FAULT LOCATION IN MEDIUM VOLTAGE NETWORKS

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INTRODUCTION

Fault location in medium voltage (MV) networks creates new problems comparing with the same task in HV and EHV transmission lines. In HV and EHV networks each transmission line may be equipped with its own Fault Locator (FL). In such a case, the FL algorithm is a numerical procedure which converts voltage and current, given in a digital form, into a single number being a distance to a fault. In contrary, in MV networks, FLs are usually assumed to be of a centralized type, i.e., they measure the quantities common for the whole substation (busbar voltages and transformer currents) what makes the accurate fault location more difficult. Three fundamental factors contribute to this:

- *when a current of a faulty line is not directly available to the FL, certain error is introduced when assuming the transformer current during a fault to be a current of the faulty line; moreover, it is no possible to compensate accurately for the pre-fault load current of the faulty line;*
- *MV lines may be multi-terminal and/or contain loops what creates well known problems in single ended fault location, generally there is no indication on a single fault position (few alternatives possible);*
- *in the case of a MV line, there are often loads located between the fault point and the busbar; since the loads change and are unknown to the FL it is difficult to compensate for them.*

The paper describes in brief the algorithm of the distance to fault calculation as well as the EMTP simulations and real test results and their comparison. Examples are given for the medium voltage grid of NUON - a distribution utility in the Netherlands.

THE BASIC ASSUMPTIONS

In modern society customers are more sensitive to the outages. Therefore, more efficient methods for fault location, supply restoration and high quality customer service, which reduce the overall costs, are required. Fast location of the faulted section in MV networks results in minimizing of inconvenience caused to the affected customers. This is becoming more important as there is an increasing emphasis placed on quality and reliability of supply and, therefore, fault location is considered to be one of the first function to be integrated into modern substation control system [1,2].

Because of economical reason, feeder-dedicated fault locators can hardly be applied in MV networks. However, substantial monitoring using digital fault recorders (DFR) is a common utility practice in most countries. Moreover, fault recording function is available in new installed digital relays. Under this circumstances, low-cost fault location has become feasible [3,4].

This paper presents a method for estimating the location of faults on radial MV system which can include many intermediate load taps. In the method nonhomogeneity of the feeder sections is also taking into account. Performance of the technique was investigated using data obtained from EMTP/ATP simulations [5]. Also data recorded during faults in real MV network were used. The voltage and current data samples obtained from EMTP/ATP simulations or delivered by DFR were converted to a MATLAB format [6]. The 1 kHz sampled data were then used in the MATLAB Fault Locator model. General structure of the used FL model is presented in Fig. 1. Some of the results are included in the paper.

Considered in tests MV grid of NUON (a distributed utility in the Netherlands) fully consists of underground cables. 10 kV substation is supplied from 150 kV system (Fig.2). The network contains of rings and subrings, containing several 10/0.4 kV transformerhouses. By having network openings in each ring and subring the network is operated in a radial way. Faults can be switched off by the circuit-breaker for the concerning feeder. After finding the faulted cable section, this section can be isolated by opening the switches in the adjacent transformerhouses. The network before the fault can be restored by closing the circuit breaker at the substation. The network behind the fault can be restored by

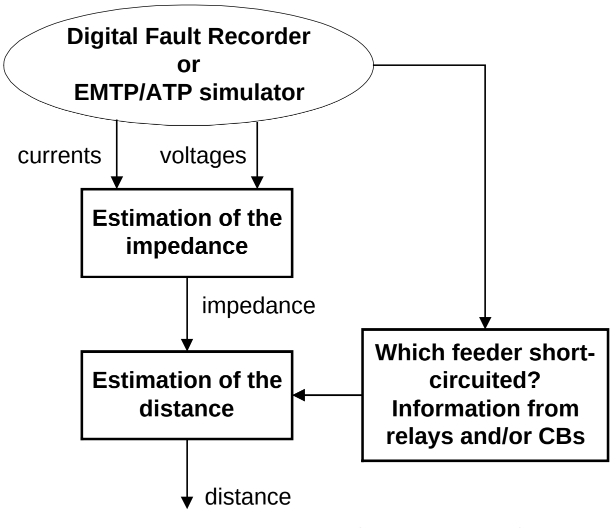


Fig. 1. The basic block diagram of the proposed fault location algorithm.

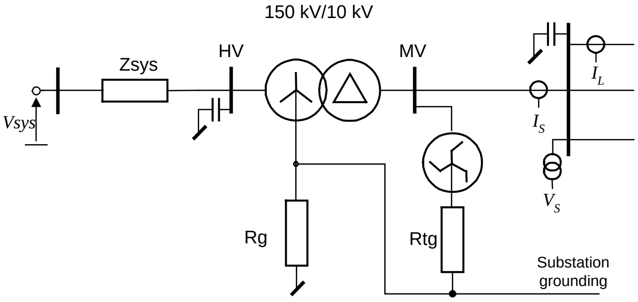


Fig. 2. Scheme of the considered system

connecting it to the other part of the (sub) ring.

Measurements of current are available at the supplying transformer (I_S) or (only few cases) at the feeders (I_L). General scheme of the feeder node is presented in Fig. 3. Practically, only separate nodes have loads or tapped cable. Cable shield is usually grounded only at the load points.

ALGORITHM FOR CALCULATING THE FAULT IMPEDANCE

In recent years, many techniques for the location of earth faults were reported [1-4]. 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. The accuracy of the fault-location was required to be less then 500 meters. In order to proof the possibility of accurate fault-location a feasibility test was performed in the 10 kV network of substation Zaltbommel.

Fault-loop impedance measurement algorithm depends on whether or not the measurements (voltage and current) are available in a faulty feeder or only at the substation level (total current is measured at the supplying transformer). Moreover, the algorithm depends on type of fault. Herein we will consider two different algorithms for phase-to-phase or three-phase faults and for phase-to-ground fault.

Measurements at the faulty feeder

As far as only one-end supplied radial networks are considered, the positive sequence fault-loop impedance is calculated according to well known equations depending on the type of fault (Fig.4).

Phase-phase fault loop (a phase-to-phase or three phase fault):

$$\underline{Z}_k = \frac{\underline{V}_{pp}}{\underline{I}_{kpp}} \tag{1}$$

where $\underline{V}_{pp}$ - phase-phase fault-loop voltage, for example:

$\underline{V}_{pp} = \underline{V}_A - \underline{V}_B$,

$\underline{I}_{kpp}$ - phase-phase fault-loop current, for example:

$\underline{I}_{kpp} = \underline{I}_{kA} - \underline{I}_{kB}$.

Phase-ground fault loop (a phase-to-ground fault):

$$\underline{Z}_k = \frac{\underline{V}_{ph}}{\underline{I}_{kph} + \underline{k}_{kN}\underline{I}_{kN}} \tag{2}$$

where: $\underline{V}_{ph}$ - voltage of a faulty phase,

$\underline{I}_{kph}$ - current in a faulty phase,

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

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

$$\underline{I}_{kN} = \underline{I}_{kA} + \underline{I}_{kB} + \underline{I}_{kC} \tag{4}$$

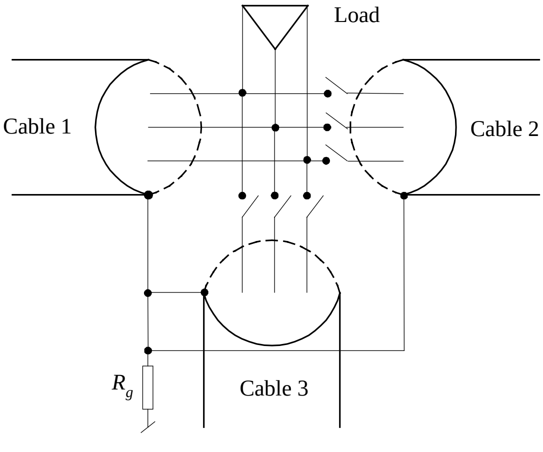


Fig. 3. General feeder node connection

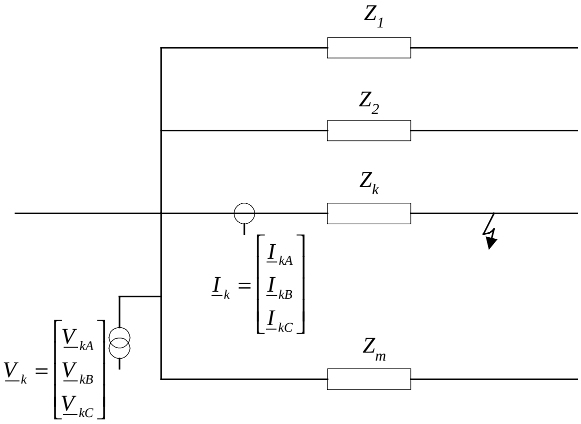


Fig. 4. Diagram of the network: measurements are taken in the faulty feeder

Measurements at the substation level

In this case we assume that faulty line is identified. Moreover, some of the described below pre-fault parameters of the network are also known or can be estimated from the SCADA information.

Let in the considered radial network, a faulty feeder (say feeder *k*) have the pre-fault equivalent impedance $\underline{Z}_{Lk}$ (Fig. 5). The remaining parallel connected feeders are represented by an equivalent branch with the impedance $\underline{Z}_L$ (i.e. $\frac{1}{\underline{Z}_L}=\frac{1}{\underline{Z}_1}+\frac{1}{\underline{Z}_2}+\ldots+\frac{1}{\underline{Z}_m}$). Both $\underline{Z}_{Lk}$ and $\underline{Z}_L$ are assumed to be the positive sequence impedances.

The aim of the analysis is to determine the post-fault positive sequence impedance $\underline{Z}_k$ under assumption that the equivalent impedance $\underline{Z}_L$ stay unchanged during a fault. The following equation is valid for the pre-fault state (Fig. 4):

$$\underline{Z}_{pre}=\frac{\underline{V}_{pre}}{\underline{I}_{pre}}=\frac{\underline{Z}_L\underline{Z}_{Lk}}{\underline{Z}_L+\underline{Z}_{Lk}} \tag{5}$$

where $\underline{V}_{pre}, \underline{I}_{pre}$ - are phase-to-phase or phase-to-ground (for symmetrical condition) variables.

Two post-fault cases should be considered:

Phase-phase fault-loop (a phase-to-phase or three phase fault) The positive sequence impedance seen from the substation is obtained from the equation:

$$\underline{Z}=\frac{\underline{V}_{pp}}{\underline{I}_{pp}}=\frac{\underline{Z}_L\underline{Z}_k}{\underline{Z}_L+\underline{Z}_k} \tag{6}$$

where $\underline{V}_{pp}$ - phase-phase fault-loop voltage, for example:

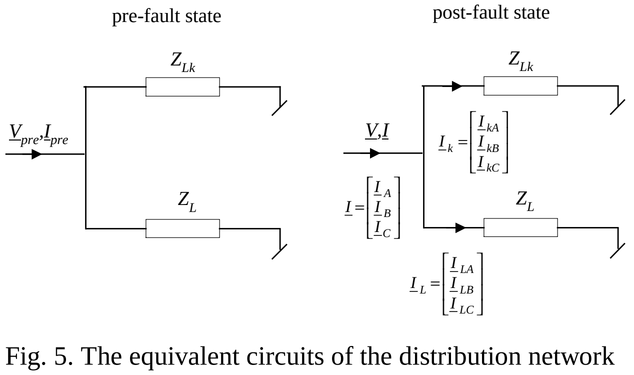
$\underline{V}_{pp}=\underline{V}_A-\underline{V}_B$,

$\underline{I}_{pp}$ - phase-phase fault-loop current taken at the substation, for example: $\underline{I}_{pp}=\underline{I}_A-\underline{I}_B$,

Combining (5) and (6) yields:

$$\underline{Z}_k=\frac{\underline{Z}\,\underline{Z}_{pre}}{\underline{Z}_{pre}-\underline{Z}(1-\underline{k}_{zk})} \tag{7}$$

where: $\underline{k}_{zk}=\frac{\underline{Z}_{pre}}{\underline{Z}_{Lk}}=\frac{\underline{S}_{Lk}}{\underline{S}_{\Sigma}}$ (8)



pre-fault state

post-fault state

Fig. 5. The equivalent circuits of the distribution network

$\underline{S}_{Lk}$ - the power in the faulty line in the pre-fault conditions,

$\underline{S}_{\Sigma}$ - the power in all the lines in the pre-fault conditions.

Combining (5) and (8) one also obtains

$$\underline{k}_{zk}=\frac{\underline{Z}_L}{\underline{Z}_L+\underline{Z}_{Lk}} \tag{9}$$

The coefficient $\underline{k}_{zk}$ for each line is estimated on the basis of the pre-fault steady-state conditions. In a substation with a large number of feeders these coefficients are close to zero and change only a little, e.g. for two identical lines $\underline{k}_{zk}=0.5$ (if only line reactance is taking into account), but for twenty lines: $\underline{k}_{zk}=0.05$. One should observe that, in general, $\underline{k}_{zk}$ is a complex number.

From equation (7) one can calculate the fault-loop impedance using the measurements from the substation. Dividing numerator and denominator of (7) by $\underline{Z}_{pre}$ and substituting (6) for $\underline{Z}$, equation (7) can be rewritten in a more convenient form:

$$\underline{Z}_k=\frac{\underline{V}_{pp}}{\underline{I}_{pp}-(1-\underline{k}_{zk})\frac{\underline{V}_{pp}}{\underline{Z}_{pre}}} \tag{10}$$

Phase-ground faulted loop (a phase-to-ground fault). In the case of a phase-to-ground fault, the positive sequence fault-loop impedance is calculated according to (2).

One can observe that as only a single phase-to-ground fault is considered (say, in feeder *k*) the zero sequence current measured in the substation contains the faulty feeder current $\underline{I}_{kN}$ and zero-sequence current flows through capacitances of the healthy feeders $\underline{I}_{CL}$. Knowing voltage and current measurements at the substation, and network parameters the fault-loop impedance can be established in the similar way as for measurements from the feeder. Final expression takes the form

$$\underline{Z}_k=\frac{\underline{Z}_g\,\underline{Z}_{pre}}{\underline{Z}_{pre}-\underline{Z}_g(1-\underline{k}_{zk})(1-\frac{\underline{V}_0}{\underline{V}_{ph}})} \tag{11}$$

where: $\underline{Z}_g=\frac{\underline{V}_{ph}}{\underline{I}_{ph}+\underline{k}_{kN}\underline{I}_{kN}}$ (12)

$\underline{V}_0=(\underline{V}_A+\underline{V}_B+\underline{V}_C)/3$.

The above equations defines fault-loop impedance for phase-to-ground fault in terms of positive-sequence impedance. For utilizing of the relationship some pre-fault measurements and steady-state estimations are needed.

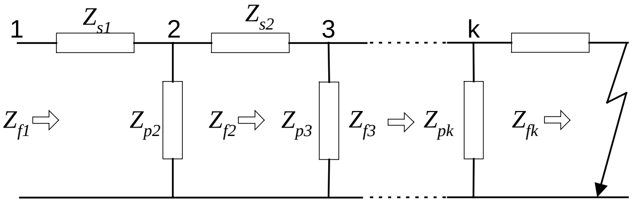


Fig. 6. Equivalent positive-sequence diagram of the faulty cable

ESTIMATION OF THE DISTANCE TO FAULT

Based on the measured fault-loop impedance and the cable parameters it is possible to estimate the distance to a fault. Chosen algorithm depends on the fault type: for phase-to-phase or 3-phase fault only positive sequence impedance calculation is needed while for phase-to-ground fault also zero-sequence fault-loop parameters should be calculated. Algorithms for these two cases are discussed below.

Algorithm for distance to a fault estimation for phase-to-phase fault

Let us consider the equivalent positive-sequence circuit of the fault-loop (Fig. 6). The shunt elements represent loads at successive nodes while the cable impedance is represented by the series elements. Defining an equivalent fault-loop impedance as seen from the substation one obtains the following recursive form

$$\underline{Z}_{fi} = \frac{\underline{Z}_{pi}(\underline{Z}_{fi-1} - \underline{Z}_{si-1})}{\underline{Z}_{pi} - \underline{Z}_{fi-1} + \underline{Z}_{si-1}} = R_{fi} + X_{fi} \tag{13}$$

In the above equation $\underline{Z}_{si-1}$ represents the cable segment impedance while $\underline{Z}_{pi}$ relates to the load impedance and/or equivalent impedance of the branches connected to the node (Fig. 7). Value of these impedances is estimated from the steady-state condition of the network.

One can see that impedance obtained in the following steps tends toward zero

$$\left|\underline{Z}_{fi-1}\right| > \left|\underline{Z}_{fi}\right| \tag{14}$$

and the last value of the impedance (as seen from the adjacent node) is (Fig. 8)

$$\underline{Z}_{fk} = l_{fk-1}\underline{Z}_{sk-1} + R_f \tag{15}$$

where: l_{fk} - p.u. distance from node *k* to the fault point (total length of the faulty segment is assumed to be 1),

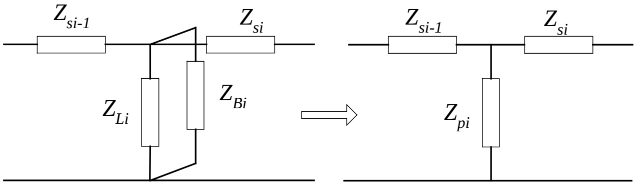


Fig. 7. Equivalenting of the node impedance

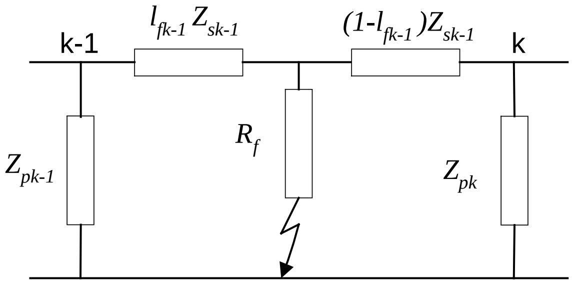


Fig. 8. Equivalent diagram of the cable segment with fault

$\underline{Z}_{sk-1}$ - impedance of the cable segment between nodes *k-1* and *k* ($\underline{Z}_{sk-1} = R_{sk-1} + jX_{sk-1}$),

R_f - fault resistance.

The algorithm for determination of the distance to fault is based on the fact that fault-loop impedance decreases when an observation point moves from the substation along the faulty feeder. It decreases from node to node according to (13). The procedure stops when a successive reactance assumes a negative value.

COMPUTER MODEL OF A SPECIFIC MEDIUM VOLTAGE NETWORK

Distribution networks have usually relatively big size. For distance to fault calculation each feeder should be represented by detail scheme with adequate line and load models. In the cable networks grounding system has different structure than feeders have (open cables may have connected grounding circuits), what should be also represented in the model. This causes to represent all feeders connected in a given substation in general simulation model. However, for proper post-fault transients analysis some simplifications can be introduced. They are based on the following assumptions:

- supplying system is described by steady-state parameters;
- analyzed feeder is represented in detail;
- all other feeders are represented by equivalented schemes

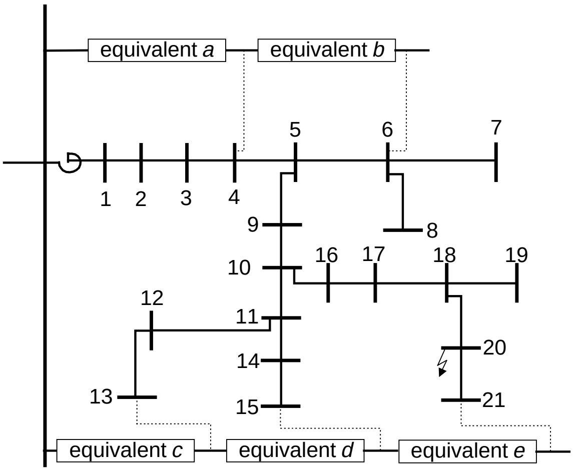


Fig. 9. Idea of the feeder model representation; dotted lines are for grounding system connection

with reproducing only the grounding system connections.

Example of the analyzed network is presented in Fig. 9. Cable sections are represented by appropriate π-schemes (3 phases and shield), while loads and equivalent circuits are described by $R-L$ or $R-L-C$ schemes. Phase-related representation of the network causes that specified model has hundreds nodes, even if adjoining feeders are equivalented.

EMTP/ATP SIMULATIONS AND ANALYSIS

EMTP model of the analyzed network has been extensively used for investigation of the proposed algorithm for distance to fault calculation. Consider the example of A-B fault at node 20 in the analyzed feeder (Fig. 9). Assumed fault resistance $R_f = 0.1\Omega$. Substation is supplied from 150 kV system as in Fig.1. MV network consists of 16 feeders which, except of one analyzed feeder, are represented by their equivalent schemes. On the following figures the measurements: phase voltage at the substation (Fig. 10), total phase currents at the substation (Fig. 11) and at the feeder (Fig. 12), and estimated reactances are presented. One can see that fault-loop reactances obtained from current measured at the substation (X_S) and in the feeder (X_F) are very similar.

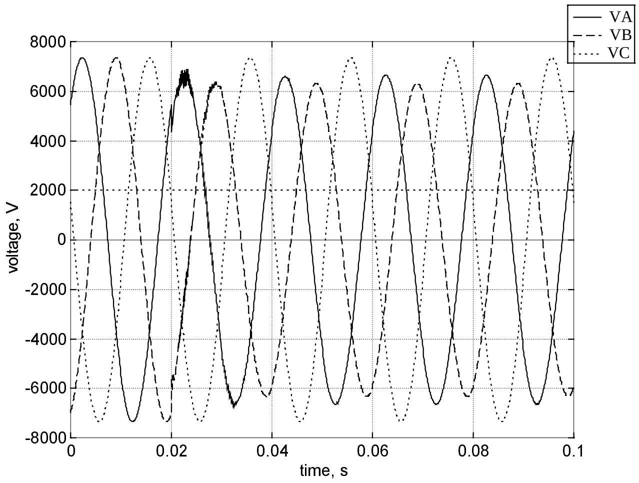


Fig. 10. Phase voltage at the substation

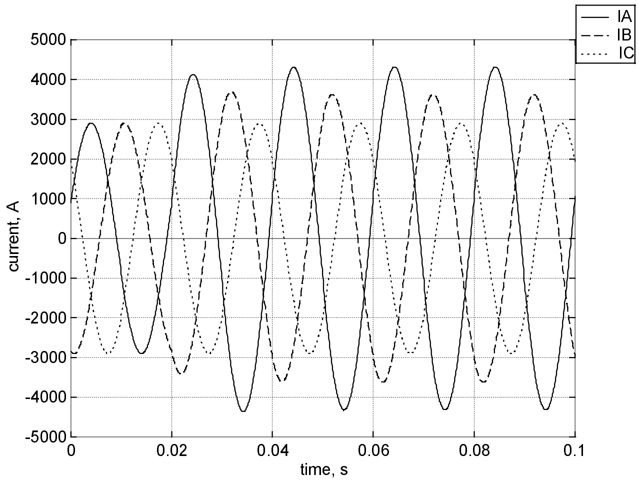


Fig. 11. Total phase current at the supplying transformer

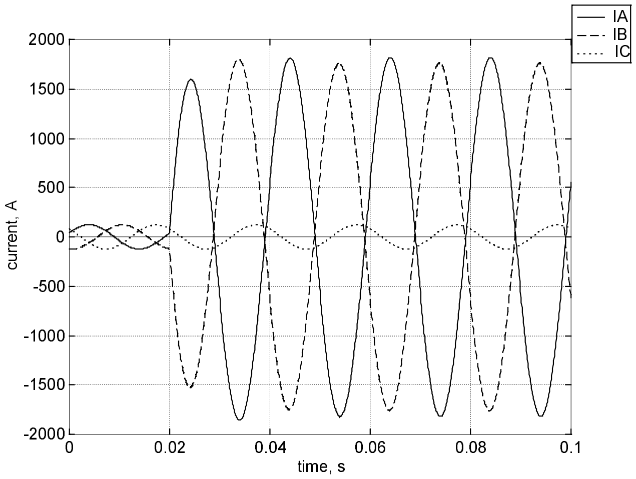


Fig. 12. Phase currents in faulty feeder

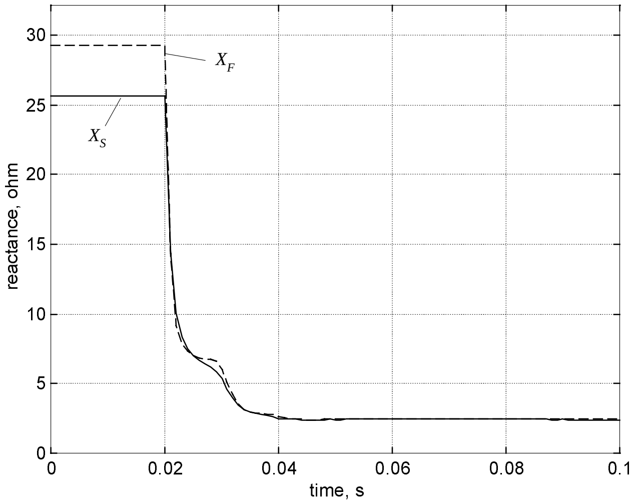


Fig. 13. Estimates of the fault-loop reactance obtained from substation (X_S) and from the feeder (X_F) measurements.

Application of the presented algorithm for distance to fault calculation with obtained fault-loop reactance gives two results, both at distance of 266 m from node 18 (see Fig. 9). The actual fault position is at 308 m from node 18.

RECORDED DATA ANALYSIS

For verification of the proposed algorithm series of field experiences have been made in the considered network. DFR was installed at the substation and in the faulty feeder.

Fig. 14 presents phase voltage recorded at the substation during A-B fault provided at the same node 20 as in EMTP simulation. Phase currents recorded at this exercise in the feeder is depicted in Fig. 15. It can be seen that pre-fault current was very small as there was staged fault. Fault duration was about 50 ms. Results of the fault-loop impedance estimation obtained from current measured at substation and in feeder is presented in Fig. 16. Both measurements give pair of distance to fault calculation results: 227 m from node 18 (for measurement in the feeder) and 64 m from

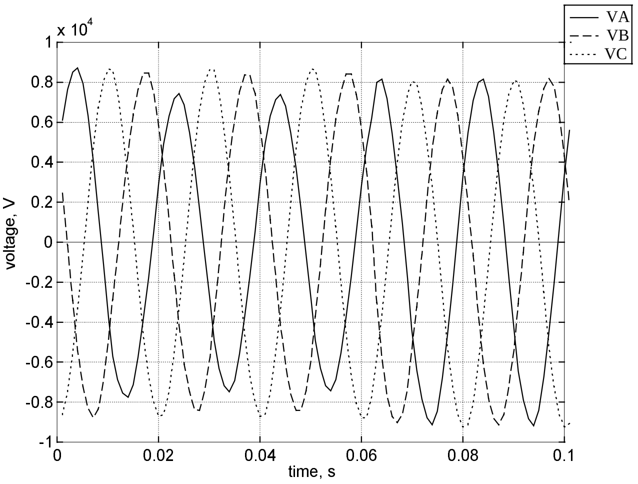


Fig. 14. Phase voltage recorded at the substation

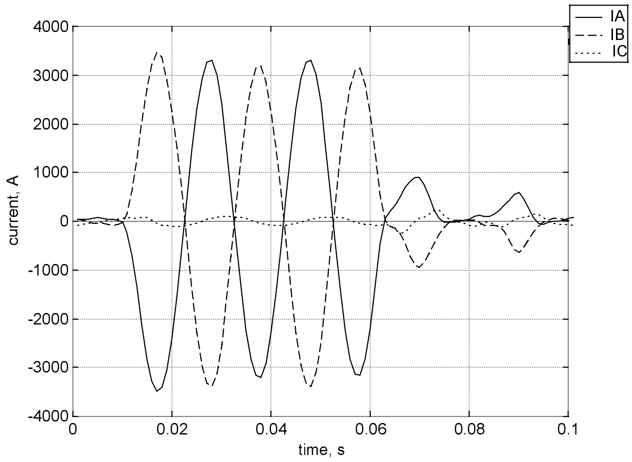


Fig. 15. Phase current recorded at the feeder.

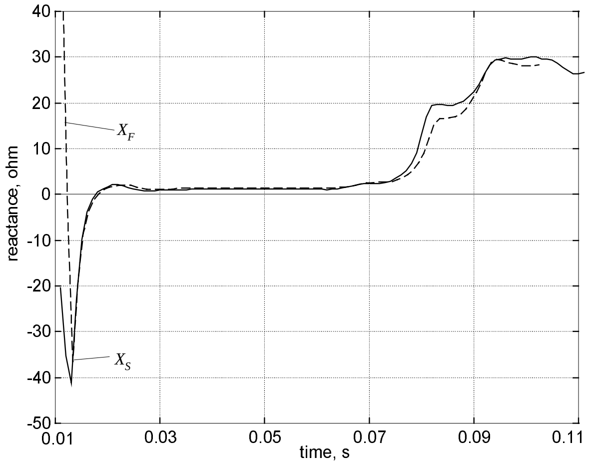


Fig. 16. Estimates of the fault-loop reactance obtained from measurements recorded at the substation (X_S) and in the feeder (X_F).

node 18 (for measurement at the substation). The actual fault position is at 308 m from node 18. The last estimate has greater error what reproduces the fact that in this case pre-fault conditions have greater influence on final result.

CONCLUSIONS

Fault locator, with their improved accuracy and reliability, can be considered as effective tool to help reduce outage duration and cost, and to prevent outages. Source signals for FL can be delivered from autonomy DFRs or adequately equipped relays.

Presented algorithm for distance to fault calculation is based on voltage and current phasor estimation. The algorithm was investigated and proved on the basis of voltage and current data obtained from EMTP/ATP simulations as well as recorded at DFR during provided field experiences.

It was checked that used in the algorithm current measurements can be delivered from faulty feeder or from the substation (as total current at the supplied line). In the last case the estimation error depends on accuracy of pre-fault condition determination in the MV substation. Distance to fault estimation error depends on accuracy of measurements as well as cable parameters.

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