma_0| &= |(R_1-Z_0)/(R_1+Z_0)| \tag{18}
\end{align*}
$$

In Equation (18), the symbol $R_1$ is the fault resistance. In fact, in addition to the direct grounding fault, there is also a fault through the fault resistance. The sign $R_1$ is less than the characteristic impedance, $Z_0$, and the sign $\phi_0$ is equal to $\pi$. This paper mainly analyzes
these two faults. By collecting the values of two monitoring points, the estimated distance $x$ from the input terminal to the fault point can be obtained. The restriction conditions are the same as in the case of a direct ground fault and are the same as described in Equation (14).

3. Construction of the Fault Location Circuit and Research on the Non-Destructive Standing Wave

3.1. The Construction of the Fault Location Circuit

Firstly, the simulation circuit is used for fault location analysis and calculation. The circuit diagram is shown in Figure 2.

![Figure 2. Schematic diagram of fault location circuit.](image-url)

An alternating constant voltage source provides an input signal with a stable frequency, $f$. The symbol $R_s$ is the actual power supply’s internal resistance, and the symbol $R_b$ is the source-side matching resistance. The matching resistance and the power supply part form a source-side matching network. When a fault occurs at cable $K$, the fault type can be two fault types: a direct ground fault and a ground resistance fault. At fault point $K$, a single-pole double-throw switch is used to select the fault type. The symbol $R_1$ is the fault resistance, and the unit is $\Omega$. The positions of detection point 1 and detection point 2 correspond to the conditions described in Equation (14), respectively. Detection points 1 and 2 output voltage amplitude values through two oscilloscopes, which are $G_1$ and $G_2$. The interval between detection point 1 and detection point 2 is symbol $d$. The distance between detection point 1 and the fault point is $x$, and the distance between detection point 2 and the fault point is $x-d$. The above situation is consistent with the environment in Equation (14).

The source end matching requires that the impedance value viewed from the signal injection end to the source end is equal to the transmission characteristic impedance. The impedance value after the parallel connection of $R_s$ and $R_b$ is required to be equal to $Z_0$ to reduce signal interference. When the unit resistance and unit inductance of the transmission line change, its characteristic impedance $Z_0$ changes. In the actual line, the value of the source’s internal resistance is certain, so it is necessary to change the matching resistance value to meet the matching of the source end.
3.2. Lossless Standing Wave with Changing Frequency

When a direct ground fault occurs at 10 km, the simulation observes the voltage amplitude characteristics of the lossless standing wave. A frequency \( f \) that does not meet the restriction of Formula (16) is set to see the change of the whole cycle. Here, we have chosen 40 kHz and 60 kHz, two kinds of frequency to carry on the simulation to study its periodic change situation. The specific operation is as follows.

The grounding-type is set as the direct grounding fault type. The parameter \( L_0 \) is set equal to 0.899197 \times 10^{-3} \text{ H/km}; parameter \( C_0 \) is set equal to 13 \times 10^{-9} \text{ F/km}; parameter \( R_0 \) is set equal to 0 \text{ Ω}. The fault point is set 10 km away from the signal input, and the voltage amplitude data are collected every 100 m. The voltage amplitude distribution from the fault point to the source terminal, corresponding to the source signal frequencies of 40 kHz and 60 kHz, is shown in Figure 3.

![Figure 3](image_url)

**Figure 3.** Simulation of the full-period variation of the lossless standing wave, corresponding to different frequency input signals, when a ground fault occurs at 10 km.

Under different test frequencies, the voltage amplitude of each point on the transmission line changes, forming a standing wave waveform with its characteristics, and the corresponding standing wave wavelengths at different frequencies are displayed.

3.3. Lossless Standing Wave with Changing \( L_0 \) and \( C_0 \) Parameters

When a direct grounding fault occurs at 10 km, the periodic variation of voltage amplitude corresponds to different parameters \( R_0 \) and \( C_0 \) by simulation. The specific operation is as follows:

Two cases, \( L_0 = 0.899197 \times 10^{-3} \text{ H/km}, C_0 = 13 \times 10^{-9} \text{ F/km} \) and \( L_0 = 5 \times 10^{-3} \text{ H/km}, C_0 = 5 \times 10^{-9} \text{ F/km} \), are respectively set when the source signal frequency, \( f \), is fixed at 50 kHz. As the characteristic impedance changes in the two cases, it is necessary to rematch the source end, and the matching resistance \( R_0 \) needs to be changed from 263 Ω to 1000 Ω. The direct grounding fault is set at 10 km, and data are collected every 100 m. The periodic change of the voltage amplitude in the two cases is shown in Figure 4.
The black line corresponds to a standing wavelength of 4 km, while the red line corresponds to a wavelength of 5.84966 km. The number of voltage amplitude cycles, corresponding to different parameters $R_0$ and $C_0$, is also different. The simulation results show that $R_0$ and $C_0$ can change the standing wave distribution at the same frequency.

4. Simulation Results

The positioning accuracy adopts the IEEE standard fault location formula of the distribution network line, and the relative error formula is as follows:

$$ e = \frac{|x - s|}{L} $$

(19)

In Formula (19), the symbol $e$ represents the percentage of the ranging error. The symbol $x$ is the estimated value of the actual distance, $s$, that is, the estimated distance from the input signal terminal to the fault point calculated by the ranging method. The symbol $s$ represents the actual fault distance. The symbol $L$ represents the total length of the cable. In the simulation, the total length of the test cable should be set first. In the experiment, the total length can be measured in advance as a known condition. Similarly, when the location of the fault point is set, the actual distance, $s$, from the signal input to the fault point is known by simulation. In the experiment, the distance from the input signal end to the fault point can also be measured as the actual distance $s$.

4.1. Simulation of the Lossy Standing Wave and Lossless Standing Wave

To observe the lossy standing wave voltage amplitude and lossless periodic changes at the same frequency, the number of periods and half-periods of standing waves corresponding to different frequencies is simulated and studied.
Under other consistent conditions, the simulation is carried out for \( R_0 = 0.2127 \, \Omega/km \), \( f = 50 \, kHz \); \( R_0 = 0 \, \Omega/km \), \( f = 50 \, kHz \); \( R_0 = 0.2127 \, \Omega/km \), \( f = 7312 \, Hz \); \( R_0 = 0 \, \Omega/km \), \( f = 7312 \, Hz \). The simulation results of the voltage amplitude collected per 100 m on a 10 km transmission line are shown in Figure 5.

![Simulation distribution of lossy and lossless standing waves at different frequencies.](image)

**Figure 5.** Simulation distribution of lossy and lossless standing waves at different frequencies.

In Figure 5, the black line represents the lossy situation at a frequency of 50 kHz, and the red line represents the lossless situation at the frequency of 50 kHz. The blue line represents the lossy situation at a frequency of 7312 Hz; the green line represents the lossless situation at a frequency of 7312 Hz; the red line represents the overlap with the black case, and the green and blue lines overlap. It can be seen that the corresponding standing wave amplitude characteristics of lossy and lossless standing waves at the same frequency are almost the same. It can also be inferred that the standing wave positioning algorithm in the mathematical model is also suitable for lossy transmission lines.

### 4.2. Accuracy Analysis of Different Frequencies under Lossy Conditions

In the simulation, the length of the line, \( L \), is 10 km, and the selected frequency, \( f \), satisfies Formula (16). The solution shows that \( f \) is less than or equal to 7312 Hz.

Two frequencies of 7312 Hz and 6000 Hz are selected for fault location on a line with a length of 10 km. On the 10 km transmission line, the interval \( d \) of two detection points is 220 m, the unit resistance \( R_0 = 0.2172 \, \Omega/km \), and other conditions remain the same.

The specific calculation process is as follows: when the frequency \( f \) is 7312 Hz, the direct ground fault is set at 5 km. Voltage amplitude detected at detection point 1 is 59.66 V, and the voltage amplitude detected by detection point 2 is 57.59 V; the current \( d \) is 220 m. The data is brought into Equation (14). It is found that \( x = 5.013 \, km \). Putting the result into Formula (19), the relative error distance is found to be 0.13%.

Source signals with frequencies of 7312 Hz and 6000 Hz are respectively used to detect 20 different fault points on the line, and the corresponding ranging errors are shown in Figure 6.
Two frequencies of 7312 Hz and 6000 Hz are selected for fault location on a line with a length of 10 km. On the 10 km transmission line, the interval $d$ of two detection points is 220 m, the unit resistance $R_0 = 0.2172 \, \Omega/km$, and other conditions remain the same. The specific calculation process is as follows: when the frequency $f$ is 7312 Hz, the direct ground fault is set at 5 km. Voltage amplitude detected at detection point 1 is 59.66 V, and the voltage amplitude detected by detection point 2 is 57.59 V; the current $d$ is 220 m. The data is brought into Equation (14). It is found that $x = 5.013 \, \text{km}$. Putting the result into Formula (19), the relative error distance is found to be 0.13%.

Source signals with frequencies of 7312 Hz and 6000 Hz are respectively used to detect 20 different fault points on the line, and the corresponding ranging errors are shown in Figure 6.

Figure 6. Distribution of lossy positioning errors at 20 fault points at different frequencies.

The horizontal axis is where the fault points occur, and the vertical axis is the difference between the measured fault distance and the actual fault distance. Under the simulation 7312 Hz source frequency, the positioning error distance is basically within 15 m. The positioning error corresponding to 6000 Hz remains within the fluctuation range of 25 m, and the relative error of ranging is 0.25%, which still has a high positioning accuracy.

The percentage of relative error distance calculated by Formula (19) is shown in the following Table 1.

| The Frequency of the Signal Source/Hz | Voltage Amplitude Value of Detection Point 1/V | Voltage Amplitude Value of Detection Point 2/V | Locating Fault Distance/km | Actual Fault Distance/km | Relative Error of Ranging/% |
|--------------------------------------|----------------------------------------------|----------------------------------------------|---------------------------|-------------------------|---------------------------|
| 6000                                 | 48.94                                        | 46.68                                        | 3.994                     | 4                       | 0.06                      |
| 6000                                 | 59.66                                        | 57.59                                        | 5.013                     | 5                       | 0.13                      |
| 6000                                 | 69.4                                         | 67.53                                        | 5.989                     | 6                       | 0.11                      |
| 6000                                 | 77.98                                        | 76.36                                        | 7.005                     | 7                       | 0.05                      |
| 6000                                 | 85.27                                        | 83.92                                        | 8.006                     | 8                       | 0.06                      |
| 7312                                 | 58.36                                        | 55.79                                        | 3.998                     | 4                       | 0.02                      |
| 7312                                 | 70.26                                        | 68                                           | 4.994                     | 5                       | 0.06                      |
| 7312                                 | 80.43                                        | 78.54                                        | 5.996                     | 6                       | 0.04                      |
| 7312                                 | 88.62                                        | 87.15                                        | 7.006                     | 7                       | 0.06                      |
| 7312                                 | 94.62                                        | 93.62                                        | 8.006                     | 8                       | 0.06                      |

4.3. Influence of Different Intervals on Positioning Accuracy

The spacing $d$ of the two measuring points in the positioning circuit is also a possible factor affecting the positioning accuracy. The research and analysis are as follows.

Other conditions are kept consistent. The interval $d$ is set to 60 m and 100 m. The relative error fluctuation between the fault location and 20 different fault point locations is shown in Figure 7.
Table 1. Analysis of fault location results.

| The Frequency of the Signal/Hz | The Voltage Amplitude Value of Detection Point 1/V | The Voltage Amplitude Value of Detection Point 2/V | Locating Fault Distance/km | Actual Fault Distance/km | Relative Error of Ranging/% |
|-------------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------|--------------------------|---------------------------|
| 6000                          | 48.94                                         | 46.68                                         | 3.994                     | 4                         | 0.06                      |
| 7312                          | 58.36                                         | 55.79                                         | 3.998                     | 4                         | 0.02                      |
| 6000                          | 59.66                                         | 57.59                                         | 5.013                     | 5                         | 0.13                      |
| 7312                          | 70.26                                         | 68                                            | 4.994                     | 5                         | 0.06                      |
| 6000                          | 69.4                                          | 67.53                                         | 5.989                     | 6                         | 0.11                      |
| 7312                          | 80.43                                         | 78.54                                         | 5.996                     | 6                         | 0.04                      |
| 6000                          | 77.98                                         | 76.36                                         | 7.005                     | 7                         | 0.05                      |
| 7312                          | 88.62                                         | 87.15                                         | 7.006                     | 7                         | 0.06                      |
| 7.312                         | 94.62                                         | 93.62                                         | 8.006                     | 8                         | 0.06                      |

4.3. Influence of Different Intervals on Positioning Accuracy

The spacing $d$ of the two measuring points in the positioning circuit is also a possible factor affecting the positioning accuracy. The research and analysis are as follows. Other conditions are kept consistent. The interval $d$ is set to 60 m and 100 m. The relative error fluctuation between the fault location and 20 different fault point locations is shown in Figure 7.

Figure 7. Relative error distribution of ranging at 20 different fault points in different intervals.

It can be seen from Figure 7 that the relative fluctuation of the interval of $d = 100$ m is small, and the relative error of ranging can be controlled within 1.722% when $d = 100$ m.

The smaller the interval $d$, the higher the accuracy required for the collected amplitude value. The actual cable length will not be very long, and the distance between the two detection points should not be too large. However, if the distance between the two detection points is too small, the accuracy of reading data will increase, so the distance should be controlled. A smaller $d$ interval within the fluctuation range of the positioning error is chosen to meet the requirements to facilitate the placement of the detection points.

4.4. Analysis of the Simulation Results of the Fault Location Method by Using Only One Detection Point

The detection effect of a detection point is verified by the simulation as follows. The simulation is chosen to be performed on the line of length $L$ equal to 10 km; two frequencies need to be chosen to satisfy the restriction of Formula (16). Here, the frequency $f_1$ of the input signal is selected as 6000 Hz; the frequency $f_2$ of the input signal is selected as 7312 Hz; the line parameter selection is $L_0 = 0.899197 \times 10^{-3}$ H/km, $C_0 = 13 \times 10^{-9}$ F/km. The data is put into Formula (15) to calculate the estimated distance $x$ from the input signal end to the fault point. The location of the direct ground fault for simulation is set; the voltage amplitude value of the monitoring point at the two frequencies, the actual fault distance, and the relative error percentage of the distance measurement are shown in Table 2.
Table 2. Location results of different fault distances.

| Locating Fault Distance/km | Actual Fault Distance/km | Relative Error of Ranging/% |
|----------------------------|--------------------------|----------------------------|
| 2.992                      | 3                        | 0.08                       |
| 5.036                      | 5                        | 0.36                       |
| 5.997                      | 6                        | 0.03                       |
| 6.987                      | 7                        | 0.13                       |
| 8.007                      | 8                        | 0.07                       |
| 9.012                      | 9                        | 0.12                       |

4.5. Trend Distribution of Traveling Standing Wave with Fault Resistance

A fault point is set at a distance of 10 km, and a fault resistance of 50 Ω, 100 Ω, and 15 kΩ is set, respectively. The traveling standing wave states along the transmission line obtained by sampling at a source frequency of 29 kHz every 100 m are shown in Figure 8.

![Figure 8](image-url)  
**Figure 8.** Distribution of traveling standing waves on transmission lines under different grounding resistance faults.

When the small resistance of 50 Ω and 100 Ω is grounded, its waveform and the waveform of a direct ground fault correspond to their respective voltage wave nodes and voltage antinodes at the same position. When the fault resistance is large, the waveform changes, and the phase angle $\phi_0$ reverses.

4.6. Analysis of Fault Location Results with Fault Resistance

When the input signal frequency, $f$, is equal to 7312 Hz, the fault resistance is equal to 50 Ω, and the characteristic impedance is equal to 263 Ω, taking the simulation data at this time as an example. The interval $d$ is equal to 0.5 km, and the voltage amplitude value of detection point 1 is known to be 34.39 V, and the voltage amplitude value of detection point 2 is 31.82 V, respectively. Combining Formula (18) can produce the following results:
It is solved that \( x = 0.506 \text{ km} \), and the actual value \( s \) is 0.5 \text{ km}. Then, the result is put into Formula (19), and the relative error percentage of the distance measurement is found to be 0.06%.

The following are the positioning situations of the following grounding faults occurring on the cable road with the length \( L = 10 \text{ km} \) and the detection point interval \( d = 100 \text{ m} \), as shown in Table 3.

### Table 3. Analysis of fault location results.

| The Value of Fault Resistance/Ω | Voltage Amplitude Value of Detection Point 1/V | Voltage Amplitude Value of Detection Point 2/V | Locating Fault Distance/km | Actual Fault Distance/km | Relative Error of Ranging/% |
|--------------------------------|-----------------------------------------------|-----------------------------------------------|----------------------------|--------------------------|----------------------------|
| 50                             | 165.5                                         | 165.1                                         | 9.039                      | 9.0                      | 0.39                       |
| 50                             | 163.1                                         | 162.5                                         | 8.523                      | 8.5                      | 0.23                       |
| 50                             | 150.1                                         | 148.9                                         | 7.02                       | 7.0                      | 0.20                       |
| 100                            | 143.1                                         | 142.7                                         | 8.778                      | 9.0                      | 2.22                       |
| 100                            | 141.2                                         | 140.7                                         | 8.379                      | 8.5                      | 1.21                       |
| 100                            | 138.6                                         | 138                                           | 7.684                      | 8.0                      | 3.16                       |

If we do not know the resistance value of fault resistance \( R_1 \), we can use Formula (14) to calculate the fault distance. This is because when the fault resistance is small, its distribution characteristics are similar to the direct grounding fault waveform, as shown in Figure 3.

The same environment is set for simulation as in Section 4.6. The difference is that we locate through Formula (14), and we no longer take the fault resistance as a known condition. The results are shown in Table 4.

### Table 4. Analysis of fault location results.

| The Value of Fault Resistance/Ω | Voltage Amplitude Value of Detection Point 1/V | Voltage Amplitude Value of Detection Point 2/V | Locating Fault Distance/km | Actual Fault Distance/km | Relative Error of Ranging/% |
|--------------------------------|-----------------------------------------------|-----------------------------------------------|----------------------------|--------------------------|----------------------------|
| 50                             | 72.84                                         | 68.35                                         | 3.021                      | 3                        | 0.21                       |
| 50                             | 117.2                                         | 113.4                                         | 4.948                      | 5                        | 0.52                       |
| 50                             | 154.5                                         | 152.4                                         | 7.485                      | 7.5                      | 0.15                       |
| 50                             | 167                                           | 166.5                                         | 9.494                      | 9.5                      | 0.06                       |
| 100                            | 58.09                                         | 54.59                                         | 3.081                      | 3                        | 0.81                       |
| 100                            | 98.77                                         | 95.66                                         | 5.043                      | 5                        | 0.43                       |
| 100                            | 132.8                                         | 131                                           | 7.491                      | 7.5                      | 0.09                       |
| 100                            | 144.1                                         | 143.7                                         | 9.538                      | 9.5                      | 0.38                       |

It can be seen that this method can accurately locate the fault. It should be noted that the actual value of the fault resistance in the table is only for reference and is not used as a known condition.

In summary, under different source frequencies and fault resistances, this algorithm can accurately locate the fault distance.

### 5. Experimental Results

#### 5.1. Environment Setting and Parameter Setting

The power cord is a two-core power cord with resistance 0.094 \( Ω/m \) and a characteristic impedance of 140 \( Ω \). There are seven sections of cables, and the lengths of the seven sections of the lines are 24 m, 54 m, 74 m, 85 m, 108 m, and 135 m, in descending order.

Steps of the experiment: 1. Set the grounding state; 2. Set the output waveform of the signal generator as a sine wave and the peak–peak value as 10 V, and adjust the signal frequency as needed; 3. Read and record the voltage amplitude value; 4. Use the cable parameters to process the measured experimental data, according to Formulas (11) and (12), according to the grounding situation, and use Formula (11) to calculate the relative error percentage.
5.2. Monitor the Distribution of Points

The distribution diagram of monitoring points on the experimental transmission line is shown in Figure 9.

Figure 9. Schematic diagram of the distribution of detection points.

Symbols W1 to W7 are cables prepared for the experiment. The vicinity of the seven-segment cable is detection point P1 to detection point P8.

5.3. The Standing Wave Trend of Short Circuit in Direct Ground Fault Is Tested

The detection point P8 is set as a direct ground fault. The cables between the detection points P8 and P1 are placed from large to small. The distance between the input signal terminal and the fault point is 500 m. A signal is inputted at the detection point P1. Due to the short length of the test cable, the measurement frequency needs to be increased. Therefore, the frequency of the input signal is 10 kHz, 20 kHz, and 100 kHz, respectively. The standing wave trend corresponding to the collected data at each test point is shown in Figure 10.

Figure 10. Actual data distribution at different frequencies of direct ground fault.

When the frequency $f$ is 10 kHz and 20 kHz, respectively, the voltage amplitude from the detection point P8 to the detection point P1 gradually increases; the two frequencies at this time both meet the restrictions in Formula (16), and the fault point can be accurately located through any two detection points. When the frequency $f$ is equal to 100 kHz, from the detection point P8 to the detection point P1, it first increases and then decreases. This
frequency is not monotonous and does not meet the restriction in Equation (16). At this frequency, any two detection points cannot be used to locate the fault point. The data at this frequency will not be processed during positioning, and they will only be reflected in the description of the standing wave phenomenon. The experimental results show that there is the same trend as the standing wave in the experiment.

5.4. Analysis of Single-Phase Direct Grounding Fault Location Results

Through Formulas (14) and (19), the results obtained by bringing the experimental data into processing are shown in Table 5.

Table 5. Location results of different fault distances.

| The Frequency of the Signal Source/kHz | Voltage Amplitude Value of Detection Point 1/V | Voltage Amplitude Value of Detection Point 2/V | Locating Fault Distance/m | Actual Fault Distance/m | Relative Error of Ranging/% |
|--------------------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------|-------------------------|----------------------------|
| 10                                   | 1.42                                          | 0.74                                          | 396                       | 402                     | 1.2                        |
| 20                                   | 1.98                                          | 1.07                                          | 133                       | 135                     | 0.4                        |
| 20                                   | 3.12                                          | 2.24                                          | 330                       | 328                     | 0.4                        |
| 20                                   | 2.96                                          | 2.64                                          | 388                       | 402                     | 2.8                        |

5.5. Analysis of Fault Location Results of the Grounding Resistance Fault

The grounding resistance fault is set at detection point P8, that is, the distance between the input terminal and the fault point is 500 m, and the fault resistance $R_1$ is set to 50 Ω and 100 Ω, respectively. The signal source frequency $f$ is 20 kHz to test the circuit. The waveform trend formed by the eight detection point data is shown in Figure 11.

Figure 11. Actual data distribution of different ground resistance faults.

Corresponding with detection point P8 to detection point P3 in Figure 11 is a cable from small to large. There is a 135 m-long cable between the detection point P3 and the detection point P2; between the detection point P2 and the detection point P1 is a 108 m-long cable. The 0 point on the horizontal axis is the fault point. It can be seen from the figure that the voltage amplitude of the fault point is not 0 when the fault resistance $R_1$ is
equal to 100 Ω and $R_1$ is equal to 50 Ω, and it shows an upward trend as the distance from the fault point increases.

Different fault points are set, the data are brought into Formula (18), and the positioning results shown in Table 6 are analyzed.

| The Value of Fault Resistance/Ω | Voltage Amplitude Value of Detection Point 1/V | Voltage Amplitude Value of Detection Point 2/V | Locating Fault Distance/m | Actual Fault Distance/m | Relative Error of Ranging/% |
|-------------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------|-------------------------|---------------------------|
| 50                            | 3.62                                          | 3.3                                          | 510                       | 500                     | 2                         |
| 50                            | 3.31                                          | 2.59                                         | 401                       | 392                     | 1.8                       |
| 100                           | 3.44                                          | 3.36                                         | 518                       | 500                     | 3.6                       |
| 100                           | 3.35                                          | 3.01                                         | 405                       | 392                     | 2.6                       |

In summary, the direct ground fault and the resistance fault in the experiment have the same trend of traveling standing waves as the simulation, and the fault location can be carried out.

6. Discussions about Engineering
6.1. Place a Detection Point Device on the Project

In actual engineering applications, the detection points can be installed in appropriate locations, such as busbars, cable-to-connectors, knife switches, or ring network cabinets, according to actual conditions. The parameters of the line can be used as known conditions by querying the cable library or through measuring. With these parameters known, the location of the fault can be located through the two detection points installed at the interface location of these distribution networks.

6.2. Standing Wave Method for Multi-Frequency One Detection Point Detection

Suppose the actual situation allows only one detection point to be installed. In that case, the method of inputting multi-frequency signals through one detection point can be used to detect the fault for the purpose of achieving the fault location.

When a direct ground fault occurs, the input terminal provides signals with stable frequencies, $f_1$ and $f_2$, respectively. The theoretical method is deduced before and after Formula (15). The two frequencies, $f_1$ and $f_2$, in this method need to meet the limitation of Formula (16). In Section 4.4, the method is simulated. The simulation results of the fault location method using only one detection point are analyzed. The results show that only one monitoring point can be used for fault location.

7. Conclusions

This paper presents a single-phase grounding fault location method for distribution networks based on the standing wave principle. Through simulation and experiment, the phenomenon of traveling standing waves on the transmission line with direct grounding fault and through the resistance grounding fault is studied. The fault distance is calculated, which proves that the method can be used for accurate location. After the formation of the traveling standing wave, the method can conduct stable detection. Compared with the traveling wave method, it does not need to calculate the time difference, thus avoiding the error caused by the time difference under the actual medium and high propagation velocity. It is applicable to solve the fault of the buried cable and diagnose effectively in a new residential area.

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