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Modern Fault Location Technique for the Utility

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***Abstract*—Fault location (FL) is one of the most important diagnostics tasks in transmission and distribution networks. Due to long distances of the power lines, the search and repair can take a long time, while modern microprocessor technology can help automate the FL process and give a precise (up to a span) location of the fault. The fault extinction time is reduced dramatically. In this report, the basic sources of FL inaccuracy in existing techniques are discussed. The new algorithms and solutions are offered in order to reach higher accuracy of the fault position estimate in application. The proposed techniques of FL and power system modeling have been tested and put in operation, which approved its characteristics conformance. The application issues of the FL implementation in autonomous intelligent electronic devices (IEDs) are outlined on the basis of a response of a large utility.**

***Index Terms*-- fault location, iterative algorithms, fault resistance, IED, modeling.**

I. NOMENCLATURE

The terminology of the information theory [11] is extensively used in this report. The most important notions:

Object is an observed part of the power system network, e.g. transmission line.

OSM is an object simulation model; this model generates voltages and currents in the given conditions of the object.

OAM is an object algorithmic model; this model associates electrical quantities in the given point with the observed voltages and currents; the model is involved in recognition process.

Recognition is the process of an object parameter identification.

Identifiability is the feature of the object, which indicates the maximum possible (theoretical) sensitivity in recognition on the basis of the given object parameter.

II. INTRODUCTION

Modern protection devices, in addition to essential functions, offer user a number of services. A group of diagnostic services is amongst the most important, as far as they may be crucial to timely elimination of primary equipment faults, prevent system faults and decrease commercial losses due to unwanted tripping in power system. This report studies transmission line fault location (FL, distance-to-fault estimation) as one of the diagnostic tasks in medium and high voltage networks. Due to long distances the transmission lines are known as the most vulnerable power object. Besides, the search and repair of faults on transmission lines can take a long time. Modern personal computers and Intelligent Electronic Devices (IEDs) can help improve the fault elimination time dramatically thanks to full automation of the distance-to-fault estimation process and high precision of calculations – down to 1-2 spans.

There are several basic approaches in FL implementation:

– active probing systems [5];

– autonomous IEDs based on traveling waves principle [1, 15];

– autonomous IEDs based on distance principle: specialized on FL or protection [1];

– software FL products based upon analysis of information stored in digital recordings or other measuring methods [3, 12].

In addition to computational module, probing and traveling waves systems require specific high-voltage equipment and, therefore, become relatively expensive. IEDs and specialized software products operating on distance principle have proved to be comparatively inexpensive in installation, maintenance and operation, while the offered precision is acceptable. Quite often such IEDs are implemented on the same platform as protection. The circumstances facilitated the high popularity of these solutions in transmission networks application. However, following the nature of the electromagnetic process a limitation on recognition is found – the basic harmonic voltages and currents offer information for the fault accompanied with high level of fault currents. The low-current faults are of another character and should be analysed using other methods. Despite the known distance principle single- and double-side observation of voltages and currents, the techniques offer different precision. Hereinafter, the precision is understood as an opposite to inaccuracy, which is a deviation of a FL estimate coordinate in comparison to the real position of the fault (e.g. found on the line). The following factors of inaccuracy in these fault locators can be noticed [12, 18]:

– methods of informational components extraction (values of voltages and currents);

– methods of power system modeling;

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– fault criteria and fault coordinate search algorithm.

This report is dedicated to single-side measurement FL based upon voltages and currents phasors found for the fundamental frequency. The emphasis is put on algorithms implemented as personal computer software of embedded software. The special attention is paid to the methods of line models adequacy improvement, as far as adequacy is crucial to FL precision. The applied approach of information theory has demonstrated a great impact on precision in application. The new performance is illustrated on real recordings and utility response.

III. INFORMATIONAL ORIGINS OF THE FAULT LOCATION

Modern microprocessor devices, implementing diagnostic functions, offer opportunity to skip the physical nature of the signals and pay most of the attention to the electromagnetic process directly related to the faulted transmission line.

A. Informational theory

Informational theory is one of the theories that gained a significant success in fault conditions analysis. It comprises methods of the informational analysis and the theory of settings [2, 11]. According to the theory, each information basis (the input data for recognition) corresponds to its limit – identifiability. Identifiability is the feature of the power object under observation [7]; for a transmission line it indicates maximum identifiable fault resistance for each given fault location.

In application to fault location the following information should be gathered in order to achieve maximum performance: all currents and voltages in fault (actual) and, if possible, pre-fault values [10]. Modern fault recording devices offer this possibility thanks to the operative memory. A collection of actual and pre-fault values is the precondition to the pure fault conditions [6], which contains most of information for recognition. The fundamental frequency complex values correlate to each other in linear systems:

$$\underline{\mathbf{V}}_{\mathrm{pu}} = \underline{\mathbf{V}}_{\mathrm{ac}} - \underline{\mathbf{V}}_{\mathrm{pr}}, \tag{1}$$

where $\underline{\mathbf{V}}_{\mathrm{pu}}$, $\underline{\mathbf{V}}_{\mathrm{ac}}$ and $\underline{\mathbf{V}}_{\mathrm{pr}}$ are the generalized phasors of voltages and currents in pure fault (pu), actual (ac) and pre-fault (pr) (brought to the time of actual measurement) conditions.

B. Simulation and Algorithmic Modeling

According to informational analysis, the analysis of fault conditions is made using two types of models: object simulation model and object algorithmic model [2, 11]. OSM (Fig. 1a) simulates the power object and, therefore, an active system. The input values of conditions parameters are used to calculate outputs, which are voltages and currents at a given point of observation.

On the contrary, the OAM [4] (Fig. 1b), which can be set to represent actual or pure fault conditions, transforms observed values to the given point of the object. The pure fault model is preferable, as it concentrates more information about the fault. In this case all values correspond to the only source in the fault point. This means better environment for the fault location algorithm due to explicit relations between values, which correspond to fault boundary conditions.

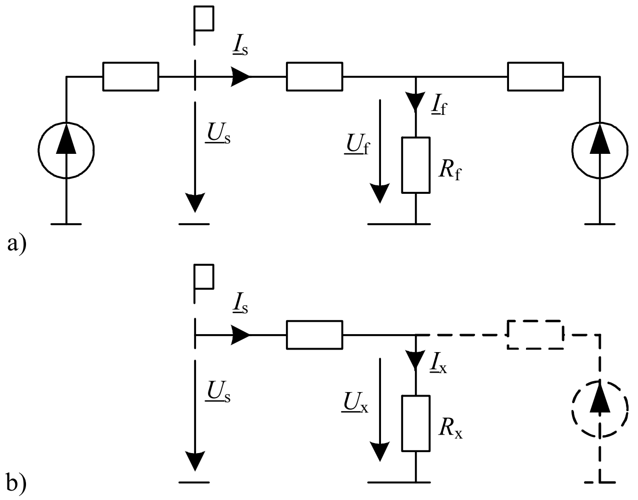

Fig. 1. Simulation (a) and algorithmic (b) models of a transmission line

For a phase-to-ground fault the boundary conditions (at the fault point) are zero voltage of the faulted phase and zero value of fault currents in unfaulted phases, e.g. for the special phase A: $\underline{U}_{\mathrm{Af}} = 0$; $\underline{I}_{\mathrm{Bf}} = 0$; $\underline{I}_{\mathrm{Cf}} = 0$.

Phase-to-phase fault is accompanied by other conditions: equalities for phase-to-phase voltage, fault current of the unfaulted phase and zero-sequence current, e.g. for the special phase A: $\underline{U}_{\mathrm{Bf}} - \underline{U}_{\mathrm{Cf}} = 0$; $\underline{I}_{\mathrm{Af}} = 0$; $\underline{I}_{0\mathrm{f}} = 0$.

Most of the modern FL techniques contain implicit description of algorithmic models, which adopt certain presumptions. This concerns even formula based methods. As a rule, simplification of the model leads to inaccuracy of the FL algorithm. In application many lines contain structural peculiarities, e.g. taps, mutual inductance to other lines, non-homogeneous electrical parameters along the line. These features may be not very important for correct protection operation, but they are significant to the pattern of the electromagnetic process. Only comprehensive models, with minimum number of presumptions, can secure high accuracy of fault location [6, 9, 19]. The application can now rely on modern microprocessor technology, which is able to perform required complex computations sufficiently fast.

C. Fault Criterion

The most general pattern is perceived as a fault criterion: equivalent fault impedance in the fault point is presumed to be resistive. This is expressed in a relation between voltages and currents (found using OAM) at the fault point:

$$Q(x_\mathrm{f}) = \mathrm{Im}\left(\underline{U}_\mathrm{f}\,\overset{*}{\underline{I}}_\mathrm{f}\right) = 0\,. \tag{2}$$

This expression of the goal function $Q(x_\mathrm{f})$ provides high degree of convergence in comparison to the root-mean-square deviation for the observed and model values (voltages and currents) [16]:

$$\sigma_1 = \left[\frac{1}{m}\sum_{i=1}^{m}\frac{\left|\underline{V}_{i\alpha} - \underline{V}_{i\beta}\right|^2}{\max(\underline{V}_{i\alpha}^2, \underline{V}_{i\beta}^2)}\right]^{\frac{1}{2}}. \tag{3}$$

There are modifications of the goal function depending on fault type. These functions take into account boundary conditions and display less sensitivity to distortion in informational components.

Besides, the goal function (2) helps to solve the multidimensional problem (3) in a single dimension – fault coordinate. The values of voltages and currents at each given position are found using object algorithmic model. The power system is counted linear and, therefore, each calculation point relates to the observation values by means of a transfer coefficient. Thus, there is a possibility to trace the goal function along the line. The search can be accelerated using an optimization algorithm.

If the measurement and modeling inaccuracy is negligible, the procedure converges to the precise distance to the fault.

FL algorithms based on simplified formulae contain similar presumption of fault resistive nature. The application reveals the main difference in ability to adapt to various line structures. These are mainly focused on homogeneous line. On the contrary, the proposed criterion (2) offers convenient formalization for the case, when the line consists of a number of known non-homogeneous sections including taps and mutual inductance.

IV. HIGH PRECISION MODELS

As indicated above, precision of the FL algorithm highly depends on its explicit or implicit power system model and varies in a wide range for different structures. In order to avoid algorithmic FL inaccuracy, several techniques are considered in this paper.

The adequacy requirement imposed on the model means equivalenting of every detail of the real transmission line, i.e. non-homogeneous specific parameters along the line. There are several reasons for this: wire type and tower construction variation, taps and transformers, mutual inductance to other lines. In practice the line is usually divided into sections, each section is conceived as homogeneous, with constant specific parameters. The introduced inaccuracy is generally much smaller than the measurement errors, if the number of sections is sufficient. Collection of the detailed and precise primary information at the utility side is a difficult and laborious task, but all efforts are refunded with the high precision.

A. Taps equivalenting

Transmission and distribution lines can be plain or tapped. For better accuracy it is highly recommended to model each tap, taking into account its transformer neutral status. The resulting inaccuracy depends upon power consumption of the tap, it can count several per cent of the total line length. Despite wide-spread practice to consider taps only for phase-to-ground faults, modeling indicates that multi-phase faults are influenced too. Thus, taps should be introduced into positive-, negative- and zero-sequence schemes. It is generally accepted that a tap and its load are regarded as a constant (in time) passive impedance. Below is the multi-pole technique [4, 8] applied to modeling.

First, each section of the line is represented in the form of a multi-pole. The multi-poles are represented in the form A (direct transfer matrix). Then, the whole network is represented as interconnected multi-poles called cascade.

A sample network of three sections is illustrated in Fig. 2: sections before the tap, after the tap and the tap itself represented by corresponding matrices $\underline{\mathbf{A}}'$, $\underline{\mathbf{A}}''$, $\underline{\mathbf{A}}^{\text{tap}}$.

Out of the boundary conditions

$$\underline{U}''_{\text{tap}} = 0; \tag{4}$$

$$\underline{U}'_{\text{tap}} = \underline{U}'_{\text{tap,eqv}} = \underline{U}''_{\text{tap,eqv}}; \tag{5}$$

$$\underline{I}'_{\text{tap,eqv}} - \underline{I}''_{\text{tap,eqv}} = \underline{I}'_{\text{tap}}; \tag{6}$$

one can derive an expression for transformation of the tap matrix into the matrix in the form A to include in the general cascade:

$$\underline{\mathbf{A}}^{\text{tap,eqv}} = \begin{bmatrix} 1 & 0 \\ \underline{\mathbf{A}}_{22}^{\text{tap}} (\underline{\mathbf{A}}_{12}^{\text{tap}})^{-1} & 1 \end{bmatrix}. \tag{7}$$

This formula is valid for both symmetrical components scheme and phase-domain scheme.

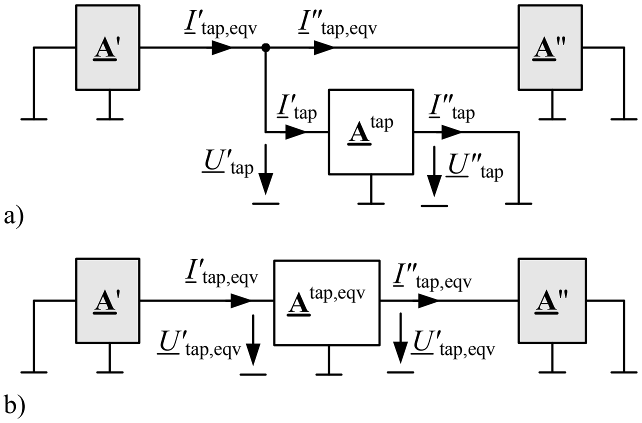

Fig. 2. Tap equivalenting in the form of a multi-pole

B. Parallel Lines Equivalenting

The parallel lines require special attention when making a model for the fault locator. The importance of correct mutual inductance calculation is outlined and the case is thoroughly studied in [13] as a function of transposition length, parallel section length and the distance to the parallel line. Coupled lines (two or more on the same towers) give the most influence. Single-phase fault current may vary up to 10 % relative to the value without mutual inductance.

In modern devices, the mutual inductance problem is usually solved using one of the methods: direct influence calculation based on measured residual current of the parallel line, equivalenting of the zero-sequence (or phase) impedance with regard to all parallel lines. The OAM processes the zero-sequence current just as any other source in the model. Both methods are discussed below.

If the zero-sequence current of the parallel line is unknown, the problem is solved as an air transformer, which comprises the two transmission lines (Fig. 3). The Kirchhoff's circuit laws:

$$\underline{U}_{\text{s}(0)} - \underline{U}_{\text{r}(0)} = \underline{Z}_{(0)} \underline{I}_{(0)} + \underline{Z}_{(01)} \underline{I}_{(1)}; \tag{8}$$

$$0 = \underline{Z}_{(01)} \underline{I}_{(0)} + \underline{Z}_{(1)} \underline{I}_{(1)}. \tag{9}$$

The parallel line current can be expressed from (9). Substituting the value in (8) one can have a known expression for the equivalent impedance of the observed line with the influence from the parallel one:

$$\underline{Z}_{\text{eqv}} = \underline{Z}_{(0)} - \frac{\underline{Z}^2_{(01)}}{\underline{Z}_{(1)}}. \tag{10}$$

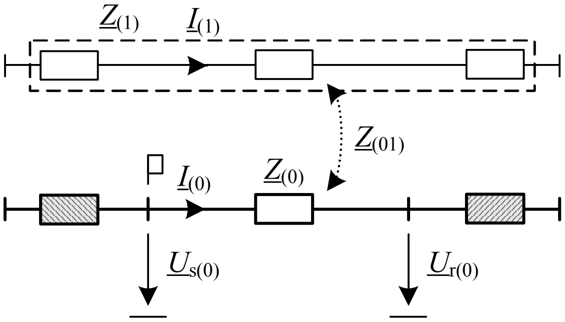

Fig. 3. Scheme of single parallel line current influence

Suppose there are several lines in parallel to the observed one (Fig. 4a). The complexity of traditional settings calculation grows significantly. The system of interconnected lines should be considered, as far as each parallel line induces voltage on the observed line, as well as on all other lines. This problem is often solved for one or two lines. To find a comprehensive solution, start with the general equation:

$$\underline{\mathbf{I}} = \underline{\mathbf{Z}}^{-1}\underline{\mathbf{U}}, \tag{11}$$

where $\underline{\mathbf{I}}$ and $\underline{\mathbf{U}}$ are phasors of currents and voltages in the lines;

$$\underline{\mathbf{Z}} = \begin{bmatrix} \underline{Z}_{(0)} & \underline{Z}_{(01)} & \cdots & \underline{Z}_{(0n)} \\ \underline{Z}_{(01)} & \underline{Z}_{(1)} & \cdots & \underline{Z}_{(1n)} \\ \cdots & \cdots & \cdots & \cdots \\ \underline{Z}_{(0n)} & \underline{Z}_{(1n)} & \cdots & \underline{Z}_{(n)} \end{bmatrix}$$

is the matrix of zero-sequence proper and mutual impedances of n interconnected lines;

$\underline{Z}_{(0)}$ is the zero-sequence impedance of the section of the main line, which is influenced by other lines under consideration;

$\underline{Z}_{(1)}$, …, $\underline{Z}_{(n)}$ are total zero-sequence impedances of the parallel lines. Each impedance is a total of line impedance and its systems;

$\underline{Z}_{(01)}$, $\underline{Z}_{(02)}$, …, $\underline{Z}_{(0n)}$ are mutual impedances between the main line and parallel lines;

$\underline{Z}_{(12)}$, $\underline{Z}_{(13)}$, …, $\underline{Z}_{(1n)}$, $\underline{Z}_{(23)}$, …, $\underline{Z}_{((n-1)n)}$ are mutual impedances between corresponding parallel lines.

Each parallel line voltage is set zero, hence, the system of equations (11) can be solved for the main line equivalent impedance:

$$\underline{Z}_{\text{eqv}} = \frac{1}{[\underline{\mathbf{Z}}^{-1}]_{(1,1)}}, \tag{12}$$

where $[\underline{\mathbf{Z}}^{-1}]_{(1,1)}$ is the first element of the first row in the inversed matrix of $\underline{\mathbf{Z}}$.

Thus, substituting the calculated value (12) instead of zero-sequence impedance for the observed line, one can take into account all parallel lines.

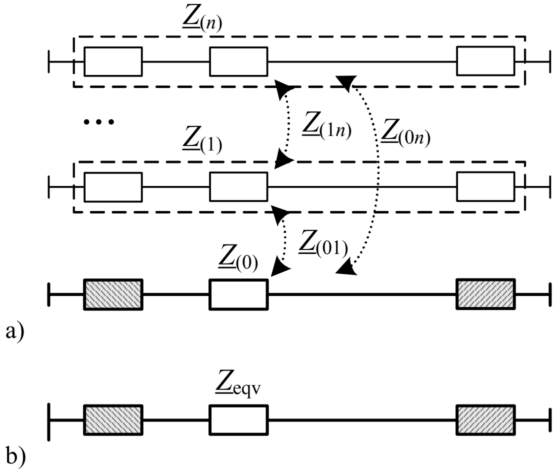

Fig. 4. Observed line and its mutual inductance. Equivalenting

Obviously, for two lines (one main and one parallel) the equation (10) can be derived from (11) and (12). In the given example, equality (11) is expressed as follows:

$$\begin{bmatrix} \underline{I}_{(0)} \\ \underline{I}_{(1)} \end{bmatrix} = \begin{bmatrix} \underline{Z}_{(0)} & \underline{Z}_{(01)} \\ \underline{Z}_{(01)} & \underline{Z}_{(1)} \end{bmatrix}^{-1} \begin{bmatrix} \underline{U}_{\text{s}(0)} - \underline{U}_{\text{r}(0)} \\ 0 \end{bmatrix}. \tag{13}$$

The transformation (12), directly leads to the equality (10).

Formula (12) takes into account magnetic influence, but not electrical interconnection between the lines. If the lines are connected, better modeling precision is reached using zero-sequence current of the most influencing line. This way the necessary voltage effect of the parallel line is introduced immediately as a value $\underline{Z}_{(01)}\underline{I}_{(1)}$ in expression (8). This will in future be possible for multiple parallel lines thanks to IEC 61850-9-2 substation communication standard.

The proposed method is not related to a specific FL algorithm or its OAM and, therefore, can be implemented for automation of any settings calculation.

In general, one should pay attention to the mode of operation of each parallel line. If maximum and minimum values of zero-sequence impedance deviate too much, it is reasonable to set up several setting groups for the fault locator.

V. PRACTICAL VERIFICATION OF THE PROPOSED TECHNIQUES

A. Sample Faults Analysis

Application issues of the proposed methods are illustrated on data obtained in real fault conditions. Recordings made on a 220 kV transmission line “Cheboksary HPP – Chigashevo”, 75,6 km (Fig. 5) have been taken as inputs to the algorithms. The observed line is not homogeneous, the wires and the parallel lines set varies along the line. The mutual inductance was counted in the algorithmic model according to (12).

The analyzed recordings corresponding to the observation in substation “Cheboksary HPP” are shown in Fig. 6: one recording (a) relates to phase A to ground fault at a distance 22,5 km; the other recording (b) displays phase-to-phase-to-ground fault (B–C–N) at a distance 45,0 km.

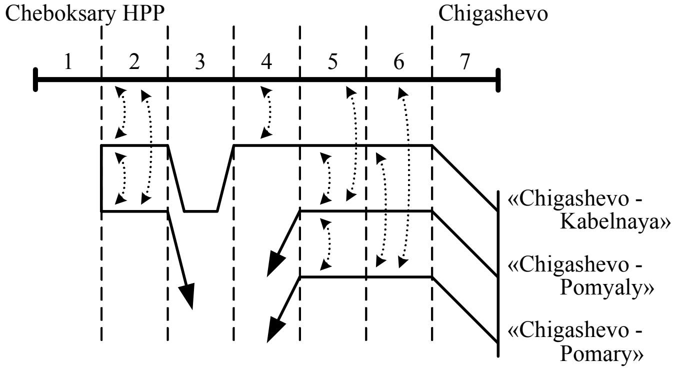

Fig. 5. Structure of the transmission line «Cheboksary HPP – Chigashevo»

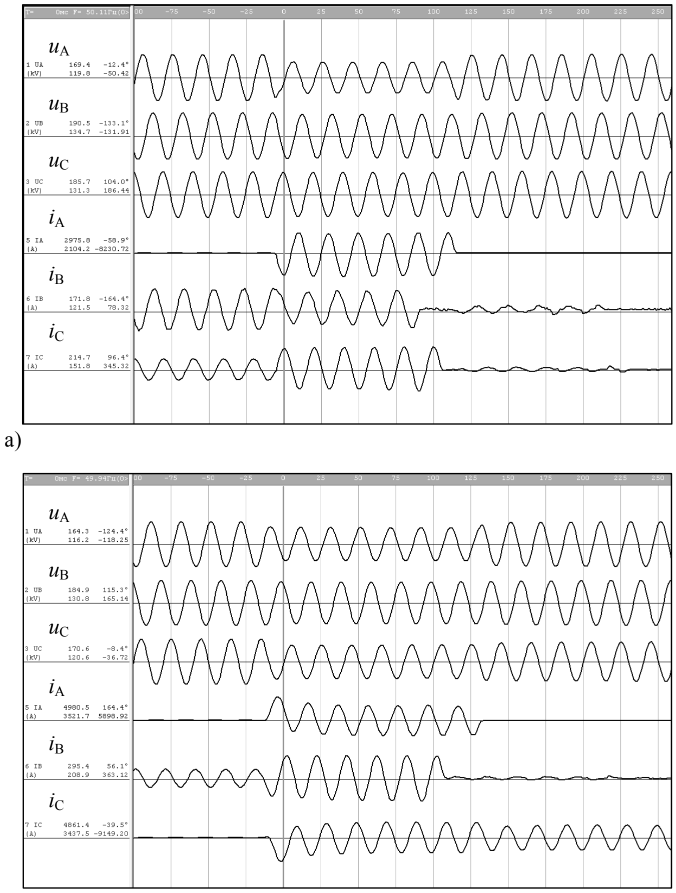

Fig. 6. Recordings of faults in the transmission line "Cheboksary HPP – Chigashevo"

The informational components (complex values of voltages and currents) have been extracted from the recordings using a specialized software. Then, the goal function $Q(x_f)$ values along the line have been estimated by means of an algorithmic model (Fig. 7a and 7b). The curves in Fig. 7 indicate the point of fault location in each case. The zero-crossing corresponds to the distances 22,2 and 43,9 km from the substation "Cheboksary HPP". This brings up inaccuracy of the FL algorithm on real data – 0,3 and 1,1 km accordingly. The higher value can be decreased if the data uncertainty for section 2 is overcome. The mistake is lower than 1,5 % of the line length. The algorithm lets estimate the fault resistance, which in these cases counts 5 and 15 Ohms.

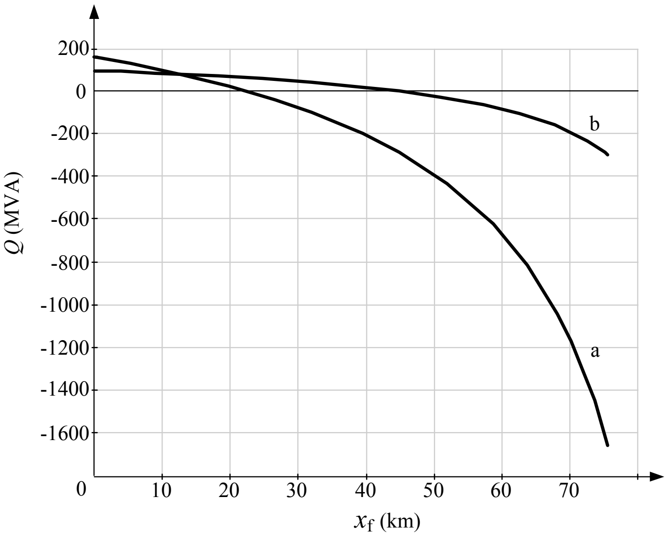

Fig. 7. The goal function values along the transmission line

B. *Application of Autonomous Fault Locators*

The proposed algorithms are implemented in the specialized IED for autonomous fault location – TOP-Locator. The general theoretical approach has been in operation for a long time as a software product [12] and it has proved to be a precise fault locator. The IED improves the FL process, as it is capable of performing complete cycle of operations:

– continuous monitoring of the transmission line;

– automatic recording in case of a fault with embedded starting elements (the selective mode of operation is also possible);

– fault analysis;

– indication (on local screen or signaling to the computer network) of the calculated distance and informational components.

The microprocessor terminal automatically selects fault and pre-fault conditions intervals, extracts informational components. The phase selection function is crucial for choosing the most suitable goal function. The optimal fault coordinate is then found together with fault resistance and other service parameters.

The practical implementation of precise fault locators is restrained by lack of detailed line information and laborious calculation. For TOP-Locator, a new approach has been accomplished – automatic settings calculation on the basis of line aerial photography reports. The user supplies design data about wire and tower types and other information, which is the input to compute line parameters. Besides, the interfaces to wide-spread network modeling software have been set up. The total fault location tuning costs have been reduced, while the accuracy has been increased.

The terminal has found an application on transmission and distribution 10-220 kV lines of various configurations. The recorded accuracy in application counted several spans. The set of services includes measuring circuits supervision. This function is important in commissioning, as well as in operation and maintenance, because a probable malfunction in fault conditions is avoided and the accuracy is guaranteed.

VI. CONCLUSION

The applied approach of the information theory has demonstrated a great impact on precision, which is significantly higher than in ordinary fault location algorithms due to complete usage of the information. A universal modeling technique has been developed to count for non-homogeneous lines with taps and influence of parallel lines. The theoretical location methods together with novel settings calculation technique have been tested and approved in practice: fault recordings reconstruction and utility response endorse high accuracy of the solution.

VII. ACKNOWLEDGMENT

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VIII. REFERENCES

[1] E. Arzhannikov, V. Lukoyanov, and M. Misrikhanov, *Fault location in high-voltages transmission lines*, Moscow: Energoatomizdat, 2003, p. 272.

[2] Y. Liamets, E. Efimov, and G. Nudelman, “Theory of settings,” in *Proceedings of research conference dedicated to 70th anniversary of “Energosetproekt” institute ORZAUM: Topical problems in relay protection*, Moscow, Russia, 2001, pp. 56-58.

[3] Y. Liamets, V. Iljin, and N. Podshivalin, “The program set for the analysis of disturbance processes and fault location in transmission lines,” *Electrichestvo*, no. 1, 1996, pp. 2-7.

[4] Y. Liamets, G. Nudelman, and A. Pavlov, “Algorithmic models of electical systems,” in *Proc. the Chuvash Republic Academy of electrotechnic sciences*, no. 1, 1999, , pp. 42-49.

[5] A. Kulikov, *Digital distance fault location in transmission lines*, Moscow: Energoatomizdat, 2006, p 315.

[6] Y. Liamets, E. Efimov, V. Efremov, V. Iljin, A. Pavlov, N. Podshivalin, G. Nudelman, and J. Zakonjšek, “Relay protection with extreme fault identification,” in *Proc. 12th Int. Conf. Power System Protection*, Bled, Slovenia, 2000, pp. 1-12.

[7] Y. Liamets, E. Efimov, G. Nudelman, and J. Zakonjšek, “The principle of relay protection information perfection,” presented at CIGRE SC 34 Colloquium and Meeting, Session Papers, Sibiu, Romania, 2001, Report 112.

[8] Y. Liamets, S. Ivanov, A. Chevelev, D. Eremeev, G. Nudelman, and J. Zakonjšek, “Algorithmic models and virtual relays in distance protection implementation,” in *Proc. of 8th Int. Conf. Developments in Power System Protection*, Amsterdam, Netherlands, 2004, pp. 441-444.

[9] Y. Liamets, A. Podchivaline, A. Chevelev, G. Nudelman, and J. Zakonjšek, “Equivalent transforms of models, conditions and measurements in relay protection,” in *Proc. 8th Int. Conf. Developments in Power System Protection*, Amsterdam, Netherlands, 2004, pp. 76-79.

[10] Y. Liamets, A. Podchivaline, A. Chevelev, G. Nudelman, and J. Zakonjšek, “Informational tasks of relay protection,” presented at CIGRE SC B5 Colloquium and Meeting, Sydney, Australia, 2003, Report 213.

[11] Y. Liamets, S. Ivanov, A. Podchivaline, G. Nudelman, and J. Zakonjšek, “Informational analysis – new relay protection tool,” in *Proc. of 13th Int. Conf. Power System Protection*, Bled, Slovenia, 2002, pp. 197-210.

[12] V. Efremov, Y. Liamets, N. Podshivalin, V. Iljin, and G. Nudelman, “Program set for the analysis of disturbances and fault location in transmission lines DISAN/LOCATOR,” presented at CIGRE SC 34 Colloquium and meeting, Florence, Italy, 1999, Report 34-205.

[13] A. Podchivalin and Y. Romanov, “Analysis of parallel transmission lines models errors,” in *Proc. IV All-Russia Scientific Technical Conf. Informational technology in Electrical Engineering and Power Industry*, Cheboksary, Russia, 2002, pp. 306-308.

[14] Y. Liamets, S. Ivanov, A. Chevelev, D. Eremeev, G. Nudelman, and J. Zakonjšek, “Algorithmic models and virtual relays in distance protection implementation,” in *Proc. 8th Int. Conf. Developments in Power System Protection*, Amsterdam, Netherlands, 2004, pp. 441-444.

[15] C. Y. Evrenosoglu and A. Abur, “Travelling wave based fault location for teed circuits,” *IEEE Transactions on Power Delivery*, vol. 20, no. 2, pp. 1115-1121, April 2005.

[16] Y. Liamets, A. Podchivaline, S. Ivanov, and G. Nudelman, “Interval transform of information and its applications in relay protection,” presented at Int. Conf. IEEE St-Petersburg PowerTech, Saint-Petersburg, Russia, 2005, Report 31.

[17] Y. Liamets, G. Nudelman, A. Podchivaline, and J. Zakonjšek, “About informational theory of relay protection,” in *Proceedings of the Russian Federation Academy of electrotechnic sciences*, no. 1, 2009, pp. 32-44.

[18] Yuan Liao and M. Kezunovic, “Optimal estimate of transmission line fault location considering measurement errors,” *IEEE Transactions on Power Delivery*, vol. 22, no. 3, pp. 1335-1341, Jul. 2007.

[19] A. Gopalakrishnan, M. Kezunovic, S. M. McKenna, and D. M. Hamai, “Fault location using the distributed parameter transmission line model,” *IEEE Transactions on Power Delivery*, vol. 15, no. 4, pp. 1169-1174, Oct. 2000.

IX. BIOGRAPHIES

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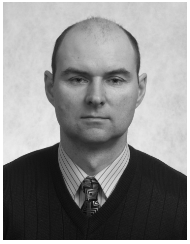

Eduard Terentyev was born in 1966 in Russia. He received his Lic. Eng. from the Moscow State Open University, Russia, in 1993. Since 1996 he has been with Kolomenskie ES MOESK, Moscow. He is currently the assistant manager of the protection service in the company. His interests primarily concern protection testing, exploitation, setting.