Fault Location Techniques

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***Abstract:** Overview of fault location techniques for HV (EHV) transmission lines as well as for distribution networks is presented. One-end and two-end fault location for traditional uncompensated transmission lines is considered first. The presented two-end fault location is based on unsynchronised measurements at the line terminals. Then the technique with phase co-ordinates approach is utilised for locating faults in series-compensated networks. A single line and parallel lines with series capacitor compensation are considered. Problems encountered in fault location in medium voltage (MV) distribution networks are discussed and the solutions are indicated. Results of large ATP-EMTP testing and evaluation of accuracy of the fault location algorithms are reported and discussed.*

I. INTRODUCTION

Fault location techniques are used in power systems for accurate pinpointing of the fault position. Benefits of accurate fault location are considered [1] as follows:

- fast repair to restore power system,
- improves system availability and performance as well as reduces operating costs,
- saves time and expense of crew searching in bad weather and tough terrain,
- aids crew in disturbance diagnostics by:
  - identifying temporary faults,
  - detecting weak spots.

Variety of fault location techniques is used to achieve the aim and the above-specified benefits. In general, the techniques can be classified as follows [1]:

- microprocessor devices with different input signals and principle of operation:
  - impedance techniques:
    - one-terminal,
    - two-terminal (or multi-terminal),
  - travelling wave techniques,
- short circuit analysis software,
- customer calls,
- line inspection,
- lightning detection system,
- terminal and tracer methods for cables.

This paper reviews the impedance techniques applied in microprocessor based fault locators.

Fault location for repair and inspection purposes requires very high accuracy, while the speed of the location is not so critical as the computations completed in minutes or even slower are acceptable [1]. Thus, more accurate phasor calculation can be applied with use the best available data window and filtering techniques. Use of all locally available information and also the obtained via communication systems is relevant for accurate fault location.

In HV (EHV) networks each a transmission line may be equipped with the dedicated Fault Locator (FL) or with FLs installed at each the line terminals. Fault location algorithms differ in many aspects, basically in:

- configuration of the transmission network (single line, parallel lines, transposed or untransposed line, uncompensated or series-compensated (s-c) line, multi-terminal lines, etc.) for which the FL is designed,
- applied measurement data (one-end, two-end without and with synchronisation) as the input of the FL,
- description of the network (symmetrical components method or phase co-ordinates approach),
- applied model of a transmission line and the assumed simplifications.

On the other hand, fault location in MV distribution networks differs considerably from the approaches applied for transmission networks. The factors contributing to entirely different nature of the fault location in distribution networks are considered in this paper as well as the possible solutions are indicated.

II. UNCOMPESATED LINES - ONE-END FAULT LOCATION ALGORITHM WITH COMPENSATION FOR REMOTE-END INFEED

The main source of errors in fault location results from remote-end infeed effect under resistive faults. Fault resistance is seen as a certain apparent impedance and in consequence the measured reactance consists of the reactance of a line up to the fault point and the reactance component contained in the seen fault resistance. This effect is known as the "*reactance effect*".

Accurate fault location can be achieved by compensating for the reactance effect. The fault location algorithms [2, 3] have introduced such the compensation with assuming the phase angle of the fault current distribution factor as equal to zero. In majority of cases this provides sufficient accuracy. Further improvement of fault location accuracy can be achieved with taking into account the actual value for this phase angle. This has been introduced in the algorithm presented in [4]. To achieve this, the algorithm requires the impedance data for the supplying systems (for the positive sequence only) as the input data. The local system impedance can be traced on-line by simple measurement while the representative value for the remote system has to be provided. High accuracy of fault location can be achieved when the remote system impedance can be sent from the remote-end recording device (no synchronisation is required for that).

In the fault location algorithm [4] the fault loop signals ($\underline{V}_{A\_p}$ - voltage, $\underline{I}_{A\_p}$ - current) are composed according to the classified fault type as in the classical distance protective relays.

Determining the voltage drop across the fault resistance (R_F) with excluding the zero sequence components [there is no $\underline{I}_{F0}$ in (1)] is a distinctive feature of the fault location algorithm [4]. This minimises adverse influence of the uncertainty with respect to zero sequence impedance of a line. The equation describing a considered fault loop (as seen from the sub-station A) is in the form:

$$\underline{V}_{A\_p} - x\underline{Z}_{L1}\underline{I}_{A\_p} - \frac{R_F}{\underline{k}_F}\left(\underline{a}_{F1}\Delta\underline{I}_{A1} + \underline{a}_{F2}\underline{I}_{A2}\right) = 0 \qquad (1)$$

where:

x – distance to fault,

R_F - fault resistance

$\underline{k}_F$ - fault current distribution factor for the positive sequence (the negative sequence) dependent only on impedance data for the line and the supplying equivalent systems,

$\Delta\underline{I}_{A1}$ - incremental (obtained as post-fault minus pre-fault) positive sequence current from the substation A,

$\underline{I}_{A2}$ - negative sequence current measured at the station A,

$\underline{a}_{F1}$, $\underline{a}_{F2}$ - coefficients dependent on a fault type.

Resolving (1) for the real and imaginary parts one gets the quadratic equation for the fault distance:

$$B_2x^2 + B_1x + B_0 = 0 \qquad (2)$$

where:

B_2, B_1, B_0 - real number coefficients determined with the local measurements as it is specified in (1).

The algorithm [4] has been successfully implemented into a product in 1982 and is in operation on single and parallel transmission lines in about 80 countries around the world.

III. TWO-END FAULT LOCATION FOR UNCOMPESATED LINES

Development of effective means of communication between the line terminals has opened the opportunity for improving the fault location accuracy. Unsynchronised sampling at the line terminals appeared as the first solutions while the synchronised sampling, provided with the Global Positioning System (GPS), is presently coming into applications as well.

In case of unsynchronised measurements at the line terminals the gathered measurement data is, generally, shifted in time. In order to utilise the relations between the measurements they have to be brought to the common time base. This requires introducing the synchronisation angle (δ), which is the extra unknown quantity.

Interesting unsynchronised two-end fault location technique has been introduced in the very respected reference [5]. Such the fault location algorithm is very useful for verification of the distance relays operation. Distance to fault is estimated from the unsynchronised measurements performed by distance relays installed at the line terminals. The relations between the relaying quantities derived for different fault types are utilised for that. The synchronisation angle is calculated from the available information.

The other fundamental reference [6] has originated the fault location algorithm based on processing the phasors for the sequence quantities. Basically, the phasors of the positive sequence voltages and currents from both the line terminals (Fig.2) are recommended for that.

Assuming the measurement at the substation B as the basis, the circuit diagram from Fig. 2 can be described:

$$\underline{V}_{A1}e^{j\delta} - x\underline{Z}_{L1}\underline{I}_{A1}e^{j\delta} - \underline{V}_{F1} = 0 \qquad (3)$$

$$\underline{V}_{B1} - (1-x)\underline{Z}_{L1}\underline{I}_{B1} - \underline{V}_{F1} = 0 \qquad (4)$$

where: δ - unknown synchronisation angle.

By subtracting these equations one obtains the equation with the eliminated unknown voltage drop at fault ($\underline{V}_{F1}$):

$$\underline{V}_{A1}e^{j\delta} - \underline{V}_{B1} - x\underline{Z}_{L1}\underline{I}_{A1}e^{j\delta} + (1-x)\underline{Z}_{L1}\underline{I}_{B1} = 0 \qquad (5)$$

The obtained equation (5) is considered for the phasors and can be resolved into its real and imaginary parts. In [6] it is derived that the synchronization angle (δ) can be solved by an iterative Newton-Raphson method. Then, the sought fault distance (x) is calculated.

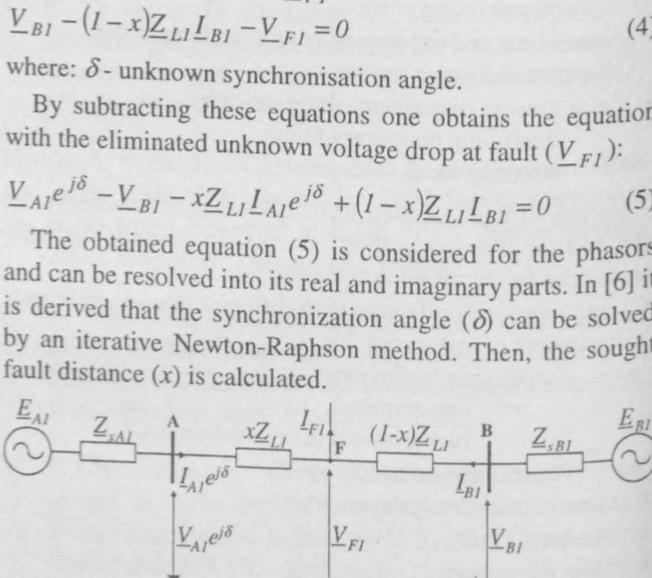

Fig. 2. Equivalent circuit diagram of a transmission system with a single line for the positive sequence

The approach proposed in [7] is based on the fundamental components of fault and pre-fault voltages measured at the two ends of a transmission line. The fault location algorithm utilises the measurements of the positive sequence of post- and pre-fault voltages at both ends of a line. In addition, the positive sequence impedance data for a line, the supplying systems and the equivalent link between the line terminals is required. The fault location algorithm is based on the *"distance factor"* determined with taking into account the admittance data for a line as well. This method can be a remedy for avoiding large estimation errors in case of deep CTs saturation [7].

IV. FAULT LOCATION IN SERIES-COMPENSATED LINES

Series compensation is an attractive way of increasing a power transfer capability and making control more flexibly. Accurate fault location in such the lines requires offsetting the series compensation effect as well as the reactance effect resulting from the remote end infeed under resistive faults. Installation of series capacitors (SCs), equipped with Metal-Oxide Varistors (MOVs) for overvoltage protection, on transmission lines causes certain problems for protective relaying and fault location [8, 9]. The series capacitors can be installed in a line in different ways. However, it is assumed here for further considerations that they are not installed at the line terminals but in some distance p [pu] from the substation A (Fig. 5). In such the cases the voltage drops across SCs&MOVs are not measurable and thus have to be estimated on the base of the available measurements. Both, the deterministic and the artificial neural networks based approaches for that purpose have been considered and deeply investigated in [8]. Usage of the fundamental frequency equivalents (Fig. 4) as the other possibility for representing SCs&MOVs has been proposed in the fault location algorithm delivered in [9]. This fault location algorithm was an adaptation of the idea of the fault locator developed for traditional uncompensated lines [4] to the specific conditions of a single series-compensated line.

A commonly used single exponential approximation of MOV characteristic (Fig. 3) is:

$$\frac{v_v}{V_{REF}} = \left(\frac{i_{MOV}}{P}\right)^q \tag{6}$$

where:

v_v - voltage drop across SC&MOV,

i_{MOV} - current flowing in MOV,

V_{REF}, P – reference voltage and current,

q – exponent of approximation.

In Fig. 4 different compensation rates (expressed in %) for a 400kV, 300km line have been considered.

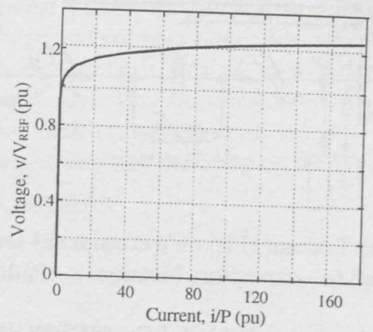

Fig. 3. Characteristic of a MOV

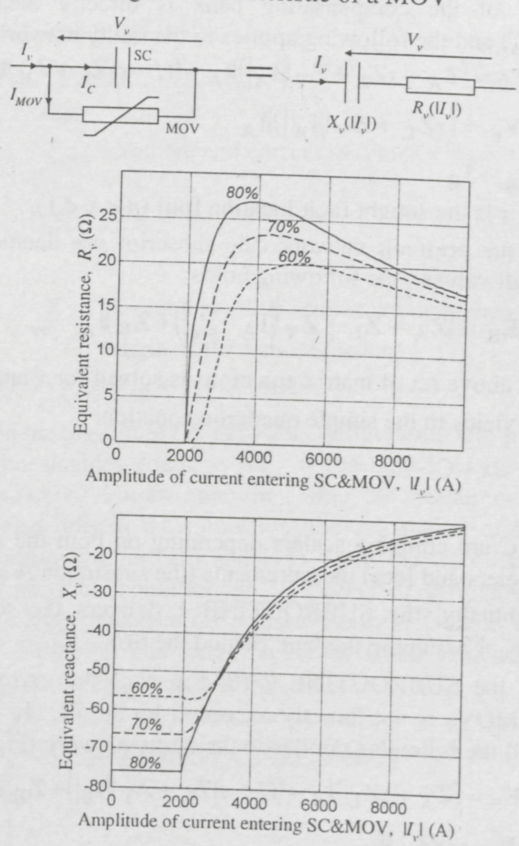

Fig.4. Fundamental frequency equivalenting of SC&MOV

The fault location algorithm presented in [9] uses phase co-ordinates approach and applies a generalised fault model:

$$\mathbf{I_F} = \frac{1}{R_F}\mathbf{K_F}\mathbf{V_F} \tag{7}$$

where:

$\mathbf{V_F}$, $\mathbf{I_F}$ - vectors of fault voltages and currents,

R_F - aggregated fault resistance,

$\mathbf{K_F}$ - fault matrix built upon the type of fault using the two-step procedure [9].

The algorithm branches into two separate subroutines considering two fault spots (Fig. 5):

- SUBROUTINE 1 – for faults behind the SCs (F_1),
- SUBROUTINE 2 – for faults in front of the SCs (F_2).

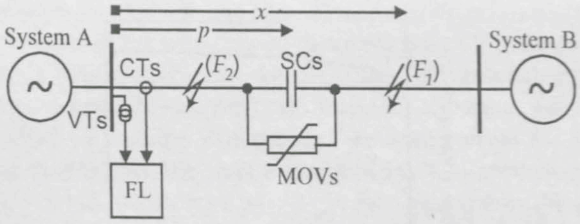

Fig. 5. Fault Locator (FL) on a considered series compensated line (p - capacitors location, x - fault location)

If the fault occurs behind SCs (SUBROUTINE 1), the current of the compensating bank is directly measured ($\mathbf{I_V} = \mathbf{I_A}$) and the following applies to the faulty network:

$$\mathbf{E_A} - \mathbf{E_B} = \left(\mathbf{Z_A} + x\mathbf{Z_L} + \mathbf{Z_V}\left(\left|\mathbf{I_A}\right|\right)\right)\mathbf{I_A} - \left((1-x)\mathbf{Z_L} + \mathbf{Z_B}\right)\mathbf{I_B} \quad (8)$$

$$\mathbf{V_A} - \mathbf{V_F} = \left(x\mathbf{Z_L} + \mathbf{Z_V}\left(\left|\mathbf{I_A}\right|\right)\right)\mathbf{I_A} \quad (9)$$

$$\mathbf{I_F} = \mathbf{I_A} + \mathbf{I_B} \quad (10)$$

where: x is the sought fault location [pu] ($p < x < 1$).

For the pre-fault network (the subscript *pre* denotes the pre-fault values), the following holds:

$$\mathbf{E_A} - \mathbf{E_B} = \left(\mathbf{Z_A} + \mathbf{Z_L} + \mathbf{Z_V}\left(\left|\mathbf{I_{A\_pre}}\right|\right) + \mathbf{Z_B}\right)\mathbf{I_{A\_pre}} \quad (11)$$

The above set of matrix equations is solved for x and R_F, which yields to the simple quadratic equation:

$$Ax^2 + Bx + C - R_F = 0 \quad (12)$$

where:

A, B, C are complex scalars depending on both the system parameters and local measurements (the substation A only).

Eventually, the SUBROUTINE 1 delivers the solution (x_1, R_{F1}) assuming the fault behind the SCs.

For the SUBROUTINE 2 ($0 < x < p$) the current of SCs&MOVs is not directly measured by the FL ($\mathbf{I_V} = \mathbf{I_B} \neq \mathbf{I_A}$) and the following applies to the faulty network (Fig. 5):

$$\mathbf{E_A} - \mathbf{E_B} = \left(\mathbf{Z_A} + x\mathbf{Z_L}\right)\mathbf{I_A} - \left((1-x)\mathbf{Z_L} + \mathbf{Z_V}\left(\left|\mathbf{I_B}\right|\right) + \mathbf{Z_B}\right)\mathbf{I_B} \quad (13)$$

$$\mathbf{V_A} - \mathbf{V_F} = \left(x\mathbf{Z_L}\right)\mathbf{I_A} \quad (14)$$

In this case, one also obtains a quadratic equation (12), but the iterative numerical solution is required (Fig. 6b). The SUBROUTINE 2 delivers the solution (x_2, R_{F2}). An extra logic block is needed to select the correct solution (Fig. 6a). The values for fault resistance and amplitude of current in healthy phases of the fault path, estimated by both the subroutines are used for judging which the subroutine is valid in particular case.

Several thousands of analysed fault cases (example: Fig. 7) prove the algorithm to be accurate [9]. The average fault location error is about 0.3%, while the maximum error does not exceed 2%. The presented algorithm exhibits high robustness against the mismatch of the source impedances and MOVs parameters [9].

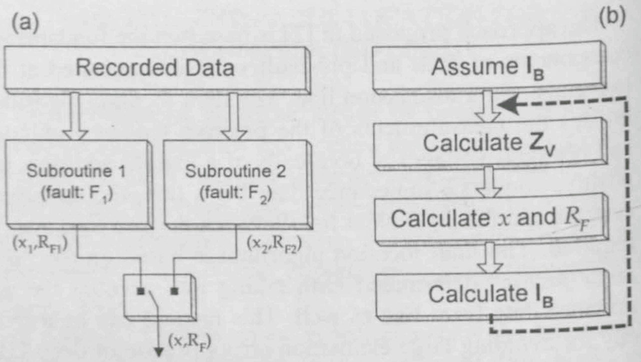

Fig. 6. Two subroutines compute two conditional fault locations (a), the SUBROUTINE 2 requires iterations (b)

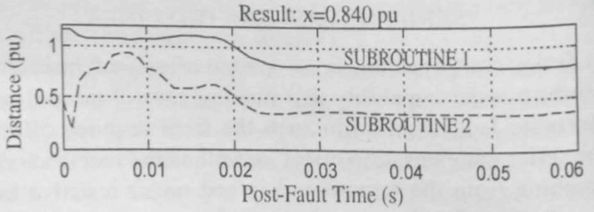

Fig. 7. Example of fault location in a single s-c line: *a-g* fault behind SCs&MOVs at x=0.833 pu

The developed fault location algorithm [9] has been implemented into existing relays and is undergoing field tests in one of Swedish utilities on 400 kV s-c lines [10].

The authors accomplished further extension of the algorithm introduced in [9] for locating faults in s-c parallel lines (Fig. 8). For faults behind SCs&MOVs but overreaching the line length, i.e. in the remote system (Fig. 8 – fault F1b) the mutual coupling between the lines is considered as limited to the whole line length only [11].

ATP-EMTP simulation example of fault location in parallel s-c lines is shown in Fig. 9. The average fault location error for thousands of fault cases was obtained as about 0.35%, while the maximal: 2%. Further improvement of the accuracy can be achieved with using communication (Fig. 8) for sending the measured source impedance and amplitudes of phase currents from the remote substation.

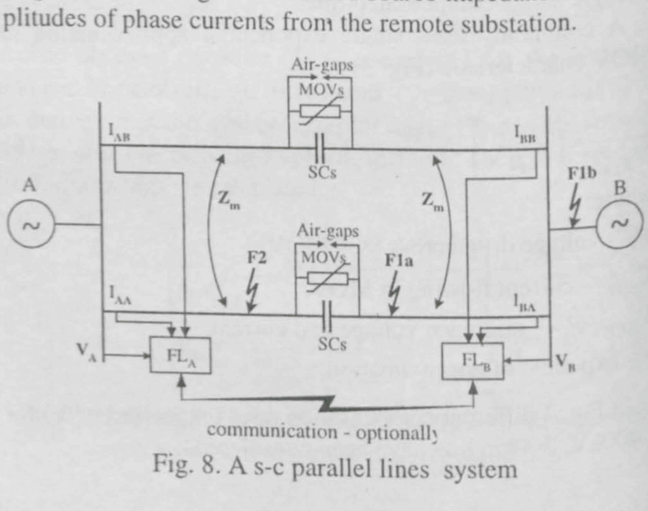

Fig. 8. A s-c parallel lines system

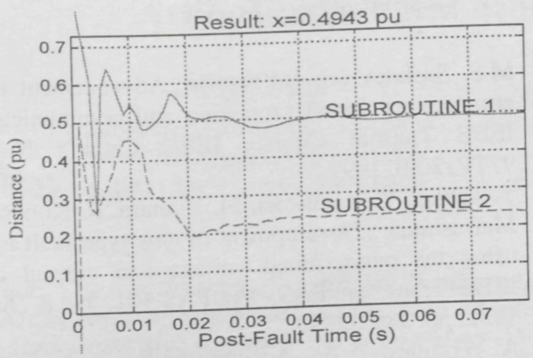

Fig. 9. Example of fault location in s-c parallel lines: *a-b-g* fault at x=0.5 pu just behind SCs&MOVs

V. FAULT LOCATION IN DISTRIBUTION NETWORKS

In recent years, many techniques for the location of earth faults were reported [12]. In opposite to the methods used in HV system, they should take into consideration of the fact that the investigated networks can consist of line sections of different cables, which parameters can change from section to section. This, however, mainly influences on the algorithm for a fault place determination. Fault-loop impedance calculation can use the same principle, which is based on voltage and phasor estimation.

In such a case the calculation of fault-location consists of two steps. First, the impedance of the feeder is calculated from voltage and current before and during the fault. Second, the impedance for the feeder and a possible fault is determined from a model of the network, which is based on the topology of the real network. By comparing the calculated feeder impedance with the measured impedance, an indication of the fault-location can be obtained.

General structure of the fault location method is presented in Fig. 10 while the equivalent scheme of the considered network in Fig. 11.

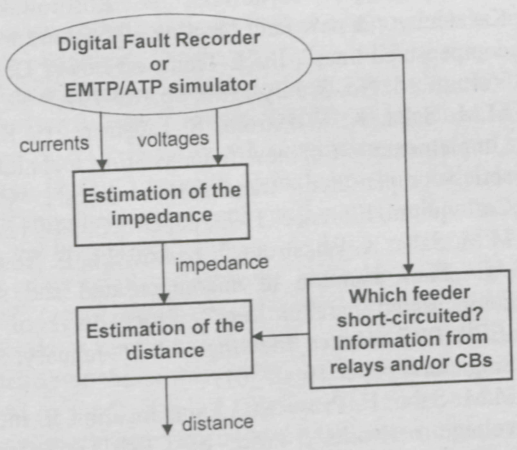

Fig. 10. The basic block diagram of the proposed fault location algorithm

The technique utilizes the fundamental frequency components of voltage and currents observed immediately before a fault and during the fault. For the case when only one-end supplied radial networks are considered, the positive and zero-sequence fault-loop impedance is calculated according to well known equations depending on the type of fault.

Phase-to-phase fault:

$$\underline{Z}_k = \frac{\underline{V}_{pp}}{\underline{I}_{kpp}} \tag{17}$$

$\underline{V}_{pp}$, $\underline{I}_{kpp}$ - phase-to-phase fault-loop voltage and current.

Phase-to-ground fault:

$$\underline{Z}_k = \frac{\underline{V}_{ph}}{\underline{I}_{kph} + \underline{k}_{kN}\,\underline{I}_{kN}} \tag{18}$$

$\underline{V}_{ph}$, $\underline{I}_{kph}$ - voltage and current of a faulty phase,

$$\underline{k}_{kN} = \frac{\underline{Z}_0' - \underline{Z}_1'}{3\underline{Z}_1'} \tag{19}$$

$\underline{Z}_0'$, $\underline{Z}_1'$ - zero and positive sequence impedance per length of the faulted feeder,

$$\underline{I}_{kN} = \underline{I}_{kA} + \underline{I}_{kB} + \underline{I}_{kC} \tag{20}$$

In the algorithm the network configuration and parameters of lines/cables, loads as well as pre-fault load flow estimation is used. For the condition, when the measurement is performed only at the substation, the calculation of fault loop impedance as in (17) and (18) needs the information from the pre-fault condition [12]. Results of estimation of the fault-loop reactance for a phase-to-phase fault as seen from the substation and from the feeder under fault at node 20 (Fig. 11) are presented in Fig. 12.

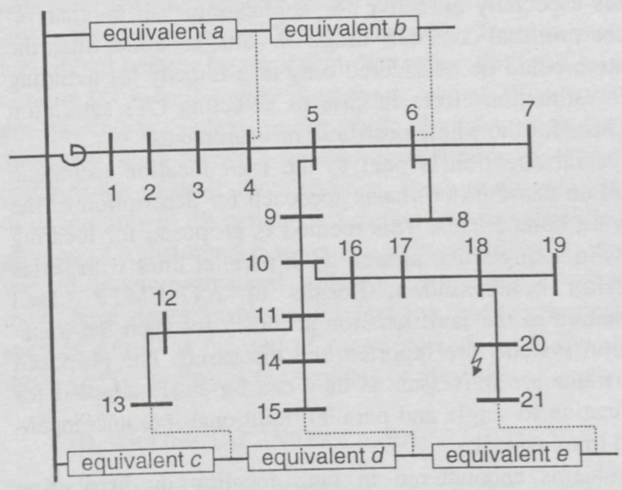

Fig. 11. Idea of the feeder model representation; dotted lines are for grounding system connection

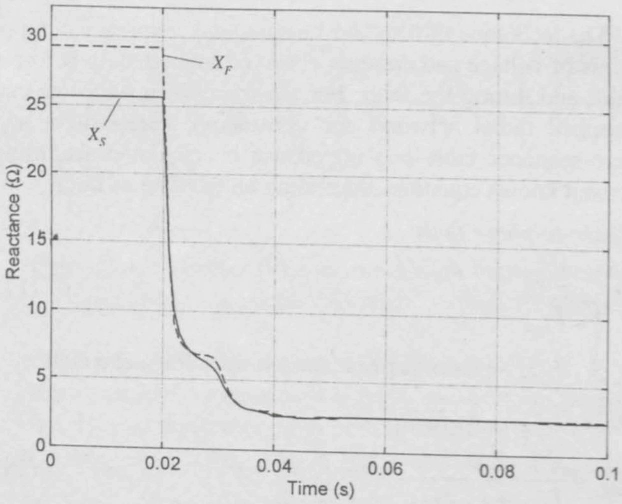

Fig. 12. Estimates of the fault-loop reactance obtained from the substation (X_S) and from the feeder (X_F) measurements

VI. CONCLUSIONS

Overview of fault location techniques for power transmission lines as well as for distribution networks is presented. Distinctive features of different fault location algorithms classified as the impedance techniques are discussed.

One-end fault location for traditional uncompensated transmission lines compensating for the infeed effect under resistive faults is presented. The issue of the location accuracy and its improvement is discussed. The two-end fault location based on unsynchronized measurements is considered. Measurements from impedance relays at the line terminals can be processed. However, the other possibility based on using only positive sequence currents and voltages seems especially attractive for application. Yet another reported proposal considers usage of voltages alone. Such the solution could be considered only as a remedy for avoiding large estimation errors in case of detecting CTs saturation that lasts for the whole post-fault measurements.

Special attention is paid to the fault location technique based on phase co-ordinates approach for description of the network components. This method is proposed for locating faults in a single line as well as in parallel lines with series capacitor compensation. Results of ATP-EMTP based evaluation of the fault location accuracy for such the transmission systems are reported and discussed. The proposed algorithms are universal, as they can be easily adapted for application to single and parallel traditional, i.e. uncompensated lines as well.

Problems encountered in fault location in distribution networks are stated and the possible solutions are indicated. The proposed solution for the considered solidly grounded network of a radial type is delivered.

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