

Statistical Algorithms for Fault Location on Power Transmission Lines

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Abstract-- This paper summarizes the application of statistical algorithms for fault location on power transmission lines. The proposed fault location algorithms utilize statistical information about the undefined parameters such as equivalent impedances of the system at the unmonitored end of the transmission line, or those containing random errors. Knowledge about the distribution of these values results in more accurate fault location for lines with grounded neutral, especially in case of distant short circuits through a large transient resistance. The proposed algorithms are based on modelling of the faulted line and the Monte-Carlo method. The algorithms calculate not only the expected value of the distance to the fault, but also another important additional characteristic for the fault location, namely, the length of the line segment, where the short circuit could have occurred. The algorithm retains its applicability in cases of all the simple fault types and needs minor modifications for conditions when one breaker is opened and a single-phase fault is sustained.

Index Terms-- Fault Location, Statistics, Transmission Lines

I. INTRODUCTION

THE opening of the electricity market and growing environmental concern raise several new issues to be met by transmission system operators: the system must be operated in more uncertain and fast changing conditions, difficulties in proving the necessity of investments and problematic acquiring the new line routes. This leads to a more stressed operation and can lead to a decrease of the reliability level. Thus, maintaining the operational condition of the power system elements and particularly, the transmission lines that are prone to external impacts, becomes critical.

Power lines of any voltage level are subjects to faults. To expedite repairs and fast restoration of power supply it is important to know where the fault is located. During the last few decades progressive fault location schemes benefited from the development of the digital techniques and microprocessor-based systems [1]-[3]. However, accuracy of the distance to the fault determination is affected by several stochastic factors. Among the major affecting factors, it could be mentioned the combined effect of the load, fault resistance and

equivalent impedances of the power systems connected to the ends of transmission line [3]-[8], as well as imprecisions of the measurements and line parameters. Consequently, the accuracy of the fault location may be insufficient.

Since the control centre is not provided with the information on the margins of the possible error of distance determination plus usually has an experience of considerable errors presence in fault location estimation, the length of the line segment subjected to inspection is in practice defined assuming the presence of maximal error, even in those cases when it is not likely that such error will appear. This can lead to less effective exploitation - either causing delays in power flow restoration or, sometimes, leaving the fault cause undiscovered. In the previous works [5]-[7] we have discussed the approach to calculate of the probabilistic distribution law of the distance, in addition to the usually used value "expected distance to the fault". Such calculations can be based on statistical information utilization and the Monte-Carlo method. In these publications the most common case of single phase to ground fault was considered. This paper covers other cases as well as discusses the generality of the algorithm.

II. THE THEORETICAL BACKGROUND

A. Power system model

Let us consider a faulted transmission line with distributed parameters connecting two power systems with known equivalent impedances (Fig. 1).

The two-port network theory [9] assumes two equations of the following form (1) to express voltage and current at one pair of terminals in terms of quantities at the other pair.

$$\begin{aligned} U_{i1}'' &= D_{i1}U_{i1}' - B_{i1}I_{i1}' \\ I_{i1}'' &= -C_{i1}U_{i1}' + A_{i1}I_{i1}' \end{aligned} \quad (1)$$

By defining the propagation constant per length unit for symmetrical transmission line with distributed parameters:

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (2)$$

and the characteristic impedance of the line:

$$Z_c = \sqrt{(R + j\omega L)/(G + j\omega C)} \quad (3)$$

the A_{i1} , B_{i1} , C_{i1} , D_{i1} parameters can be evaluated, as [9]:

$$A_i = D_i = \cosh(\gamma \cdot L_F) \quad (4)$$

$$B_i = Z_c \cdot \sinh(\gamma \cdot L_F) \quad (5)$$

$$C_i = \frac{1}{Z_c} \cdot \sinh(\gamma \cdot L_F) \quad (6)$$

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where L_F - is the distance to the fault.

Taking into consideration that in the fault point, in general case behind the fault impedance, there is an equality of sequences powers S_i [9]:

$$\sum_{i=0}^2 S_i = U_1 I_1^* + U_2 I_2^* + U_0 I_0^* = 0, \quad (7)$$

where U_i , I_i is respectively voltage and current of sequence i in the fault point, I^* is complex conjugate value of current I . Assuming that the fault impedance is purely resistive and therefore consumed power is also active, it can be obtained:

$$\text{Im} \left[\sum_{i=0}^2 S_i \right] = \text{Im} \left[\sum_{i=0}^2 \left(U_{i1}'' \cdot I_i^* \right) \right] = 0. \quad (8)$$

Equation (8) can be employed as a basic one for several developed algorithms [5]-[7] and fault types as shown below.

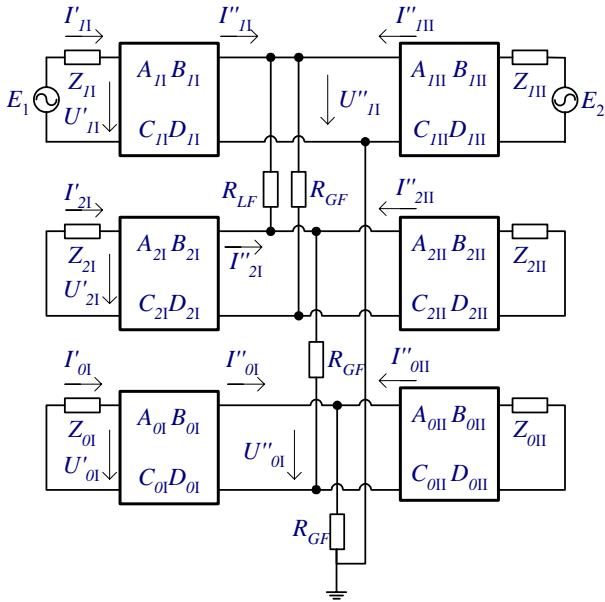


Fig. 1. Diagram of the transmission line in single phase to phase to ground fault conditions

B. Single-phase-to-ground case

The basic equations, results and aspects of the algorithm in case of single phase to ground fault were described by the authors in [5]-[7]. These results are used in this paper only to summarize the method properties.

C. Double-phase-to-ground fault case

This type of fault introduces unsymmetry in a power line model. Nonetheless for application of the symmetrical components method the fault could be modelled as simultaneous single phase to ground and phase-to-phase faults that occurred at the same point (Fig. 1.). Still (8) is true. Let us observe the necessary modifications in the earlier proposed equation [5]:

$$\text{Im} \left\{ \sum_{i=0}^2 \left[\left(D_{i1} U_{i1}' - B_{i1} I_{i1}' \right) \cdot \frac{\left(-C_{i1} U_{i1}' \text{ fault} + A_{i1} I_{i1}' \text{ fault} \right)^*}{k_{i1}^*} \right] \right\} = 0 \quad (9)$$

where $U_{i1}' \text{ fault}$, $I_{i1}' \text{ fault}$ are the fault components of U_{i1}' , I_{i1}' , k_{i1}^* is the conjugate value of the current distribution coefficient

$$k_{i1} = \frac{Z_{i \text{ inII}}}{Z_{i \text{ inI}} + Z_{i \text{ inII}}} = \frac{\frac{B_{i11} + Z_{i11} A_{i11}}{D_{i11} + Z_{i11} C_{i11}}}{\frac{B_{i1} + Z_{i1} D_{i1}}{A_{i1} + Z_{i1} C_{i1}} + \frac{B_{i11} + Z_{i11} A_{i11}}{D_{i11} + Z_{i11} C_{i11}}},$$

$Z_{i \text{ inII}}$ and $Z_{i \text{ inI}}$ are the equivalent impedances of the four-pole and the system behind with respects to the fault point.

The expression of the voltages at the output terminals of the four-pole by the known parameters do not need to be modified, which also applies for the currents. The current distribution in two branches feeding the fault point from the local (I_{i1}'') and the remote (I_{i11}'') line end and thus, coefficient k_{i1}^* allowing to determine the fault current will depend for positive, negative and zero sequences on the systems' equivalent impedances, line parameters and the distance to the fault. Obviously, this coefficient will not depend on the fault type. Therefore, the equation (9) is valid for the double phase to ground fault type and no modifications are required. Furthermore, current distribution coefficients will be equal for all the fault types assuming the same distance to the fault. These properties allow us to considerably simplify the implementation of the algorithms in protective devices.

Analysing (8) and (9) it can also be noticed that the algorithm can use the sequence components of the measurements of any phase, since the transformation operand a will not distort the equality. Thus, the algorithm does not require faulted phase identification and can be run for all the three phases with subsequent result optimisation for the improvement of the algorithm accuracy, for example in cases of partially defect measurements.

D. Phase-to-phase fault case

In this case the system is balanced and no zero sequence currents are present. Thus, in (8) only positive and the negative sequence should be considered.

E. 3-phase fault case

For the 3-phase fault conditions the system is symmetrical and only positive sequence currents are present. In (8) only positive sequence should be considered.

Despite that computation of fault distance is identical for mentioned fault types, the algorithm accuracy and the sensitivity to the parameters errors will vary.

F. Autoreclosing in case of sustained fault

For high, extra and ultra-high voltage power transmission lines the automation that performs single (or three) phase autoreclosing has been widely used. In case of single phase to ground fault only one - the faulted phase is tripped and, after delay for arc extinction, the phase is switched back starting with the breaker at one end.

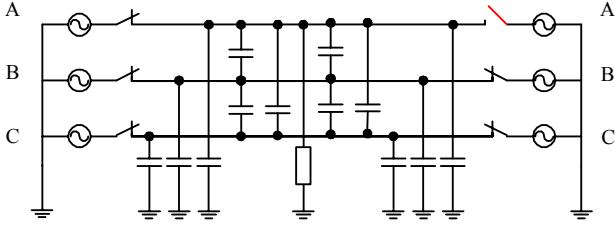


Fig. 2. Power system in phase-to-ground fault and simultaneous single-phase autoreclosing conditions.

If a sustained fault has occurred, then the operational state transforms to complex fault conditions of single-phase to ground fault combined with simultaneous phase opening at one of the line ends (Fig. 2.). The structure of the circuit equivalent changes and so, do the equations that describe the processes caused by the fault.

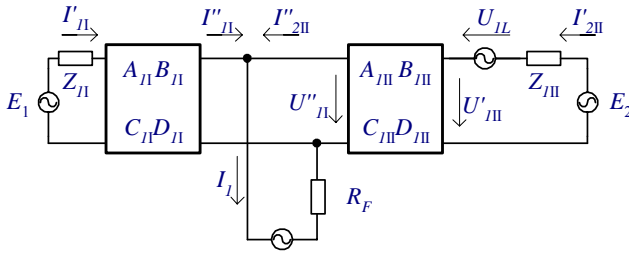


Fig. 3. One-line diagram of the positive sequence in autoreclosing state.

From the opened breaker side the fault is fed by currents flowing through distributed capacitance and conductivity. The network equivalent for the positive sequence in these conditions is shown in Fig. 3.

To obtain the distance to the fault expressed in terms of the measured or known parameters, both the single phase to ground and the interruption boundary conditions are involved. Let us observe (8). Since at the phase-to-ground fault point all the currents at the fault point are equal, only one value of the current can be used, for example I_2 :

$$\text{Im} \left(I_2^* \cdot \sum_{i=0}^2 U_{ii}'' \right) = 0 \quad (10)$$

The value could be calculated as follows:

$$I_2 = -C_{2I} U'_{2I} + A_{2I} I'_{2I} + U''_{2II} K_2 + U_{2L} (A_{2II} K_2 + C_{2II}) \quad (11)$$

$$\text{where } K_i = \frac{D_{ii} + C_{iii} Z_{iii}}{-A_{iii} Z_{iii} - B_{iii}}$$

Analogous equation can be written for the 0-sequence scheme.

The unknown voltage U_{ii} , which equal for all the sequences, could be expressed involving both negative and zero sequence equations of the view (11):

$$U_{2L} = \frac{\sum_{i=0,2} (-1)^{0.5i} \cdot (C_{ii} U'_{ii} - A_{ii} I'_{ii} - (D_{ii} U'_{ii} - B_{ii} I'_{ii}) K_i)}{\sum_{i=0,2} (-1)^{0.5i} \cdot (A_{iii} K_i + C_{iii})} \quad (12)$$

It is evident that equation (10) with the help (11), (12) and (1) allows to determine the fault point during the discussed

operating conditions by utilizing measurements U_{ii}, I_{ii} from the single line end, parameters A_i, B_i, C_i, D_i and the equivalent impedances of the systems Z_{ii}, Z_{iii} .

III. THE STOCHASTIC APPROACH

Summarizing the stated above equations, one can declare that the distance to the fault L_F is linked to the measured phasors of the currents I and voltages U and unknown equivalent impedances Z_{iii} of the remote transmission line end system by relation of the following form:

$$L_F = \Phi(I, U, Z_{iii}) \quad (13)$$

where Φ is for some procedure of the distance L_F calculation. The procedure employs the measurement results of the controlled currents and voltages and information of the impedance Z_{iii} values.

On the other hand, taking into account that the measured current and voltage data contain random errors - correspondingly ΔI and ΔU , and, in general, values of the uncontrolled impedance Z_{iii} can also be treated as random, the equation (13) could be considered as basic one to determine the distribution law of the estimate of the distances to the fault L_{est} or its numerical characteristics.

It was shown in the previous works [5]-[7] that these numerical characteristics allow to define optimal strategy of the faulted point search on power transmission line. To determine distribution density $g(L_{est})$ of the L_{est} on the base of (13), it is necessary to know the distribution relative density function $g(I, U, Z_{iii} / I_{est}, U_{est})$ - the density of the current, voltage and impedance distribution under obtained measurement results I_{est}, U_{est} . Theoretically, Bayes theorem could be involved [10]. Determination of the desired distribution function $g(I, U, Z_{iii} / I_{est}, U_{est}, Z_{iii})$ is possible on the base of faulted line processes simulation and Monte-Carlo method utilization. For this purpose, a significant number of trials should be performed, and consequently, notable processing time will be needed.

However, a more effective procedure could be obtained, using the linearization method, taking into account the physical nature of the measured values and relatively small values of measurement errors, and supposing that measurements errors are additive with the zero value of mathematical expectation, it can be stated that [10]:

$$\sigma(\Phi(I, U, Z_{iii})) \cong \sigma(\Phi(I_{est} + \Delta I, U_{est} + \Delta U, Z_{iii})) \quad (14)$$

where $\sigma(\dots)$ is standard deviation.

Statement (14) is strictly true for linear functions. In considered non-linear case, there could appear allowable for practical utilization errors. On the other hand it becomes possible to employ more efficient procedure for Monte-Carlo method application.

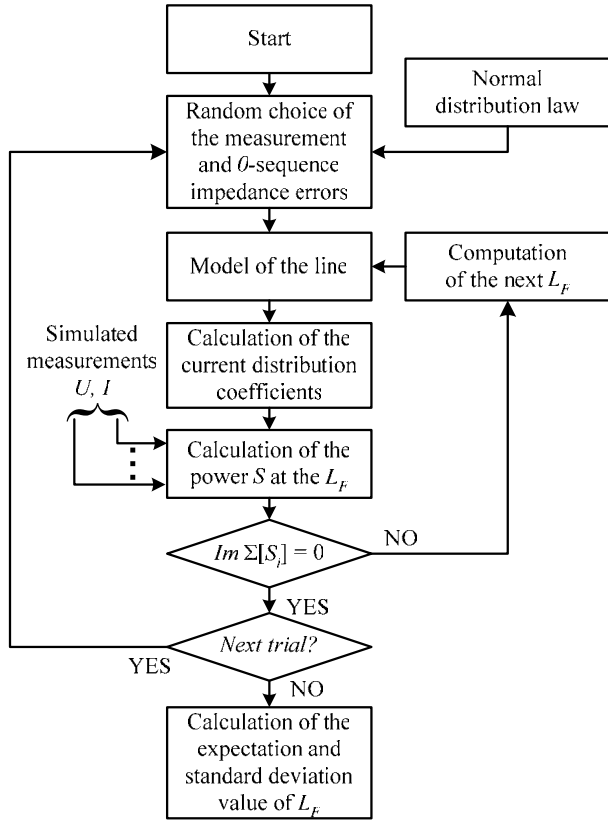


Fig. 4. Error of the distance to fault as determined by conventional algorithm.

The algorithm for estimation of the mathematical expectation $E[L_F]$ and standard deviation $\sigma[L_F]$ values based on the Monte-Carlo simulations shown in Fig. 4.

The approach could be easily applied for different types of faults to single ended algorithms, when in addition to parameters' uncertainties, it is necessary to model the unknown impedance of the unmonitored line end equivalent system, as well as to double-ended algorithms [6] to model the inaccuracies of the measurements and line parameters.

IV. RESULTS OF SIMULATIONS

Let us incorporate both the modeling of the processes in the faulted transmission lines and the algorithm for fault distance estimation to describe the performance and main properties of the discussed algorithms.

We consider first, the deterministic model. In the conditions when single or three-phase autoreclosing is performed (Fig. 2.), the conventional algorithms will produce an error. For example, an algorithm that is similar to described in [1] can be studied:

$$L_f = \text{Im} \left(\frac{U_f}{I_0} \right) / \text{Im} \left(Z_{1sp} \cdot \frac{I_f + K \cdot I_0}{I_0} \right), \quad (15)$$

$$\text{where } K = \frac{Z_{0sp} - Z_{1sp}}{Z_{1sp}}.$$

Fig. 5 shows the result of the algorithm applied to fault location in power system with following data:

- the nominal voltage of the modeled system is 330 kV;
- the line length is 200 km;
- the pre-fault power flow through the line is 400 MW;
- line specific parameters are:

$$Z_{1,2} = 0.040 + j0.314(\text{ohm/km}), \quad \omega C_{1,2} = 3.52 \cdot 10^{-6} (\text{s/km})$$

$$Z_0 = 0.188 + j0.785(\text{ohm/km}), \quad \omega C_0 = 1.63 \cdot 10^{-6} (\text{s/km})$$

- system equivalent impedances are:

$$Z_{1,2I} = 4.76 + j29.36 \quad Z_{0I} = 1.48 + j35.23(\text{ohm})$$

$$Z_{1,2II} = 1.83 + j15.3 \quad Z_{0II} = 0.73 + j13.77(\text{ohm})$$

This data describes realistic line of the Latvian power system.

The accuracy of the conventional algorithm will in general depend on various factors. Let us note that in general, that conditions of autoreclosing are favourable for the algorithm performance since the impact of the infeed from the remote line end is decreased or even, in case of three-phase autoreclosing is avoided. The major cause of the error will then be neglect of the line charging and distributed nature of the line parameters. Fig. 5 shows the error of the determined distance to the fault increasing with the increase of the fault resistance value. For the single-phase autoreclosing, the algorithm error will be higher if in pre-fault conditions power flows out of the controlled substation. For the three-phase autoreclosing, obviously, the accuracy is not dependent on the pre-fault current value or direction. However, in case of higher fault resistance values, the error will be noteworthy. At the same time, in case of single-phase autoreclosing, the algorithm (10) is capable of providing the precise result. Furthermore, the algorithm can be extended for application to three-phase autoreclosing conditions.

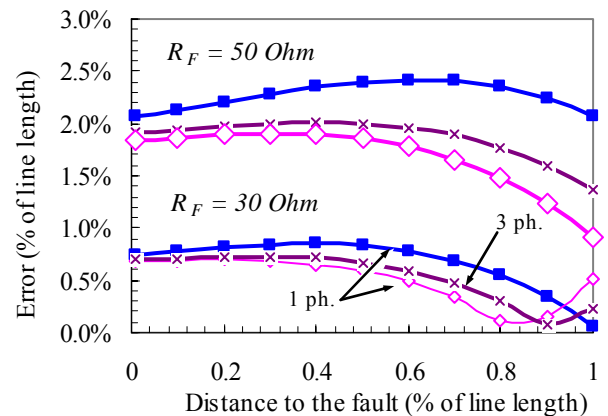


Fig. 5. Error of the distance to fault as determined by conventional algorithm.

Next, let us study the stochastic model. It is emphasized that Monte-Carlo simulations are used twice:

- to simulate uncertainties of the parameters in the faulted line model. The values of the controlled voltages and currents are obtained;

- to estimate the distance to the fault according to the algorithms (9). Since the reviewed algorithm defines the evaluation results of distance as random values, the accuracy will be characterized by the standard deviation of the obtained distribution law of the determined distances to the fault.

Fig. 6-10 represent the modeling results of the described above algorithms. The simulations were run for the following test system in Fig. 1:

- the nominal voltage of the modeled system is 330 kV;
- the line length is 200 km;
- the pre-fault power flow through the line is 200 MW;
- line specific parameters are:

$$R_{1,2} = 0.040, \omega L_{1,2} = 0.314 \text{ (ohm/km)},$$

$$\omega C_{1,2} = 3.52 \cdot 10^{-6} \text{ (siemens/km)}$$

$$R_0 = 0.188, \omega L_0 = 0.785 \text{ (ohm/km)},$$

$$\omega C_0 = 1.63 \cdot 10^{-6} \text{ (siemens/km)}$$

- system equivalent impedances are:

$$R_{1,2I} = 0.066, X_{1,2I} = 62.15,$$

$$R_{0I} = 0.0119, X_{0I} = 68.01 \text{ (ohm)}$$

$$R_{1,2II} = 0.24, X_{1,2II} = 46.87,$$

$$R_{0II} = 0.008, X_{0II} = 28.66 \text{ (ohm)}$$

The errors of the current and voltage phasors measurements were taken as being independent and normally distributed in two dimensions, moreover, it was assumed, in accordance with the equipment producers data, that real error existence margins (3σ rule [10]) are ∇m percents for the measurements of currents and voltages vectors magnitudes, and ∇a degrees for the measurements of the vectors angles.

Fig. 6 shows example of fault location results for phase-to-phase and phase-to-phase-to-ground cases in presence of the measurement errors. The distributions of the distances L_F are determined by the algorithm when the fault occurred at 81% of the line length and fault resistance equals to 30Ω . The error of the mathematical expectation for both the fault types is below one percent of the line length, while the standard deviations are 0.018 and 0.012 for LL and LLG fault respectively.

Fig. 7 studies the performance of the algorithm under the influence of the remote system equivalent impedance that is unknown precisely, but defined with the distribution. A uniform distribution law was assumed and variation limits are $\pm 50\%$ for magnitude and 1° for angle.

Fig. 8 represents main properties of the concerned algorithms in respect to fault location on the line and fault resistance variations in the presence of the measurement errors. Actually, two types of fault resistances are involved: in accordance with the fault type, phase-to-phase and phase-to-ground. Both values were assumed to be $R = 30 \Omega$. In case of

the symmetrical LLG fault the resistance to the ground is dividing symmetrically the fault resistance between the phases. For the unsymmetrical LLG fault both phase-to-phase resistance and phase B to ground resistance were modeled as $R = 30 \Omega$. Obviously, these two fault types are identical when the fault resistances equal to zero. It can be observed that due to present measurement error, the fault resistance increases standard deviation value for all the fault types, except the three-phase fault.

Fig. 9 reflects the influence of the uncertainty of zero sequence specific parameters of the line that could vary due to several reasons [9] (corona, earth condition and humidity, and etc). Results are obtained under the hypothesis that R_0, L_0, C_0 are normally distributed. It was assumed, and modeled in respect to 3σ rule [10], that variation of impedance magnitude may reach ∇z_m percents, and the angle variations are in range of ∇z_a electrical degrees.

Fig. 10 shows algorithm accuracy in case of uncertainty simultaneously in measurements and zero sequence parameters data.

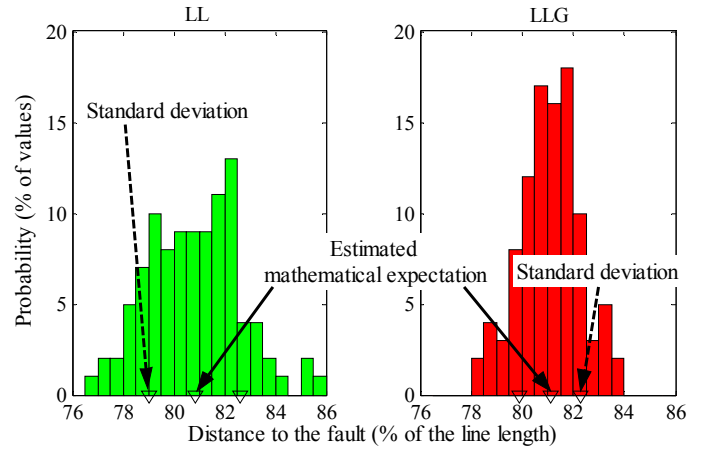


Fig. 6. Distribution of the estimated distances L_F in case of the uncertainty of the measurements

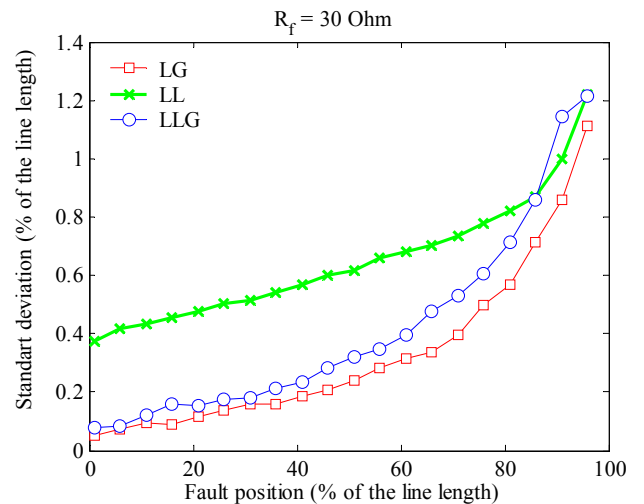


Fig. 7. Standard deviation of the estimated distances L_F as a function of fault position in case of uncertainties of the remote system impedance

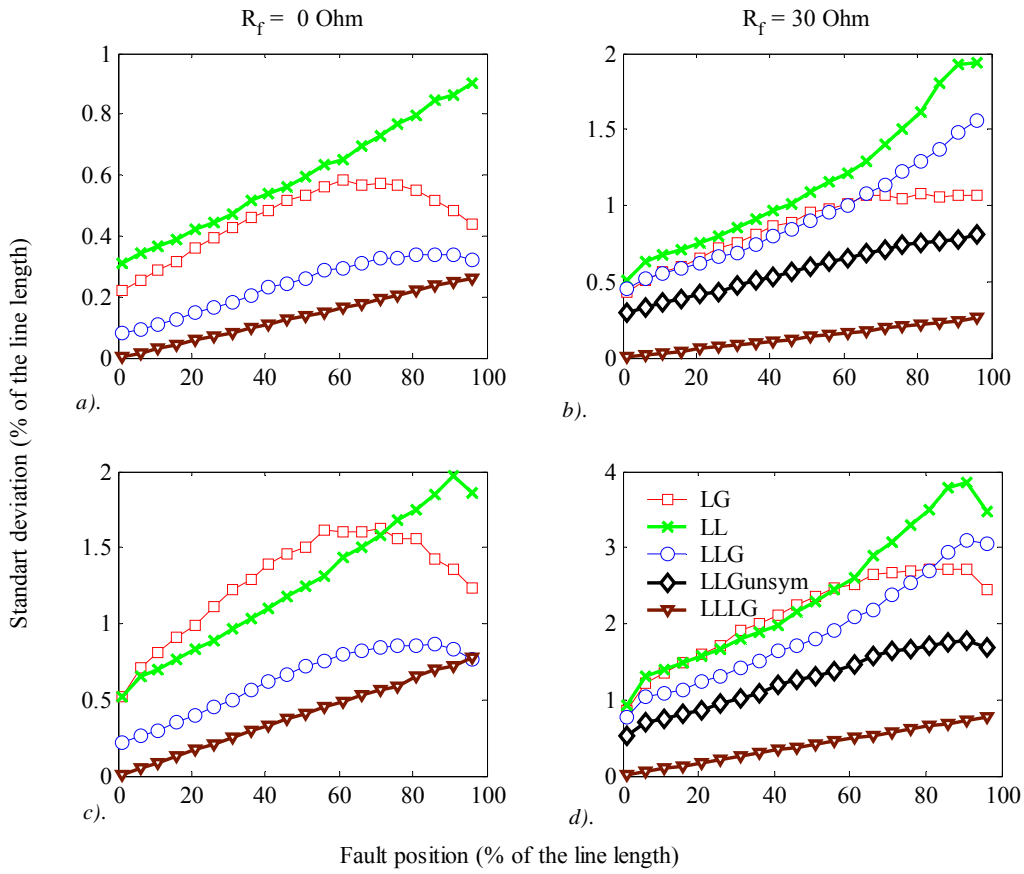


Fig. 8. Standard deviation of the estimated distances L as a function of distance to the fault and fault resistance value at various measurement errors. a), b) $\nabla m = 1\%$ for measurement parameter magnitude, $\nabla a = 1^\circ$ for phase; c), d) $\nabla m = 3\%$ and $\nabla a = 1.5^\circ$ respectively; a), c) $R_f = 0$; b), d) $R_f = 30$ ohms.

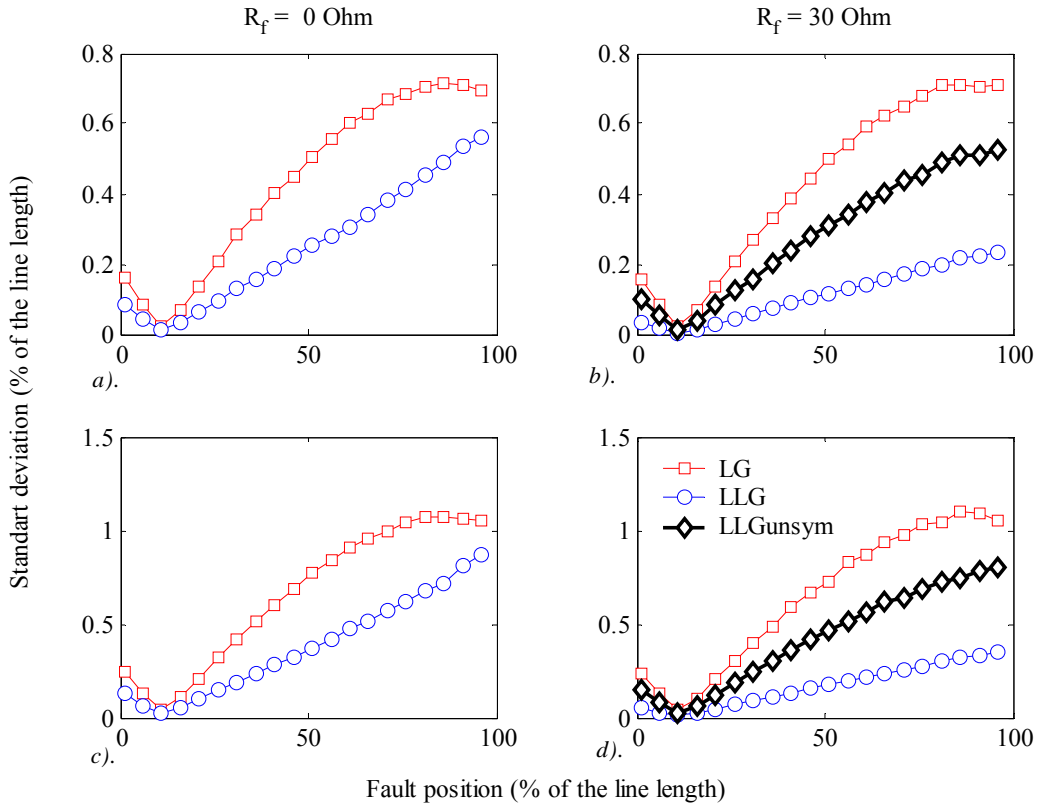


Fig. 9. Standard deviations of the estimated distances L due to uncertainty of 0-sequence apparent parameters of the line. a), b) $\nabla z_m = 10\%$ for parameter magnitude, $\nabla z_a = 1^\circ$ for phase; c), d) $\nabla z_m = 15\%$ and $\nabla z_a = 2^\circ$ respectively; a), c) $R_f = 0$; b), d) $R_f = 30$ ohms.

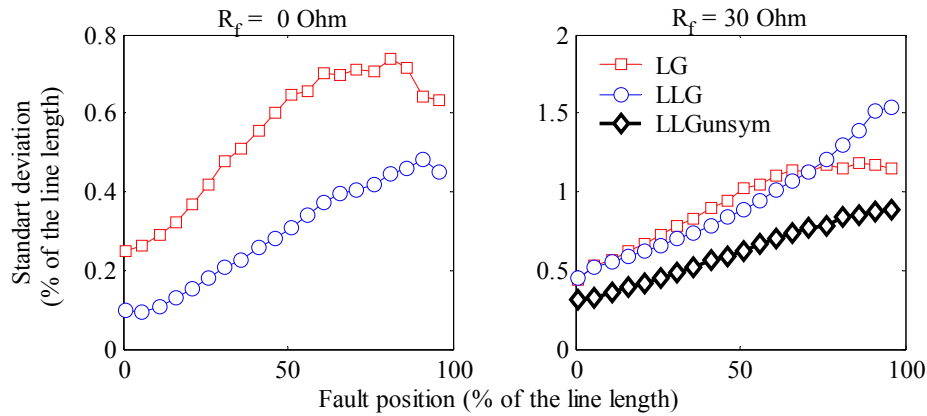


Fig. 10. Standard deviations of estimated distances distribution under influence of measurements errors and uncertainty of the 0-sequence specific parameters of the line ($\nabla z_m = 10\%$, $\nabla z_a = 1^\circ$, $\nabla m = 1\%$, $\nabla a = 1^\circ$).

V. CONCLUSIONS

The algorithm for fault location and recommendation of segment to inspect can be developed taking into account the probabilistic nature of the measurement errors and power system parameters. The simulation results show that the accuracy of the fault location is acceptable under the tested situations that include different fault types, fault resistances, fault locations, prefault loading conditions and various impedances of the sources. The generality of the algorithm basic formula is shown and capability to operate without identification of the faulted phase.

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES



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Göran Andersson (M'86, SM'91, F'97) was born in Malmö, Sweden. He obtained his M.S. and Ph.D. degree from the University of Lund in 1975 and 1980, respectively. In 1980 he joined ASEA:s, now ABB, HVDC division in Ludvika, Sweden, and in 1986 he was appointed full professor in electric power systems at the Royal Institute of Technology (KTH), Stockholm, Sweden. Since 2000 he is full professor in electric power systems at the Swiss Federal Institute of Technology (ETH), Zürich, where he heads the power systems laboratory. His research interests are in power system analysis and control, in particular power systems dynamics and issues involving HVDC and other power electronics based equipment. He is a member of the Royal Swedish Academy of Engineering Sciences and Royal Swedish Academy of Sciences and a Fellow of IEEE.