Adaptation of power lines fault location methods to voltage characteristics deviations

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Abstract. The influence of voltage characteristics deviations, acceptable in normal operation of power grid, at power lines emergency state fault location methods precision is considered. The error distributions of emergency state fault location methods across power line length under frequency deviation, single rapid voltage changing and supply voltage unbalance variation are received. The way of emergency state fault location adaptation to voltage characteristics deviations is offered.

Introduction

Ensuring reliable supply of electricity to consumers is one of the main goals of organization, existence and development of power systems. As part of this issue, it is necessary to quickly and correctly locate the faults. Modern digital computing equipment used by relay protection and fault location devices is sensitive to voltage characteristics deviations [1]. In practice, voltage characteristics for networks of different voltage levels and purpose can deviate from ideal ones and lie both within [2] and outside [3] the limits.

The existing directions of research in this area can be separated into two groups:

1) the use of voltage characteristics as an argument of the fault location method [4];

2) development of fault location methods adapted to voltage characteristics deviations [5].

The approach implemented in [4] involves permanent analysis of voltage characteristics over the entire area of the observed network, using synchronized measurements. In case of violation of electric power quality caused by fault, iterative algorithm of multi-terminal fault location [6] is implemented (argument of fault location formula is vector of voltage drops at observed points). It is obvious that such an approach involves high requirements for network infrastructure and, consequently, a significant amount of investment.

The approach implemented in [5] eliminates the possible influence of supply voltage unbalance due to the calculation in phase coordinates. Iterative algorithm of one-terminal fault location with target function as reactive component of fault resistance is implemented. The disadvantage is the introduction of an additional error associated with the representation of the entire load concentrated at the most electrically distant point.

Thus, the described fault location methods are either expensive to implement or have a certain methodological error. Research in general tends to focus on excluding or compensating for the influence of some single voltage characteristic.

In this work, the way of adaptation of fault location methods to deviations of voltage characteristics, existing in normal mode, is investigated. It can be implemented both one-terminally and multi-terminally. The adaptation method is not a source of additional methodological error. In the case of known deviations of voltage characteristics, it is possible to use the adaptation algorithm to compensate for the influence of any of them.

The study of normative documentation on voltage characteristics issues [7] and previous studies [8] have shown the expediency of studying the effect on the accuracy of emergency state fault location of the following voltage characteristics long-term existing in normal network operation: frequency deviation, single rapid voltage changing, supply voltage unbalance. According to [7], simulated deviations of voltage characteristics were within the limits specified in Table 1.

Table 1. Range of voltage characteristics deviations

№	Voltage characteristic	Range
1	Frequency deviation, %	± 5
2	Single rapid voltage changing	± 6
3	Supply voltage unbalance, %	0-4

1. Fault location methods and power line model

For the study, a group of one-terminal impedance based emergency state fault location methods was selected.

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The calculation formulas and the decryption of the values used are shown in Figure 1 and Table 2.

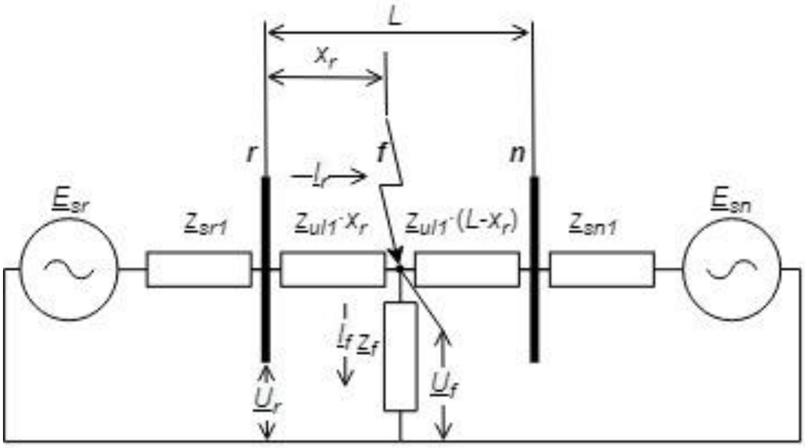

Fig. 1. Diagram of faulted line in post fault mode

Table 2. Information about fault location methods

№	Algorithm	Formulas and explanations
1	Takagi [9]	$$x_e = \frac{\mathrm{Im}\left(\underline{U}_r \cdot \Delta\hat{\underline{I}}_r\right)}{\mathrm{Im}\left(\underline{I}_r \cdot \Delta\hat{\underline{I}}_r \cdot \underline{z}_{ul1}\right)} \quad (1)$$, where $\underline{U}_r$ voltage at measuring point; $\underline{I}_r$ – current at measuring point; $\Delta\hat{\underline{I}}_r$ – complex conjugate pure fault current at measuring point; $\underline{z}_{ul1}$ – positive sequence line impedance per 1 km ; x_e fault location evaluation from measuring point.
2	Ericsson [10]	$$x_e = \frac{B_1 - \sqrt{B_1^2 - 4 \cdot B_2 \cdot B_0}}{2 \cdot B_2} \cdot L \quad (2)$$, where $B_2 = \mathrm{Im}\left(\hat{\underline{k}}_3\right)$; $B_1 = \mathrm{Im}\left(\hat{\underline{k}}_3 \cdot \underline{k}_1\right)$; $B_0 = \mathrm{Im}\left(\hat{\underline{k}}_3 \cdot \underline{k}_2\right)$; $\underline{k}_1 = \frac{\underline{U}_r}{\underline{I}_r \cdot \underline{z}_{ul1}} + 1 + \frac{\underline{z}_{sn1}}{\underline{z}_{ul1}}$; $\underline{k}_2 = \frac{\underline{U}_r}{\underline{I}_r \cdot \underline{z}_{ul1}} \cdot \left(1 + \frac{\underline{z}_{sn1}}{\underline{z}_{ul1}}\right)$; $\hat{\underline{k}}_3$ complex conjugate of $\underline{k}_3 = \frac{\Delta\underline{I}_r}{\underline{I}_r \cdot \underline{z}_{ul1}} \cdot \left(1 + \frac{\underline{z}_{sn1} + \underline{z}_{sr1}}{\underline{z}_{ul1}}\right)$; $\underline{z}_{sn1}$ positive sequence impedance of system behind measuring point; $\underline{z}_{sr1}$ positive sequence impedance of remote system.
3	Ankamma [11]	$$x_e = \frac{\mathrm{Im}\left(\underline{U}_r \cdot \hat{\underline{I}}\right)}{\mathrm{Im}\left(\underline{I}_r \cdot \hat{\underline{I}} \cdot \underline{z}_{ul1}\right)} \quad (3)$$, where $\hat{\underline{I}}$ - complex conjugate of $\underline{I} = \underline{a}_{f1} \Delta\underline{I}_{r1} + \underline{a}_{f2} \Delta\underline{I}_{r2}$; $\underline{a}_{f1}, \underline{a}_{f2}$ – weighting coefficients; $\Delta\underline{I}_{r1}$, $\Delta\underline{I}_{r2}$ – pure fault positive and negative currents at measuring point, respectively.
4	Wiszniewski [12]	$$x_e = \frac{X_r}{x_{ul1}} - \frac{R_r \cdot \tan(\varphi_l) - X_r}{x_{ul1} \cdot \left(\frac{a}{b} \cdot \tan(\varphi_l) - 1\right)} \quad (4)$$, where $R_r = \mathrm{Re}\left(\frac{\underline{U}_r}{\underline{I}_r}\right)$; $X_r = \mathrm{Im}\left(\frac{\underline{U}_r}{\underline{I}_r}\right)$; $\varphi_l = \arg\left(\underline{z}_{ul1}\right)$; $a = \mathrm{Re}\left(\frac{\Delta\underline{I}_r}{\underline{I}_r \cdot e^{j \cdot \gamma}}\right)$; $b = \mathrm{Im}\left(\frac{\Delta\underline{I}_r}{\underline{I}_r \cdot e^{j \cdot \gamma}}\right)$; $\gamma = \arg\left(\frac{\underline{z}_{ul1} \cdot L - X_r \cdot \cot(\varphi_l + j) + \underline{z}_{sn1}}{\underline{z}_{sr1} + \underline{z}_{ul1} \cdot L + \underline{z}_{sn1}}\right)$.
5	Arzhannikov [13]	$$x_e = \frac{\left(X_r - R_r \cdot \tan(\alpha - \beta)\right) \cdot \tan(\varphi_l)}{\left(\tan(\varphi_l) - \tan(\alpha - \beta)\right) \cdot x_{ul1}} \quad (5)$$, where $\alpha = \arg\left(\frac{\underline{I}'_f}{\underline{I}_r}\right)$; $\beta = \arg\left(\frac{\underline{I}'_f}{\underline{I}_r}\right)$; $\underline{I}'_f$ current, calculating by values at measuring point, with phase close to phase of fault current

The power line model was created using the SimPowerSystems section blocks of the Simulink library of the MATLAB software package. In order to solve the system of equations of the model in the state space, the Fixed-step discrete solver with a sampling period of 32 samples per period of industrial frequency (sampling frequency - 1600 Hz) was selected, which showed sufficient accuracy in performing similar tasks [14]. The power supply source was set by the Three-Phase Programmable Voltage Source, deviations of voltage characteristics were simulated by changing parameters of this unit. The Three-Phase Series RLC Branch block modeled little active resistance to avoid parallel connection of the voltage source and capacitive branches of the following blocks. The resistance of the positive and zero sequence system was modeled by the Three-Phase PI Section Line unit of unit length; Power line sections - Three-Phase PI Section Line; Fault - Three-Phase Fault; Load - Three-Phase Series RLC Load. The Three-Phase V-I Measurement, From, to Workspace, and Scope blocks are designed to visualize and export data to the MATLAB workspace. The powergui unit is required for the operation of the SimPowerSystems units.

Parameters of the simulated system are given in Table 3. The scheme of the simulation model of the power line in Simulink is shown in Fig. 2.

Table 3. Data for simulation

Parameter	Value
Nominal voltage, kV	110
Neutral grounding	Solid
Positive/zero sequence system impedance, Ohm	3,900+j9,900/ 3,200+j13,300
Positive/zero sequence line impedance per 1 km, Ohm/km	0,118+j0,142/ 0,268+j1,260
Line length, km	40
Loading power, MVA	14+j26

All types of faults (phase-to-ground, phase-to-phase, phase-t-phase-to-ground, three-phase) were imitated.

Complex amplitudes from instantaneous values were obtained by quadrature filters of industrial frequency using discrete Fourier transform of one period by sliding window method [15].

The analyzed time of the model operation was 20 full periods of industrial frequency - 0.4 s: 10 periods were for normal mode of operation; 10 for emergency.

2. Analysis of fault location error distribution along power line length under voltage characteristics deviations variations

Relative fault location error is determined by formula (6):

$$\varepsilon = \frac{x_e - x_r}{L} \cdot 100\% , \quad (6)$$

, where x_r real distance to fault; L line length (Fig.1).

The fault location error distributions over the line length during variation of voltage characteristics deviations on the example of phase A phase-to-ground fault for the Ericsson method are shown in Figure 3. Similar distributions have been obtained for all studied fault location methods and types of faults.

Analysis of Figure 3 shows that frequency deviation has the greatest impact on the accuracy of the emergency state fault location. For a single rapid voltage changing and supply voltage unbalance, the error of the fault location during variation of voltage characteristics deviations is explained by the methodological error of the implemented algorithms. The noted patterns are qualitatively repeated for all investigated fault location methods in any types of fault.

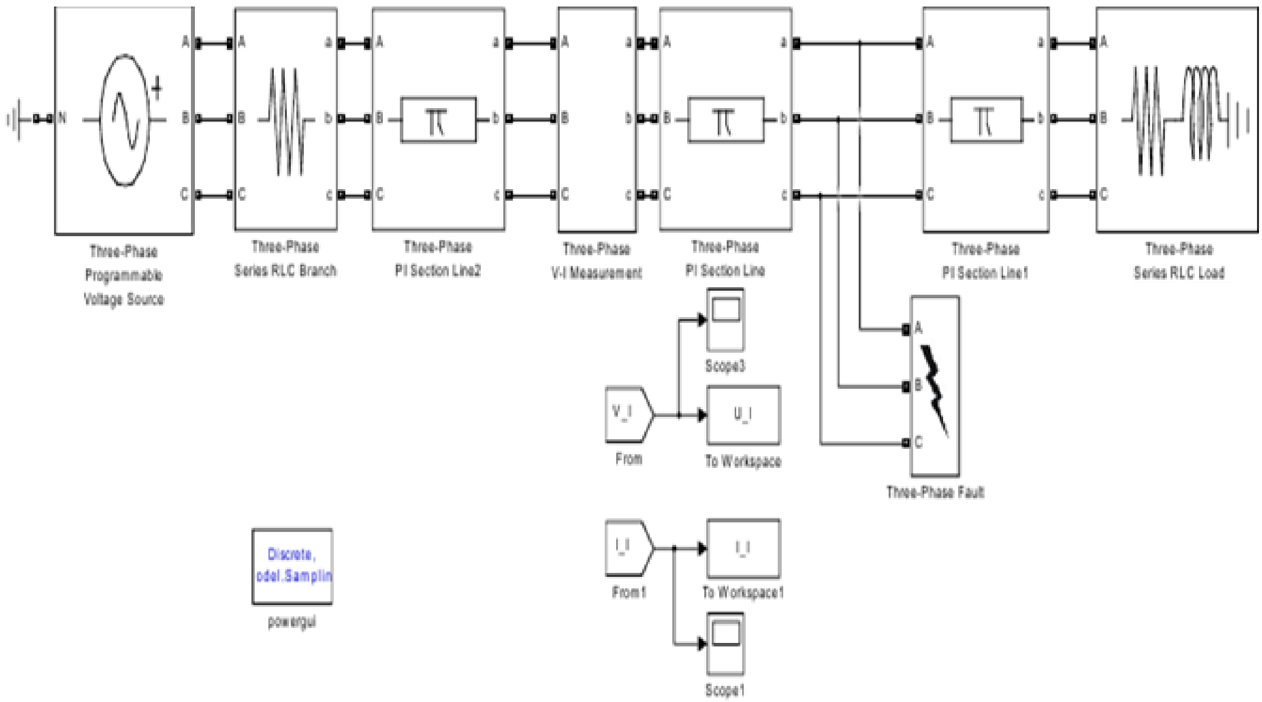

Fig. 2 Scheme of imitation model in Simulink

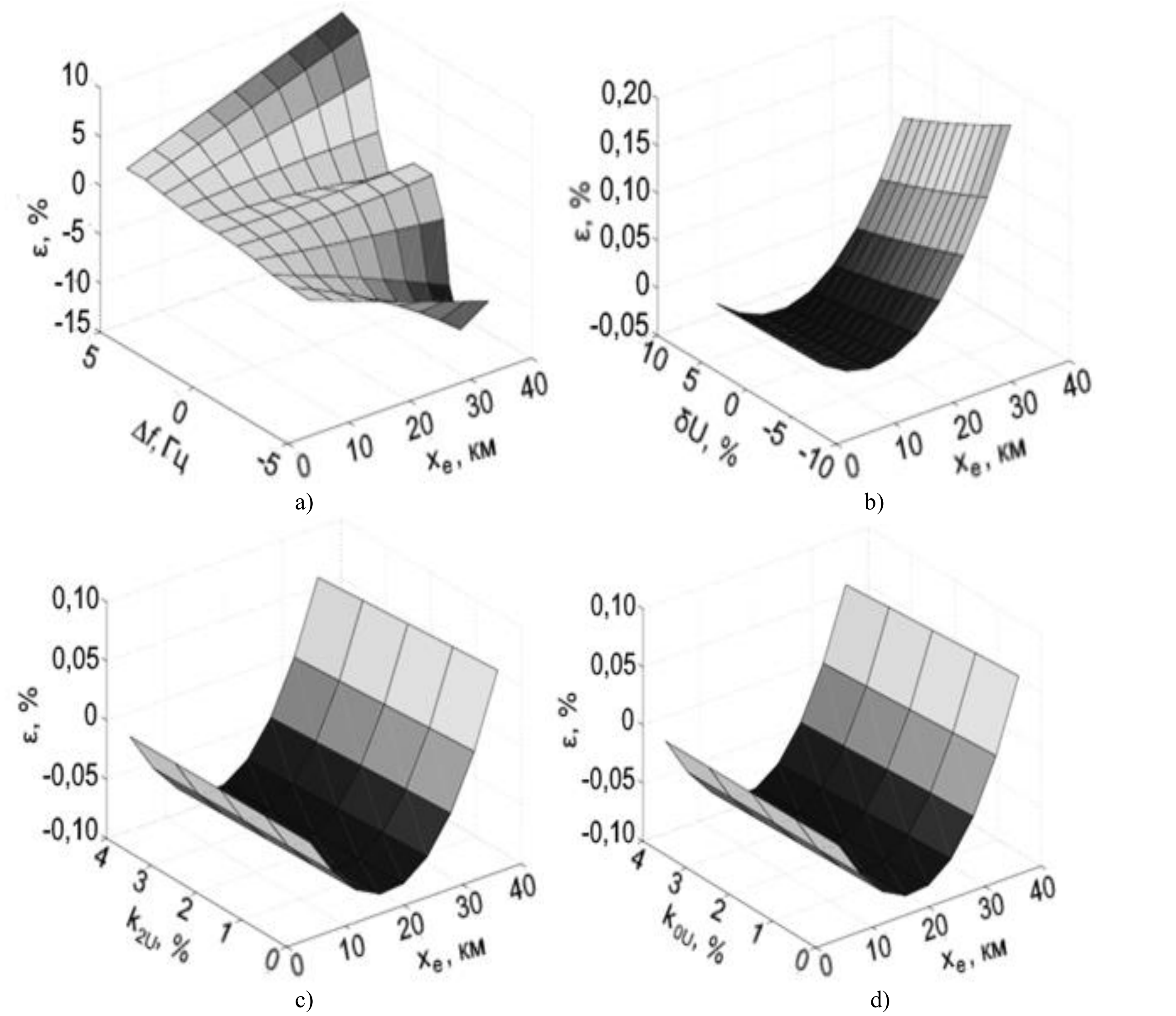

Fig. 3 Distribution of relative error of Ericsson method phase-to-ground faults at variation of: a) frequency deviation; b) single rapid voltage changing; c) negative sequence supply voltage unbalance; d) zero sequence supply voltage unbalance

3. The way of adaptation of emergency state fault location algorithms to voltage characteristics deviations.

Figure 4 shows the flow chart of the algorithm implementing the way of adaptation of emergency state fault location to voltage characteristics deviation - the algorithm of emergency state fault location adaptation to voltage characteristics deviations.

In case of fault, current and voltage oscillograms are recorded and complex amplitudes of this margins are obtained by quadrature filters of industrial frequency. Further, recorded instantaneous values and obtained estimates of complex amplitudes of currents and voltages are used to check presence of deviations of voltage characteristics (for example, by algorithms proposed in [4]). If there is no deviation of voltage characrteristics, the result of fault location will be values obtained from non-adaptive formulas (1-5). In case of voltage characteristics deviation, the value of the nearest error is determined based on the results of simulation database of fault location methods error distributions along the length of the power line at voltage characteristics deviations. The result of fault location will be the value obtained by the adaptive formula (7).

$$x_f = x_e - \frac{\varepsilon_e \cdot L}{100}, \qquad (7)$$

, where x_f – fault location evaluation from measuring point after adaptation, ε_e – nearest error in falt location errors database, corresponding to found voltage characteristic deviation and x_e.

Figure 5 shows the results of the proposed method of adaptation in case of random deviations of different voltage characteristics for phase-to-phase faults. As can be seen from the results for the simulated example, the application of the proposed adaptation method not only significantly reduces the error of the emergency state fault location methods from the deviation of the voltage characteristics, but also compensates for their own errors.

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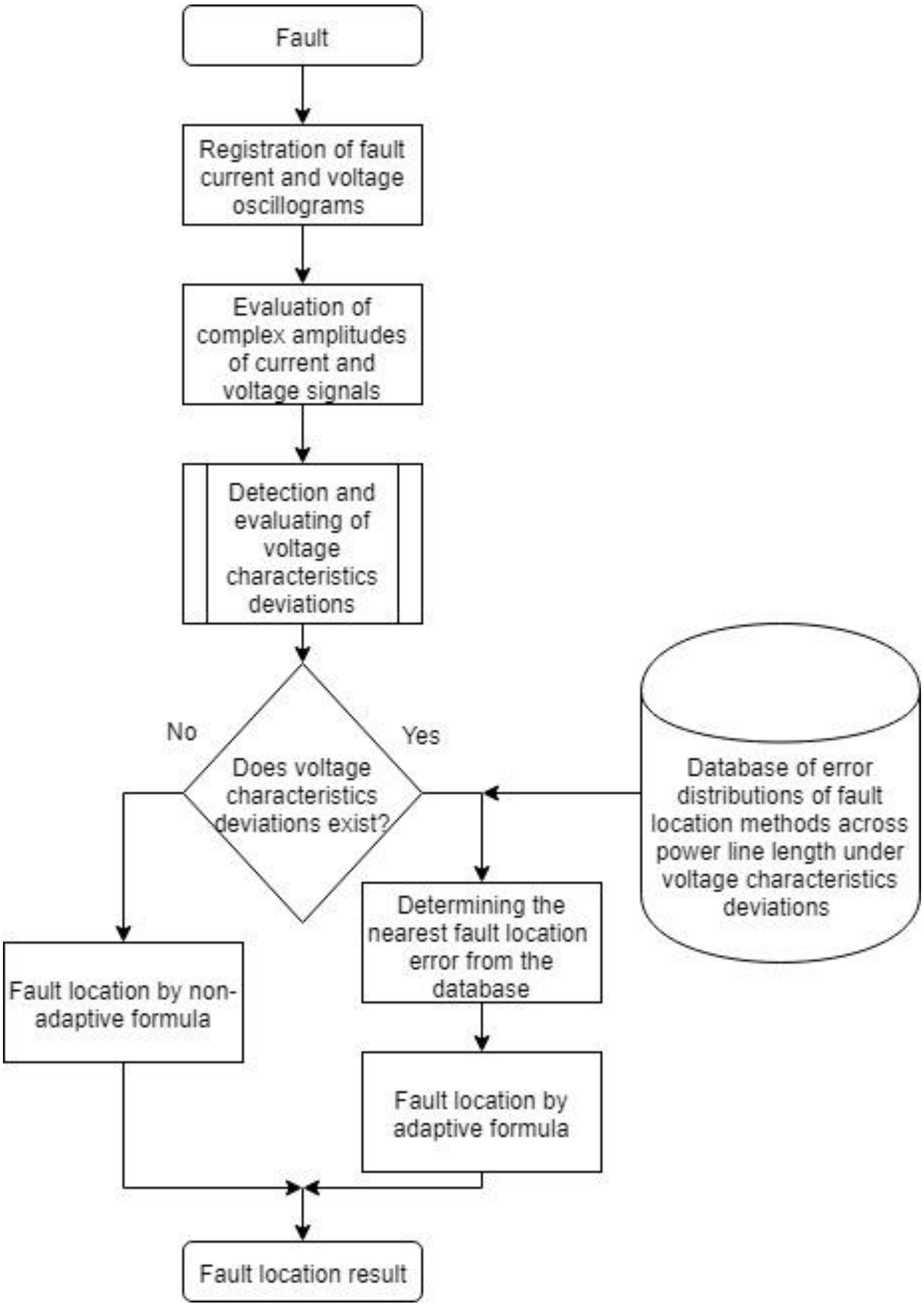
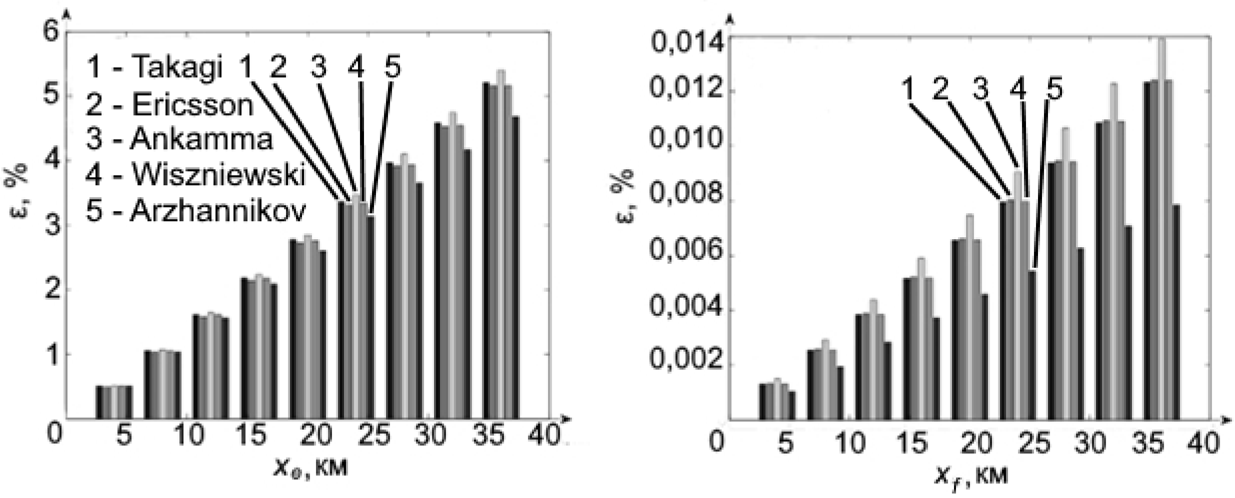


Fig. 4 – The algorithm of emergency state fault location adaptation to voltage characteristics deviations



a) e)

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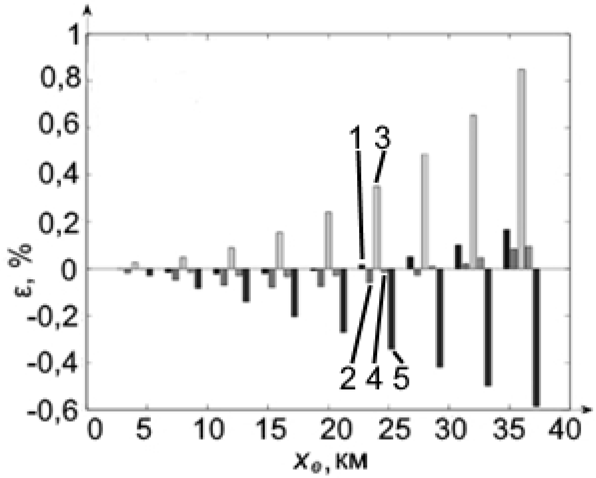

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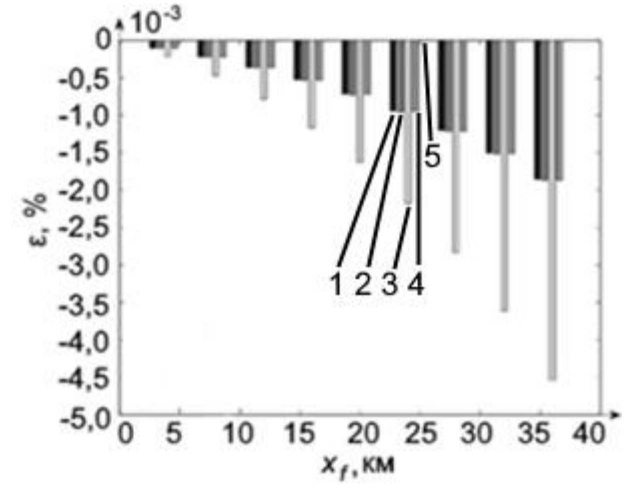

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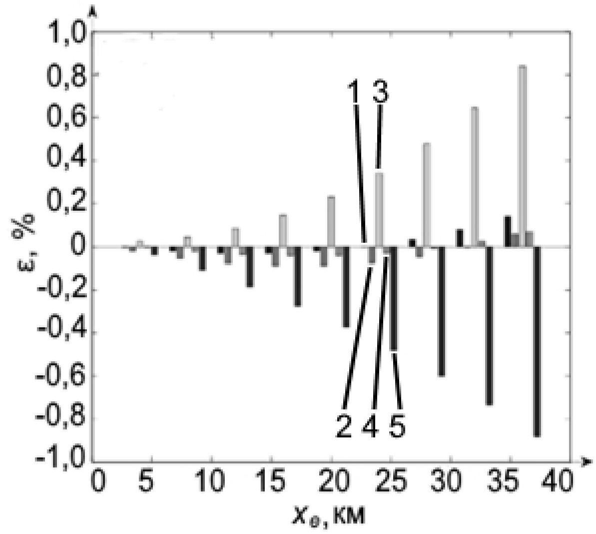

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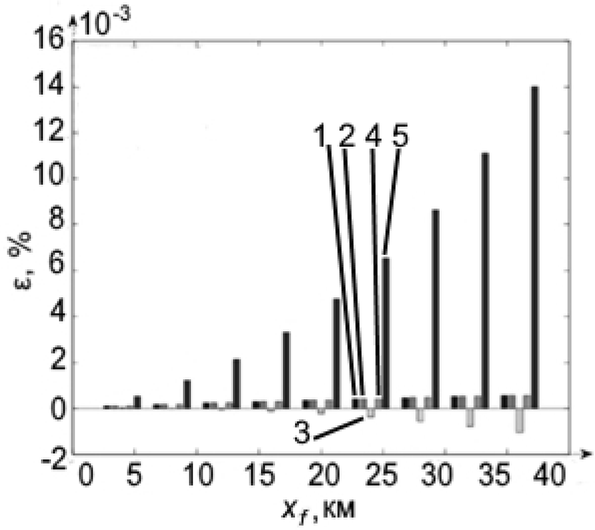

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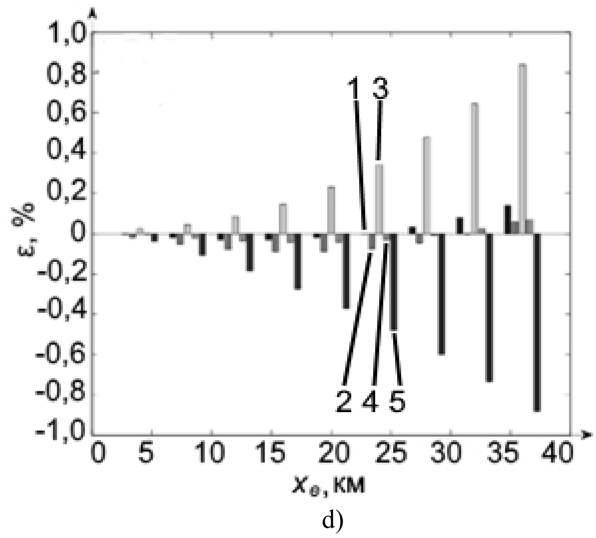

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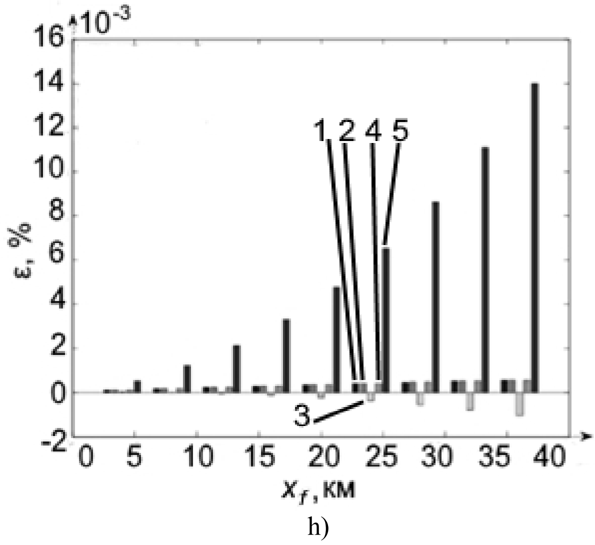

h)

Fig. 5 – Error distribution of emergency state fault location under voltage characteristics deviations: without adaptation: a) under frequency deviation $\Delta f = 3{,}14$ Гц; b) under single rapid voltage changing $\delta U = -2{,}66\%$; c) under negative sequence supply voltage unbalance $k_{2U} = 3{,}83\%$; d) under zero sequence supply voltage unbalance $k_{0U} = 3{,}71\%$; with adaptation: e) under frequency deviation $\Delta f = 3{,}14$ Гц; f) under single rapid voltage changing $\delta U = -2{,}66\%$; g) under negative sequence supply voltage unbalance $k_{2U} = 3{,}83\%$; h) under zero sequence supply voltage unbalance $k_{0U} = 3{,}71\%$;

Conclusion

Proposed way allows to correct both methodological error of fault location and additional error introduced into calculation by voltage characteristics deviations. Of scientific and practical interest is the extension of the studies carried out to the combinations of voltage characteristics deviations characteristic of specific groups of electric users existing in the normal operation of network. Further development of the study will be useful in correcting the results of multi-terminal fault location under voltage characteristics deviations.

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