

# Enhancing Fault Location Performance on Power Transmission Lines

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**Abstract**— This paper discusses supporting algorithms for fault location on power transmission lines.

The performance of fault location algorithm is strongly dependent on the accuracy of line model. Short circuit recordings contain valuable data, from which line parameters can be computed. Two algorithms for line parameter calculation are presented, as well as the results of application to field recordings.

The advantages of statistical fault location algorithms are discussed. These algorithms can compute the expected value of the distance to the fault and evaluate margin of possible error. Obtained distribution of the fault distance allows to determine the best for particular conditions strategy for line inspection, leading to faster fault discovery and the optimized inspection costs.

**Index Terms**— Fault Location, Statistics, Transmission Lines

## I. INTRODUCTION

THE power transmission line is the most frequently faulted element of the transmission system. The possible causes of faults are numerous. In any case, protection should isolate the faulted transmission line from the power infeed. Then, the operator actions are following - computing the fault location and directing the line inspection team.

The fault location devices are widely used for this purpose on the high voltage overhead transmission lines. A modern fault location device is, basically, a digital computer. It obtains data from voltage and current measurement transformers dedicated to short circuit conditions. These fault recordings can be processed directly at the substation by the fault location device or downloaded by the system operator to control center and processed by the personal computer.

Significant number of different fault location methods was proposed in the literature. Still, errors in the computed fault distance are inevitable, due to several contributing factors, such as measurement errors, inaccuracies of line parameters, fault resistance, operating state etc [1]. Therefore, inspection team starts searching for the fault in the vicinity of the computed distance. The length of this line segment is derived from the previous experience and particular fault conditions are not taken into account. For the particular state, the segment length might be inadequate, causing delays in fault discovery.

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Fig. 1 shows that possible fault location interval can be large only in rare cases of distant high resistance faults.

Thus, the necessary components to insure successful and fast fault discovery can be summarized, as follows:

- measurements of the fault currents and voltages,
- accurate transmission line model,
- fault location algorithm capable to evaluate uncertainty associated with the results,
- a good strategy for the inspection team.

In the previous papers [2],[3] we have suggested fault location algorithm, which, using measurement and parameter statistics, computes fault distance as well as margins of the possible error. Particular combination of the contributing factors is taken into account. The algorithm can be easily implemented in modern microprocessor based devices.

This paper addresses another prerequisite listed above, namely, transmission line model and parameter calculation from the available field measurements. Several line impedance estimation techniques dealing with the positive sequence has been developed [4]. An interesting work on calculation of line parameters from the unsynchronized two-sided fault recordings was reported in [5]. Another method requiring synchronized sampling was suggested in [6]. We propose two new algorithms for line parameter calculation from the unsynchronized two-sided recordings of the external to the monitored line fault.

We also continue discussion about advantages of the statistical approach to fault location by demonstrating the arising possibility to define optimal line inspection strategy.

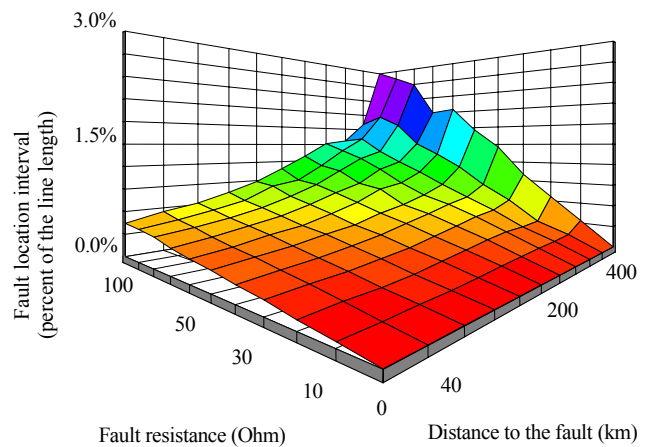


Fig. 1. Possible fault location interval as a function of fault resistance and distance to the fault on 500 kV transmission line [3].

## II. CALCULATING LINE PARAMETERS

### A. Model of the transmission line

Correct line parameters are essential for the successful operation of any algorithm. A valuable source of data for power system model verification is short circuit recording.

Let us consider transmission line model in Fig. 2, substations  $S$  and  $R$  are equipped with disturbance recorders - a standard part of the modern microprocessor based protection device or a separate device. The fault conditions in the network trigger the initialization of disturbance recorders, which save the results of analog-digital conversion of voltages and currents. Sequence components of the measured signals are computed from the phase values, for example, by the Fourier transformation. The sampling of measurements at the line ends  $S$  and  $R$  can be unsynchronized.

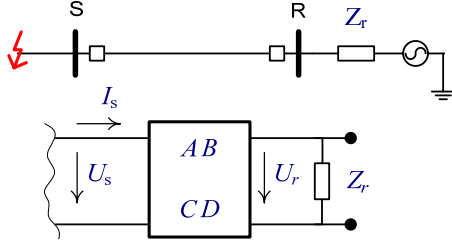


Fig. 2. Single line diagram and equivalent circuit of the modeled system at external fault.

In the general case, transmission line can be seen as a two-port with  $ABCD$  transmission constants defining the dependence of voltage and current at the input and output terminals, as follows [8]:

$$\begin{aligned} U_s &= AU_r + BI_r \\ I_s &= CU_r + DI_r \end{aligned} \quad (1)$$

where  $U$  and  $I$  are complex voltage and current. This expression holds for the positive, negative or zero parameter sequence.

### B. The simplified method – determining RL parameters

In the simple case, the shunt admittance of the transmission is neglected and line is modeled just by the series impedance  $Z_l$ , then:

$$A = D = 1, B = Z_l, C = 0. \quad (2)$$

In the conditions of the external short circuit, for example, behind the substation  $S$ , the following expression is valid:

$$Z_s = Z_r + Z_l, \quad (3)$$

where  $Z_s$  and  $Z_r$  are impedances of Thevenin equivalents at node  $R$  and  $S$ , respectively.

Taking into account that for zero and negative sequence impedance  $Z_s = \frac{U_s}{I_s}$  and  $Z_r = \frac{U_r}{I_r}$ , we get:

$$Z_l = \frac{U_s}{I_s} - \frac{U_r}{I_r}. \quad (4)$$

If measurements of the currents and voltages are ideal, containing no error, line impedance can be easily determined from this expression.

Using balance of the apparent powers we can write for the nodes  $R$  and  $S$ :

$$\begin{aligned} U_s I_s^* &= U_r I_r^* + |I_r|^2 Z_l \\ U_r I_r^* &= U_s I_s^* - |I_s|^2 Z_l \end{aligned} \quad (5)$$

where  $I^*$  is the complex conjugate of current  $I$ .

The left side of the expression corresponds to the power measured directly in the node, while the right side determines the power indirectly from the measurements at the remote end and computed the losses in the line.

Equations (5) can be easily regrouped as:

$$Z_l = \frac{U_s I_s^* - U_r I_r^*}{I_r I_r^*}, \quad (6)$$

$$Z_l = \frac{U_r I_r^* - U_s I_s^*}{I_s I_s^*}. \quad (7)$$

Since voltage and current measurements contain some error, the line impedance provided by (4),(6),(7) will slightly differ. The sensitivity of the results to these errors varies from case to case. Thus,  $Z_l$  can be determined as an average of three results.

Let us emphasize that measurement synchronization at the line ends is not required by these equations.

### C. Determining RLC parameters

For the generalized line model and an unsymmetrical short circuit occurring externally to the line  $SR$ , the equivalent impedance at node  $S$  can be expressed, as:

$$Z_s = \frac{A + BZ_r^{-1}}{C + DZ_r^{-1}}. \quad (8)$$

Similarly to (5) above, the apparent power consumed by the circuit can be expressed, as follows [2],[8]:

$$U_s I_s^* = (A + BZ_r^{-1})U_r \cdot (C + DZ_r^{-1})^* U_r^*. \quad (9)$$

Assuming  $\pi$ -model of the transmission line with the series impedance  $Z_l$  and shunt impedances  $Z_c$ ,  $ABCD$  constants become:

$$A = D = 1 + \frac{Z_l}{Z_c}, B = Z_l, C = \frac{2Z_c + Z_l}{Z_c^2}. \quad (10)$$

Proceeding with rearrangements of (9), one obtains:

$$Z_l = \frac{Z_c^2 - \frac{1}{Z_r} Z_c^2 Z_{in} - 2Z_{in} Z_c}{-\frac{1}{Z_r} Z_c^2 + \frac{1}{Z_r} Z_c Z_{in} + Z_{in} - Z_c}, \quad (11)$$

where  $Z_s$  and  $Z_r$  can be determined from the current and voltage measurements, as in the previous subsection.

From (9) and (10), separating real and imaginary parts of the complex series line impedance and, for the simplification denoting  $y = \frac{1}{Z_c} + \frac{1}{Z_r}$ , it is possible to get:

$$R_l = \frac{1}{yy^*} \cdot \text{Re} \left( \frac{U_s J_s^*}{U_r U_r^*} - \frac{1}{Z_c^*} - y^* \right) \quad (12)$$

$$\begin{aligned} X_l^2 yy^* \frac{1}{Z_c^*} + X_l \left( yy^* - \frac{2\text{Im}(y)}{Z_c^*} \right) &= \dots \\ &= -\frac{R_l^2 yy^* + 2R_l \text{Re}(y)}{Z_c^*} + j \text{Im} \left( \frac{U_s J_s^*}{U_r U_r^*} - \frac{1}{Z_c^*} - y^* \right) \end{aligned} \quad (13)$$

The system of equations (11)-(13) can be solved for the unknown line impedances  $R_l$ ,  $X_l$  and purely imaginary  $Z_c$ . Let us note that (11) can be decomposed into real and imaginary part, thus, three variables are overdetermined by four equations. The averaging can be applied again to improve the estimates.

### III. RESULTS OF SIMULATIONS AND TESTS

#### A. Transmission Line Model

Let us assess the accuracy of the line parameter determination from the external fault measurement recordings on the following system example:

- Nominal voltage of the modeled system is 110 kV;
- Operational voltage of the buses is around 1.0 pu;
- Line positive and zero impedances are:

$$R_{1,2} = 6.0, X_{1,2} = j18.0(\text{ohm})$$

$$R_0 = 16.0, X_0 = j49.0(\text{ohm})$$

- System equivalent impedances at sending, receiving and external end are respectively:

$$Z_{0s} = 2.40 + j22.29, Z_{1,2s} = 2.30 + j13.87(\text{ohm})$$

$$Z_{0r} = 17.96 + j72.22, Z_{1,2r} = 6.45 + j29.25(\text{ohm})$$

$$Z_{0m} = 5.26 + j38.38, Z_{1,2m} = 3.59 + j27.35(\text{ohm})$$

- The pre-fault power flow through the lines is 50 MW;
- Fault resistance is 5 ohm;

Faults are simulated at the increasing distances on the adjacent, twice longer line with the similar parameters. The errors of phase current and voltage measurements were assumed to be independent and normally distributed in two dimensions: standard deviation of the measurement magnitude

error is 1% and 1° of the measured angle. These assumptions correspond to realistic errors reported by equipment producers. Thus, a number of fault recordings performed at both line ends is simulated for the different external faults.

#### B. Line Parameter Calculation

We apply the simplified method as described in section II. B. to computation of the line resistance and reactance from double sided unsynchronized measurements which are taken at different external short circuit conditions.

Fig. 3 shows results of zero sequence line impedance computation depending on the fault location on the adjacent line. For each of the fault locations, 300 Monte-Carlo simulations were run to obtain the line impedance distribution. The expected values of the real and imaginary part of the impedance, as well as standard deviation of the distribution are shown. Fig. 4 demonstrates similar result for negative sequence impedance.

It can be noted that standard deviation and, therefore, possible error in line parameter, is inversely proportional to fault current value. This can be easily explained once the measurement errors are analyzed. Line impedance computation is based on sequence components of current and voltage and an error in the phase value measurement transforms to sequence component error. If the fault is distant, the sequence components of currents and voltages are small. Thus, a small relative to phase value error represents large deviation in the sequence component. Therefore, if the system is characterized by small short circuit currents, the line parameters shall be determined from relatively close short circuit recordings.

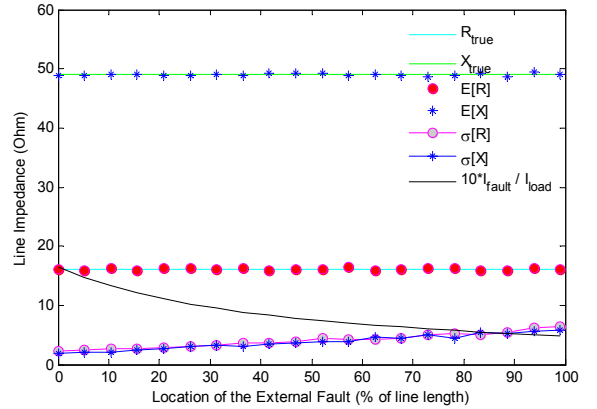


Fig. 3. Computation results of zero sequence line impedance.

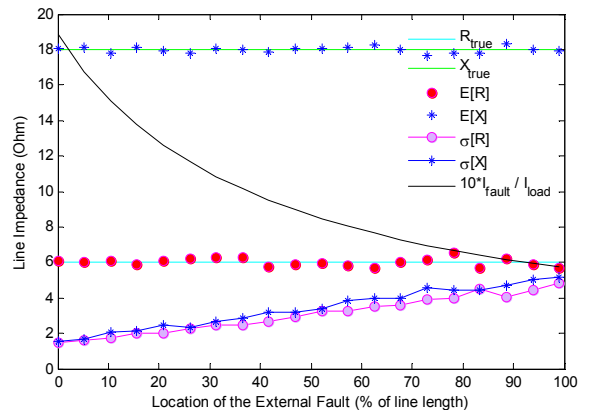


Fig. 4. Computation results of negative sequence line impedance.

### C. Field Recordings Test

The simplified line parameter computation method described in II. B. was applied to field recordings of short circuits on the adjacent line to following monitored line:

- the nominal voltage of the studied system is 110 kV;
- the line length is 47.94 km;

An example of the external fault recording used for the computations is provided in Fig. 5, showing print screen of the software application for fault recordings analysis developed at Riga Technical University.

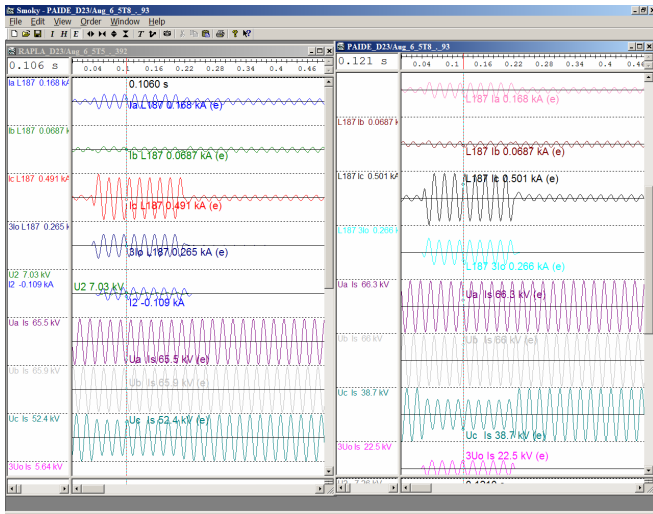


Fig. 5. Fault recordings at two ends of 110 kV line during the external fault.

Table I and Table II present expected values and standard deviations of line parameters obtained as the results of 10 available external short circuit recordings processing. For the comparison, line design parameters are provided in the brackets.

TABLE I  
EXPECTED VALUES OF THE LINE IMPEDANCES

$E[R_1]$ , Ohm	$E[X_1]$ , Ohm	$E[R_0]$ , Ohm	$E[X_0]$ , Ohm
6.01	18.53	16.25	51.5
(6.184)	(18.88)	(16.395)	(49.522)

TABLE II  
STANDARD DEVIATIONS OF LINE IMPEDANCES

$\sigma[R_1]$ , %	$\sigma[X_1]$ , %	$\sigma[R_0]$ , %	$\sigma[X_0]$ , %
1.2	1.1	2.9	1.3

Line parameters can be specified more accurately, when the additional fault recordings will be available.

### IV. STRATEGIES OF LINE INSPECTION

Many efforts and bright ideas have been invested in development of more accurate fault location algorithms. However, inaccuracy of results cannot be avoided due to measurement errors and other uncertain parameters. Therefore, the line inspection team usually assumes, based on the previous experience, the presence of some error and searches through some line segment. This fault distance error guess may be too large or too small for the particular fault conditions. As the result, inspection takes longer time than necessary.

Naturally, it cannot be prevented, if the possible error associated with the computed fault distance is unknown. In the previous papers [2],[3] we have proposed fault location algorithm that applies Monte-Carlo simulations to the evaluate impact of the uncertainties. The result provided by the algorithm is the probability distribution of the distance to the fault, which can be interpreted as the probability that inspection of particular line segment will be successful.

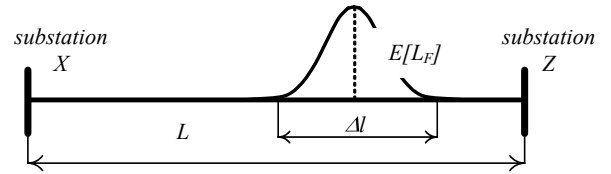


Fig. 6. Results of the statistical fault location algorithm and inspection optimization.

We would like to continue the discussion of the new possibilities provided by statistical fault location algorithm: an optimal in terms of time and costs strategy of line inspection can be determined, as demonstrated below. Let us assume that the following parameters are available:

- estimated distance to the fault  $L_F$  follows normal distribution  $N(E_{L_F}, \sigma_{L_F}^2)$  with the mathematical expectation  $E_{L_F}$  and the standard deviation  $\sigma_{L_F}$ ;
- $V$  is the line inspection speed in  $km/h$ ;
- $q$  is the cost of inspection per  $km$ .

Fig. 6 shows the result provided by statistical fault location algorithm and the optimal inspection segment  $\Delta l$  to be determined. If the fault has not been discovered on the segment  $\Delta l$ , then the whole line route of the length  $L$  is subjected to the inspection and a uniform probability fault distance distribution is assumed.

Considering these assumptions, the mathematical expectation  $E[q]$  of the costs of fault location can be evaluated as follows:

$$E[q] = \underbrace{q \cdot P_{\Delta l} \cdot \frac{\Delta l}{2}}_{\text{inspection of } \Delta l} + \underbrace{q \cdot (1 - P_{\Delta l}) \cdot \frac{L}{2}}_{\text{inspection of whole line}} \quad (14)$$

where  $P_{\Delta l}$  is the probability of fault location in the recommended for inspection segment,  $\Delta l$  is the length of the segment.

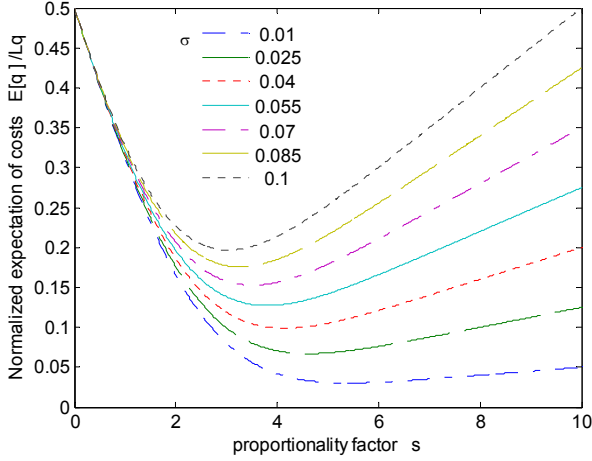


Fig. 7. Normalized mathematical expectation of the costs as a function of proportionality coefficient  $s$  at various standard deviation values.

The segment length  $\Delta l$  is chosen to be proportional to the standard deviation  $\sigma_{LF}$  with  $E_{LF}$  centre of the segment:

$$\Delta l = s\sigma_{LF}, \quad (15)$$

where  $s$  - is the proportionality factor.

Thus, it is possible to obtain:

$$E[q] = q \frac{L}{2} \left( 1 + P_{\Delta l} \cdot \left[ \frac{s\sigma_{LF}}{L} - 1 \right] \right), \quad (16)$$

where probability  $P_{\Delta l}$  can be computed using cumulative distribution function  $F(l)$  of a normal distribution [7]:

$$P_{\Delta l} = F\left(E_{LF} + \frac{\Delta l}{2}\right) - F\left(E_{LF} - \frac{\Delta l}{2}\right). \quad (17)$$

It can be concluded that the expected costs are dependent on both  $s$  and  $\sigma_{LF}$ .

The plot of the function (16) is shown in Fig. 7. It is clear that given the  $\sigma_{LF}$  value, one can determine  $s$  and consequently  $\Delta l$  corresponding to the minimum of expected costs of the fault location. For an illustration, let us assume that resulting fault distance distribution has  $\sigma_{LF} = 4\%$  of the line length. Then, as follows from Fig. 7, the minimal value of the mathematical expectation of the costs corresponds to factor  $s \approx 4$ . Therefore, recommended for inspection segment length is  $4 \cdot \sigma_{LF}$ .

Other fault location strategies can be preferred to the one described above. For instance, inspection could consist of the following three steps: first relatively short segment is subjected for the inspection, then wider searching zone is defined, at last, in case of unsuccessful efforts, the whole line should be inspected. Still, the described cost minimization approach can be employed to find the length of the segment. The diagrams in Fig. 8 demonstrate strategies used in practice for the line inspection.

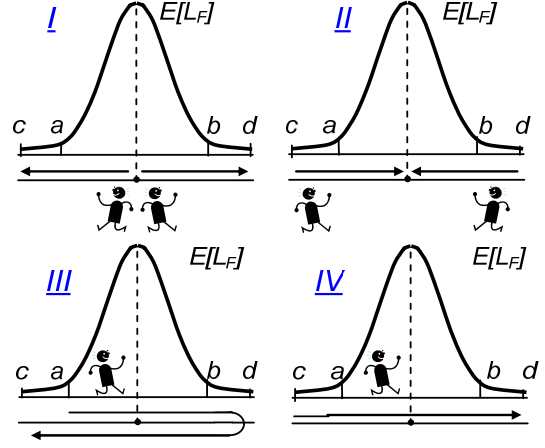


Fig. 8. Line inspection strategies: *I* and *II* by two inspection teams, *III* and *IV* by one inspection team.

In contrast to the previous case, prior to the whole line inspection we prefer to check line segment  $[cd]$ , which is 99% confidence interval for the fault location. For the simplicity of explanation, the need for the whole line inspection, which is equally probable and time consuming in all the cases, is neglected in the following derivations.

The mathematical expectation of the time till the fault is discovered can be determined, as follows:

$$E[T_F] = E[L_F] / V. \quad (18)$$

For the case III, as the most general example, the expected inspection distance in (18) can be computed, as:

$$E[L_F] = \underbrace{E[L_F|ab]}_{\text{if fault is on ab}} P_{ab} + \underbrace{(L_{ab} + E[L_F|bd])}_{\text{if fault is on bd}} P_{bd} + \underbrace{(2L_{ad} + E[L_F|ac])}_{\text{if fault is on ca}} P_{ca} \quad (19)$$

where:

- $E[L_F|ab]$ ,  $E[L_F|bd]$ ,  $E[L_F|ac]$  are the conditional mathematical expectations of the distance to the fault from  $a, b, a$  respectively under condition that the fault occurred on corresponding line segment:  $ab, bd, ac$ ; Since expected value of the random variable  $X$  admitting probability density function  $f(x)$  can be computed, as:

$$E[X] = \int_{-\infty}^{\infty} x \cdot f(x) dx,$$

conditional mathematical expectation of  $L_F$ , for example for the segment  $[bd]$ , is:

$$E[L_{LF} | bd] = \underbrace{\int_{-\infty}^b l \cdot f(l) dl}_{=0} + \int_b^d l \cdot f(l) dl + \underbrace{\int_d^{\infty} l \cdot f(l) dl}_{=0},$$

in this case,  $f(l)$  is a probability density function of a normal distribution defined on the segment  $[bd]$  and being equal to zero elsewhere.

- $P_{ab}, P_{bd}, P_{ca}$  - are the probabilities of fault location on the corresponding segment, which can be calculated using cumulative distribution function  $F(l)$ , for example:

$$P_{ab} = F(b) - F(a).$$

Proceeding in the similar manner, one can derive the expressions for each of the line inspection strategies in Fig. 8. The results of computations are summarized in Table III, assuming the inspection speed  $V = \sigma / h$ .

TABLE III  
EXPECTED TIME TILL THE DISCOVERY OF THE FAULT

Strategy	Mathematical Expectation of the inspection time $E[T_F]$ , hours	Remarks
I	0.39	two inspecting teams
II	2.60	two inspecting teams
	2.89	$ab = \sigma$
	2.38	$ab = 2\sigma$
III	2.13	$ab = 3\sigma$
	2.23	$ab = 4\sigma$
	2.99	$ab = 6\sigma$
IV	2.99	

These results determine the optimal transmission line inspection strategy. Furthermore, it naturally follows:

- Strategy II is significantly worse than Strategy I. This option is being discussed, since it is applied sometimes in the practical exploitation of power systems.
- Strategy III and  $ab = 3\sigma$  has the highest efficiency in case of single inspection team, also comparing to the frequently preferred strategy IV.

Decision between the strategy I and III shall be made based on the significance of line outage for the system, costs and speed of the line inspection: the line route inspection may require special equipment including helicopters or even climbing outfit.

## V. CONCLUSIONS

The paper discusses possibilities for support and extension of the fault location algorithms, targeting faster fault discovery.

Short circuit recording is a useful source for the verification of the transmission system model used in fault location. Two algorithms for line parameter computation are presented and verified by the simulations. Results of the field recordings processing are presented as well. The obtained estimates of the line parameters are consistent and match the design values.

An application of statistical fault location algorithm is demonstrated. Statistical fault location algorithm allows optimization of the line inspection strategy, resulting in shorter inspection and/or line outage time.

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## VII. BIOGRAPHIES



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