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The Novel Method for Determining Locations of a Double Ground Fault in Networks with Isolated Neutral

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***Abstract*—The problem of determining locations of a double ground fault in networks with isolated neutral is much more complicated due to a topographic remoteness of faults places. The necessary level of perfection of the novel method for determining locations of such faults is ensured through the use of many algorithmic network models. The general algorithmic model of the network is used to calculate the voltage at the supposed place of a fault. Algorithmic models of an undamaged network and models of a pure fault regime allow dividing electrical quantities into components, related only to the measured voltages at the installation location of the device, and into components that are completely determined by the fault currents. Such property of the models allows the algorithm to be theoretically independent of short circuit resistances. An important role in fault locations is played by the hypothesis of the resistivity of the ground fault circuit. Following this idea, the new algorithm uses an objective function to fault location on the line, which is a measure of the transmitted reactive power in the transverse circuit between phase and ground. The stability and accuracy of the algorithm do not depend on the remoteness of faults places from each other.**

Keywords*—fault location, network with isolated neutral, double-ground fault, power line, algorithmic models of an undamaged section, algorithmic models of a pure fault regime of network

I. Introduction

In networks with isolated neutral, a single-phase ground fault often becomes a double ground fault [1–3], which requires the immediate disconnection of a damaged power line by relay protection devices. It is difficult to locate a double ground fault due to a topographic remoteness of faults places. Besides, when developing fault location devices, it is necessary to take into account the feature of distribution networks, which consists of their branching and multiplicity. Therefore, in electrical power systems to increase the profitability of devices, predominantly single-end fault location methods based on fault regime parameters are used. [4]. A double-end fault location is not widely used because of their high cost and the need to use communication equipment and synchronization devices.

II. Background

Various principles are used to locate double ground faults in networks with isolated neutral.

Until recently, it was quite widespread to use for locating double ground faults of topographic fault location devices [5, 6]. Unfortunately, they require significant time-consuming to bypass the field crew along the line. During all this time, while the fault location is determining, the power line is disconnected, that leading either to a decrease in electricity sales to consumers or a worsening state of distribution network.

Therefore, topographic methods are being replaced by remote (centralized [8]) methods for determining the fault location. Their effectiveness is ensured primarily by a simple hardware realization of the method. The use of currents and voltages measurements only from one end of a controlled power line allow excluding an expensive and often unreliable communication and synchronization equipment [4, 7].

In turn, remote methods are divided into traveling waves, pulse methods, and methods based on the application of fault regime parameters of a line.

It is proved that traveling wave methods are autonomous in the sense that their characteristics are less susceptible to the influence of measuring instruments and the nature of processes at a fault location. However, researches and experiments show that they are not preferable for use in distribution networks due to the low level of electromagnetic waves, generated during a short circuit, and the difficulty of detecting the primary wave from the fault against the background of the entire cascade of waves arriving at the substation [8–10].

Pulse methods are also not without this disadvantage [8, 11], and, also, they are associated with the use of expensive equipment for generating injected pulses into the network and measuring return pulses [12, 13]. These disadvantages did not allow pulse methods to find applications for fault locations in distribution networks.

The experience of using various methods for a fault location on power lines summarized in a method based on the use of an objective function, the physical meaning of which is associated with the property of resistivity of a fault on the line [4]. In other words, the idea of the criterion for fault location is to assume that the place of fault is an element, the processes in which are purely dissipative, and are accompanied by the

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conversion of the energy of the electromagnetic process into heat. We call such an objective function as the energy criterion.

This article develops methods for the single-end fault location of a double ground fault in a network with isolated neutral, based on the use of algorithmic models of the protected network and the energy criterion for determining fault locations.

III. Basic Prerequisites

Phase voltages and line currents measurements at the device location are used. Distances to fault points are calculated from a measurement point, therefore, the coordinate of the device location is $x = 0$. Then, all electrical quantities measured by the device – phase voltages $\underline{U}_\nu(0)$ and line currents $\underline{I}_\nu(0)$ – have a zero-argument $(\nu = \overline{A,B,C})$. Following these rules, all calculated quantities are further provided with an argument x, meaning that quantities are calculated at a distance x from the installation location of the device; a phase voltage and a phase current will be written as $\underline{U}_\nu(x)$ and $\underline{I}_\nu(x)$ respectively.

The method uses the algorithmic network model. Its difference from the network model consists of the branches representation with transient active resistances in the *supposed* places of ground faults by current sources equal to ground fault currents of corresponding phases. For certainty, we assume that the faults occurred in phases *B* and *C*, then it will be replaced with sources with currents $\underline{I}_{Bf}(x)$ and $\underline{I}_{Cf}(x)$.

According to the principle of compensation at the point of measurement (installation location of the device), known voltages $\underline{U}_\nu(0)$ can be replaced by appropriate sources of EMF. Then the algorithmic model of the network will have the form shown in fig. 1.

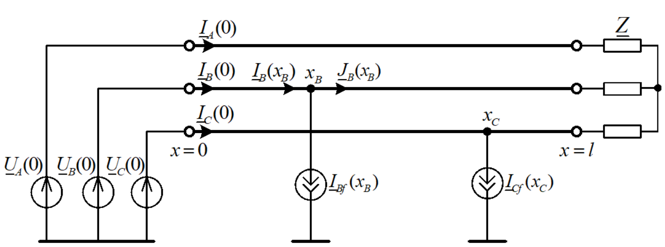

Fig. 1. The algorithmic model of the network with a double ground fault on a protected power line. Known measured quantities – phase voltages $\underline{U}_\nu(0)$ and phase currents $\underline{I}_\nu(0)$, as well as the quantity of the load $\underline{Z}$. The locations of the sources $\underline{I}_{Bf}(x)$ and $\underline{I}_{Cf}(x)$ are unknown and their location in the network is conditionally

IV. The General Principle for Determining Locations of a Fault

It is accepted that resistance of a fault circuit is resistive [4]. This important assumption about the nature of the fault is physically quite justified and important for the reason that it allows organizing the process of searching for fault locations based on clear representation, one of which is to understand that the transverse flow of energy at the fault, directed from the phase wire to the ground, is purely dissipative. In other words, at the fault location, the power in the transverse fault circuit is purely active, and to determine the fault location, it is enough to find the point on the damaged phase of the line at which the calculated reactive power will be zero.

It will look as follows. The device, using measurements of phase voltages $\underline{U}_\nu(0)$ and phase currents $\underline{I}_\nu(0)$, for each point of the line with a coordinate x in the algorithmic model (fig. 1) determines currents of current sources $\underline{I}_{Bf}(x)$, $\underline{I}_{Cf}(x)$ and voltages $\underline{U}_B(x)$, $\underline{U}_C(x)$, and calculates the complex power of sources. Following the common principle, the point on the line at which the objective function (in our case - reactive power) passes through zero is taken as the fault location on the damaged phase (fig. 2).

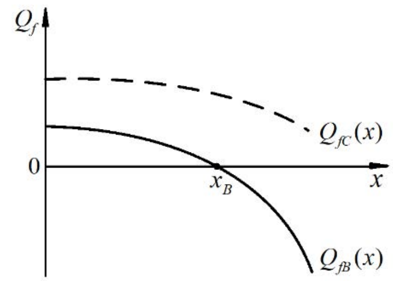

Fig. 2. The change in objective functions of phases *B* and *C*, depending on the supposed coordinate of the first fault. It can be seen that the fault closest to the device location is placed at the distance x_B on phase *B*

V. Method for Determining the First Place of a Fault

A. Line with distributed parameters

To determine the first place of a fault, the device using an algorithmic network model (fig. 1) first converts the measured quantities $\underline{U}_\nu(0)$ and $\underline{I}_\nu(0)$ into phase voltages $\underline{U}_\nu(x)$ and line currents $\underline{I}_\nu(x)$ of the *supposed* fault place. Then on their basis, currents of current sources $\underline{I}_{Bf}(x)$ and $\underline{I}_{Cf}(x)$ are formed.

Following the superposition method, the algorithmic network model (fig. 1) can be represented as two models: the model of the undamaged network for a protected power line when measured phase voltages are applied at its inputs (fig. 3) and the model of a pure fault regime for a protected power line (fig. 4) with current sources $\underline{I}_{Bf}(x)$ and $\underline{I}_{Cf}(x)$.

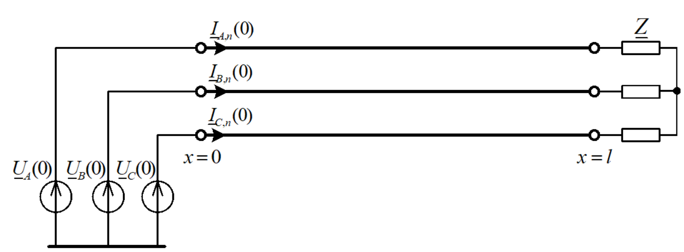

Fig. 3. The algorithmic model of an undamaged network for a protected power line when measured phase voltages are applied at its inputs. Currents $\underline{I}_{\nu,n}(0)$ at the input of the model are determined ($\nu = \overline{A,B,C}$)

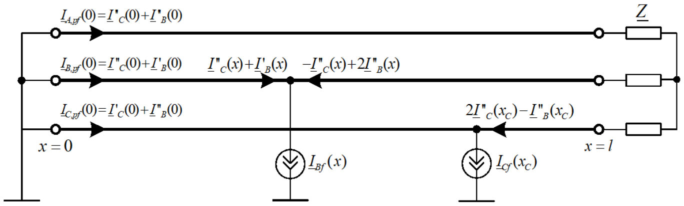

Fig. 4. The algorithmic model of pure fault regime for a protected power line. $\underline{I}'_B$ and $\underline{I}'_C$ – currents flowing in faulted phases, $\underline{I}''_B$ and $\underline{I}''_C$ – currents flowing in undamaged phase from current sources in phases B and C respectively

Pure fault currents in the network can be expressed as the sum of currents from current sources (fig. 4). In this connection, the currents of current sources are defined as follows:

$$\underline{I}_{Bf}(x) = \frac{\underline{I}_{A,pf}(x) - \underline{I}_{B,pf}(x)}{\left[\underline{k}_{d,nz}(x) + \frac{\underline{k}_{d,0}(x)}{2}\right] - 1},$$

$$\underline{I}_{Cf}(x) = \frac{\underline{I}_{A,pf}(x) - \underline{I}_{C,pf}(x)}{\left[\underline{k}_{d,nz}(x) + \frac{\underline{k}_{d,0}(x)}{2}\right] - 1},$$

where $\underline{k}_{d,nz}(x)$ – the coupling coefficient between non-zero current components of the current source and the phase current to the right of it, defined for the coordinate of the supposed place of a fault x; $\underline{k}_{d,0}(x)$ – the coupling coefficient between the zero-sequence current components of the current source and the phase current to the right of it; $\underline{I}_{\nu,pf}(x) = \underline{I}_{\nu}(x) - \underline{I}_{\nu,n}(x)$ – pure fault phase currents; $\underline{I}_{\nu,n}(x)$ – phase currents in the model of an undamaged network (fig. 3).

Then, according to the common principle, the device generates objective functions for damaged phases. The first place of damage x_η will correspond to the point at one of the damaged phases $\eta = \overline{B, C}$, in which the objective function passes through zero, and the coordinate of which is closer to the installation location of the device (fig. 2).

B. *Line with lumped parameters*

For lines with small capacitive currents, a model with lumped parameters is used without taking into account the capacitive conductivity. In this case, currents of current sources in the supposed place of a fault on the power line will take the form:

$$\underline{I}_{Bf}(x) = \frac{\underline{I}_{A,pf}(0) - \underline{I}_{B,pf}(0)}{\underline{k}_{d,nz}(x) - 1},$$

$$\underline{I}_{Cf}(x) = \frac{\underline{I}_{A,pf}(0) - \underline{I}_{C,pf}(0)}{\underline{k}_{d,nz}(x) - 1}.$$

VI. Method for Determining the Second Place of a Fault

A. *Line with distributed parameters*

The coordinate of the second place of a fault is determined based on a new algorithmic network model constructed for the protected section to the right of the first place of a fault (fig. 5).

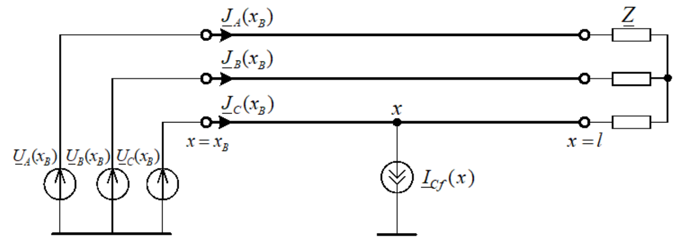

Fig. 5. The new algorithmic network model for the protected section to the right of the first place of a fault. $\underline{J}_{\lambda}(x_B)$ – line currents to the right of the first fault place

Again, as in the search for the first place of a fault, the new algorithmic model (fig. 5) can be represented as a model of an undamaged network for the protected section to the right of the first place of a fault when phase voltages of the first fault are applied at its inputs (fig. 6), and a model of a pure fault regime for the protected section to the right of the first place of a fault (fig. 7) with the current source $\underline{I}_{Cf}(x)$. Since the phase voltages $\underline{U}_{\nu}(x_B)$ at the first place of a fault are calculated, according to the compensation principle, the corresponding EMF sources can be switched on instead of them.

To calculate the objective function from already calculated line currents $\underline{J}_{\nu}(x_B)$ to the right of the first place of a fault and voltages in the first place of a fault $\underline{U}_{\nu}(x_B)$, the voltage $\underline{U}_C(x)$ at the current source is determined in the new algorithmic network model (fig. 5). Then from the new algorithmic model of a pure fault regime (fig. 7), the current of the current source is calculated as:

$$\underline{I}_{Cf}(x) = \frac{3\underline{J}_{C,pf,nz}(x)}{2\underline{k}_{d,nz}(x)},$$

where $\underline{k}_{d,nz}(x)$ – the coupling coefficient between non-zero current components of the current source and the phase current to the left of it, defined for the coordinate of the supposed place of a fault x; $\underline{J}_{C,pf,nz}(x)$ – the non-zero component of the pure fault current of the second damaged phase at the supposed place of a fault. A new algorithmic model of an undamaged network for the protected section to the right of the first place of a fault is additionally used to calculate pure fault components (fig. 6).

The second place of a fault is the point where the objective function passes through zero.

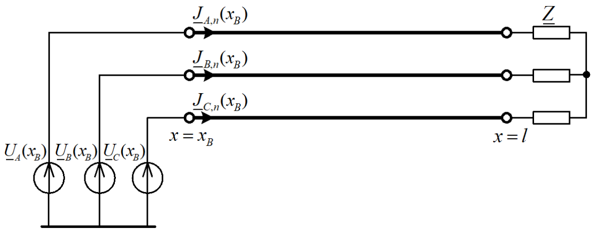

Fig. 6. The algorithmic model of an undamaged network for the protected section to the right of the first place of a fault when phase voltages of the first fault are applied at its inputs

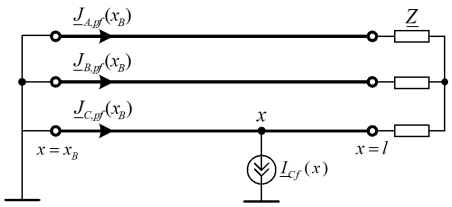

Fig. 7. The algorithmic model of a pure fault regime for the protected section to the right of the first place of a fault

B. Line with lumped parameters

For lines with small capacitive currents, determining the current of the second place of a fault $\underline{I}_{Cf}(x_C)$ is easier. In this case, it can be taken equal to the current of the first place of a fault with the opposite sign

$$\underline{I}_{Cf}(x_C) = -\underline{I}_{Bf}(x_B).$$

Then the distance from the first place of a fault to the second place of a fault will be determined as:

$$x_C - x_B = \frac{|\underline{U}_C(x_B)|\sin\alpha}{|\Delta\underline{U}_C^0|\sin\beta}, \quad (1)$$

where

$$\Delta\underline{U}_C^0 = \left[\underline{Z}_1^0 \underline{J}_{C,nz}(x_B) + \underline{Z}_0^0 \underline{J}_0(x_B)\right] -$$

– voltage drop at the per unit length power line located between faults;

$$\beta = \arg\left[\underline{I}_{Cf}(x_C)\right] - \arg\left[-\Delta\underline{U}_C^0\right] -$$

– the phase difference of the second fault current and the voltage drop at the per unit length power line;

$$\alpha = \arg\left[\underline{U}_C(x_B)\right] - \arg\left[\underline{I}_{Cf}(x_C)\right] -$$

– the phase difference between the voltage of the second damaged phase in the first fault place and the current of the second fault.

Expression (1) corresponds to the vector diagram shown in fig. 8.

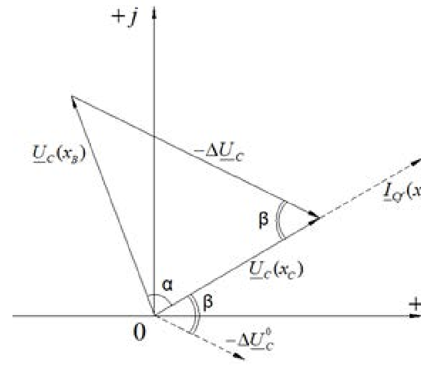

Fig. 8. The vector diagram of electrical quantities between the first and second place of faults

VII. Digital Signal Processing

The new algorithm uses signals from different network modes. Based on the electrical quantities of the previous regime, the algorithm calculates the load value of the protected line. Fault regime signals are used in algorithmic models of an undamaged network and pure fault regime. Therefore, the software module for digital signal processing of the device must divide the signal into appropriate sections, taking into account the features of the processes of a double ground fault.

Fig. 9 shows a signal segment, including the signal of the previous and fault regime (for simplification of the exposition, the conditional signal is considered). The signal of the previous regime is usually sinusoidal, in fig. 9 it is represented by a segment of the signal duration t_p. The signal of the fault regime can include fast-flowing free components, they appear immediately after a fault and are located between the segment of the previous steady state regime and the segment of a fault process signal. For the proposed algorithm, it makes no sense to take into account the components of a fast-flowing free process. Therefore, to analyze the signals of the fault process, a signal segment of duration t_f is used, taking into account with offset for the time $t_{f,g}$ to the right from the moment of short circuit occurrence, which allows excluding from consideration signal samples containing fast-fading and high-frequency components of the transient process [14].

Complex RMS values estimates of a previous and a fault regime signals against the background of possible components of the free process are carried out by the adaptive structural analysis [14 – 17].

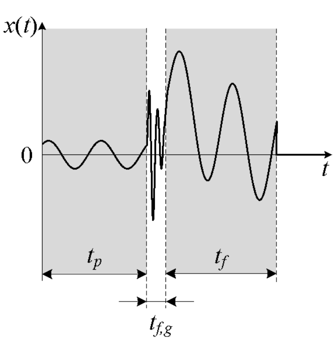

Fig. 9. Signals of previous and fault regime

To represent the electrical network signal in the general case the fundamental idea of adaptive structural analysis is to use a hybrid model, which is an integral part of a hybrid filter

$$e(k) = \hat{c}\cos(k\omega T_s) - \hat{s}\sin(k\omega T_s) + \sum_{m=0}^{M} a_m x(k - m\nu),$$

the non-adaptive part of which ($\hat{c}$ and $\hat{s}$ – coefficients of a non-adaptive operator – estimates of the fundamental frequency orthogonal components, ω – fundamental frequency) forms an estimate of the signal harmonic components, and the adaptive part (a_m – adaptive operator coefficients, M – order of adaptive part of filter) – an estimate of free process components of a network. Here T_s – sampling period, k – sample number, ν – coefficient of within model decimation (rarefaction), $e(k)$ – the output signal samples of the filter (the discrepancy of the model).

To reduce the requirements for the computing resources of the device, the filter is configured using the method of model superposition [18]. It implements the solution of the problem of approximating the model to the signal by the least squares method and uses normal equations (here $M = 2$):

$$\sum_{l=k-N+1}^{k} e(l)\begin{Bmatrix}\cos(l\omega T_s)\\ -\sin(l\omega T_s)\\ x(l-1)\\ x(l-2)\end{Bmatrix} = 0,$$

where N – width of the data window.

After configuring the filter, it is necessary to eliminate the influence of the adaptive part on the estimates of the non-adaptive part parameters of the model by replacing the variables:

$$\hat{c}' + j\hat{s}' = \frac{\hat{c} + j\hat{s}}{\underline{H}(j\omega T_s)}.$$

The complex values of the signals of the previous and fault regimes are calculated relative to the start of the previous regime. Therefore, the complex value of the fundamental frequency component of the fault regime electrical signal $\underline{X}_{tf}$, determined on its segment, must be synchronized with the complex signal value of the previous regime by introducing a phase shift $\Delta\psi = \omega\Delta t$ corresponding to the time difference $\Delta t = t_p + t_{f,g}$ between the beginning of the previous and fault regimes:

$$\underline{X}_f = \underline{X}_{tf} e^{-j\Delta\psi},$$

where $\underline{X}_f$ – complex RMS value of the fault regime electrical quantity, synchronized with the previous regime electrical quantity.

VIII. Conclusion

The perfection of the proposed method for determining locations of a double ground fault in networks with isolated neutral is provided by using a variety of network algorithmic models that consider the different regimes of the network in the algorithmic scenarios of fault locations. The general algorithmic model of the network is intended to calculate the voltage at the supposed place of a fault. It takes into account an important regularity that all electrical quantities before the fault place can be calculated from measurements at the device installation location, i.e. the algorithmic model in this section is fully adequate to the model of the network itself. The introduction into consideration of the undamaged network algorithmic models and a pure fault regime models allow dividing electrical quantities into components related only to the measured voltages at the device installation location, and into components that are completely determined by the fault currents. Such a property of the models allows the algorithm to be theoretically independent of short circuit resistance quantities.

The hypothesis of the resistivity of the ground fault circuit is played an important role in fault locations. Following this idea, the new algorithm uses an objective function to fault location on the line, which is a measure of the transmitted reactive power in the transverse circuit between phase and ground. In each case, when the objective function changes sign, the proposed algorithm fixes the coordinate of a fault place at the line. The stability and accuracy of the algorithm do not depend on the remoteness of faults places from each other.

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