

REVIEW OF FAULT LOCATION TECHNIQUES FOR DISTRIBUTION SYSTEMS

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Introduction

Electric power systems have grown rapidly over the past fifty years. This has resulted in a large increase of the number of lines in operation and their total length. These lines experience faults which are caused by storms, lightning, snow, freezing rain, insulation breakdown and, short circuits caused by birds and other external objects. In most cases, electrical faults manifest in mechanical damage, which must be repaired before returning the line to service. The restoration can be expedited if the location of the fault is either known or can be estimated with reasonable accuracy.

Fault locators provide estimate for both sustained and transient faults. Generally, transient faults cause minor damage that is not easily visible on inspection. Fault locators help identify those locations for early repairs to prevent recurrence and consequent major damages.

The subject of fault location has been of considerable interest to electric power utility engineers and researchers for over twenty years. Most of the research done till date, has been aimed at finding the locations of transmission line faults. This is mainly because of the impact of transmission line faults on the power systems and the time required to physically check the lines is much larger than the faults in the subtransmission and distribution systems. Of late, the location of faults on subtransmission and distribution systems has started receiving some attention as many utilities are operating in a deregulated environment and are competing with each other to increase the availability of power supply to the customers.

The primitive method of fault location consisted of visual inspection [1]. Methods, proposed in literature or implemented in practice, for estimating the location of transmission line faults consist of using voltages and currents measured at one or both terminals of a line. The methods can be divided into three categories: methods that are based on traveling waves, methods that use high frequency components of currents and voltages and, methods that use the fundamental frequency voltages and currents measured at the terminals of a line. The last method, also classified as impedance-based method, consists of calculating line impedances as seen from the line terminals and estimating distances of the faults. Impedance-based methods are more

popular among utilities, because of their ease of implementation. The methods in this category can be further classified into two sub-categories: methods that use measurements from one terminal of the transmission line [2-3] and methods that use measurements taken from both terminals.

Methods have also been proposed in the past for estimating fault locations on radial transmission lines [4]. These methods when used for distribution lines are prone to errors because of non-homogeneity of lines, presence of 'laterals' and load taps. A method using fundamental frequency voltages and currents has been proposed for rural distribution feeders [5]. It does not consider dynamic nature of the loads. Performance of the technique in situations where cables are used could also be an issue.

This paper reviews selected fault location techniques proposed for distribution systems.

DMS Based Fault Location [6]

Reference [6] presents a fault location method, which has been developed as part of Distribution Management System (DMS) development. The basic idea of DMS has been to develop a new information system based on integration of network information system and distribution automation. From fault location point of view, the basic idea means that only the existing device and data should be used instead of developing a method that requires more accurate network modeling and special devices in the network level. This basis is of great importance from practical point of view because the method can be taken into use without remarkable investments.

The principle of distance based fault location is very simple: finding the similarity of calculated and measured fault current. The database of network information system includes the data needed for fault current analysis of the distribution network, which originally carried out as part of off-line engineering analysis. This network modeling and fault current calculation method are also part of DMS and together with real time topology information it provides the basis for fault location. The measured fault current can be obtained for microprocessor based relays, which are quite common nowadays. Even one relay with such capability is

sufficient if it is located in the incoming bay of the substation. As a result the algorithm finds one or several possible faulted line sections based on distance.

The DMS provides excellent environment for further processing, because the distance based fault location result is not explicit. The information of possible fault detectors and even the terrain and weather conditions can be taken into account. In the further processing fuzzy logic is applied. An important part of fault location is the user interface of the DMS, which provides geographic view to the network and fault location results. In addition to the fault location the DMS provides a whole concept of fault management, including for example restoration and fault reporting.

The method has been used in several utilities for many years and the experience is very good. The accuracy is very good and by using the method the mean outage time of customers has been reduced significantly. The method is now part of commercial DMS product and is so far limited to short circuit faults.

Method of Novosel et al. [7]

The method is based on the idea of fault location applied for short transmission lines [3], with all loads, including tapped lines, represented by a lumped-parameter impedance model placed behind the fault. This way of compensating for tapped loads is accurate as tapped load impedances are much larger than feeder impedance.

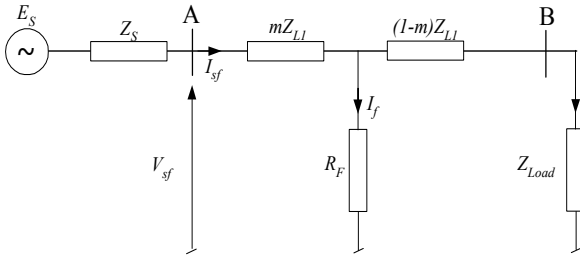


Figure 1. Equivalent scheme of the distribution feeder.

The method is based on calculating both source and load impedances based on pre-fault and fault voltages and currents measured at the substation. From Figure 1, the load impedance and the impedance behind the fault locator are:

$$Z_{load} = \frac{V_{ps}}{I_{ps}} - Z_{L1} \quad Z_s = -\frac{\Delta V_s}{\Delta I_s}$$

V_{ps} and I_{ps} are the pre-fault voltage and current measured at the substation and $\Delta V_s = V_{sf} - V_{ps}$, $\Delta I_s = I_{sf} - I_{ps}$. To avoid inaccurate calculation of source impedance for a small difference between pre-fault and fault values, a negative sequence network is used for unbalanced faults. The basic relation is obtained from the following equation for measured fault loop impedance:

$$Z_{meas} = \frac{V_{sf}}{I_{sf}} = mZ_{L1} + R_f \frac{I_f}{I_{sf}} \quad (1)$$

From this equation one can obtain the quadratic relation for distance to fault [7]:

$$m^2 - mk_1 + k_2 - k_3 R_f = 0 \quad (2)$$

$$\text{where: } k_1 = \frac{V_{sf}}{I_{sf} Z_{L1}} + \frac{Z_{Load}}{Z_{L1}} + 1$$

$$k_2 = \frac{V_{sf}}{I_{sf} Z_{L1}} \left(\frac{Z_{Load}}{Z_{L1}} + 1 \right)$$

$$k_3 = \frac{\Delta I_s}{I_{sf} Z_{L1}} \left(\frac{Z_s + Z_{Load}}{Z_{L1}} + 1 \right),$$

Complex equation (2) has two unknowns m and R_f . By separating this equation into real and imaginary parts., value of m can be obtained from after elimination of R_f using:

$$m = \frac{-b - \sqrt{b^2 - 4ac}}{2a}, \quad a = 1$$

$$b = - \left(\text{Re}(k_1) - \frac{\text{Im}(k_1) \times \text{Re}(k_3)}{\text{Im}(k_3)} \right)$$

$$c = \text{Re}(k_2) - \frac{\text{Im}(k_2) \times \text{Re}(k_3)}{\text{Im}(k_3)}$$

The fault type is considered by including the adequate voltages and currents. Unlike other methods using only local data [1, 2], this method is not affected if the fault current at a fault locator is not in phase with current at the fault. In conclusion, immunity to effects of load current and fault resistance is achieved. Compensation for tapped loads enables this method to provide accurate results, although, for heavily tapped feeders, the accuracy may degrade toward the end of the feeder.

The method was tested on an EMTP model of a typical distribution tapped network (Duke Power, 12.47 kV, three-phase, 4-wire) with approximately 200 fault cases by varying fault locations (main feeder and taps), fault resistances and fault inception angle. Sample results are shown below, where m [%] is calculated fault location:

Fault resistance\Feeder fault at	50%	90%
$R_f = 10$ ohms	$m=49.8\%$	$m=88\%$
$R_f = 50$ ohms	$m=49.2\%$	$m=82\%$

Additional means are required to distinguish if the fault is on the tap or on the feeder. Accuracy improvements to this method will be discussed in next sections.

Technique of Das et al. [8]

Reference [8] suggested a technique that uses the fundamental frequency voltages and currents measured at a line terminal before and during the fault.

The fault location technique is described by considering a single-phase-to-ground fault on a radial system, shown in Figure 2. The selected system consists of an equivalent source G , the line between nodes M and N and laterals. Loads are tapped at several nodes and conductors of different types are used on this circuit. The fault location technique consists of six steps.

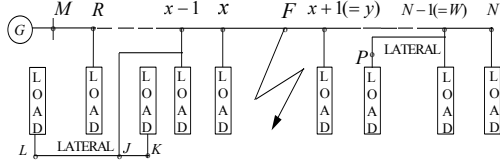


Figure 2. The single line diagram of a radial line experiencing a fault at F .

A. Apparent Faulted Section

A preliminary estimate of the location of the fault is made, say between nodes x and $x+1(=y)$. Line parameters, the type of fault and phasors of the sequence voltages and currents are used to obtain this estimate.

B. Equivalent Radial System

All laterals between node M and the apparent location of the fault are ignored and the loads on a lateral are considered to be present at the node to which the lateral is connected.

C. Load Modeling

The effects of the loads are considered by compensating for their currents. Static response type models are used for all loads up to node x and also for a consolidated load at the remote end. For a load at node, say R , this model is described by

$$Y_r = \left(G_r |V_r|^{n_p - 2} + jB_r |V_r|^{n_q - 2} \right) \quad (3)$$

where, V_r is the voltage at node R , Y_r is the load admittance, G_r and B_r are constants proportional to the conductance and susceptance respectively and n_p and n_q are the response constants for the active and reactive components of the load.

The constants G_r and B_r are estimated from the pre-fault load voltages and currents and, appropriate values of n_p and n_q . These constants and voltages are used to estimate load admittances and sequence currents during the fault.

D. Voltages and Currents at the Fault and Remote End

The sequence voltages and currents at node F during the fault are estimated by assuming that all loads beyond node x are consolidated into a single load at N , as in Figure 3.

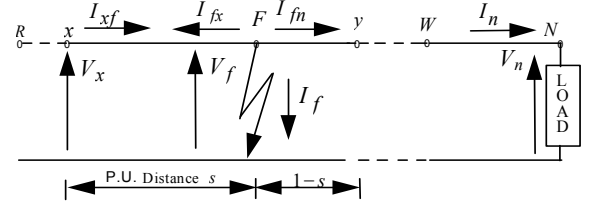


Figure 3. Fault voltages and currents at nodes F and N .

The voltages and currents at nodes F and x are related by

$$\begin{bmatrix} V_f \\ I_{fx} \end{bmatrix} = \begin{bmatrix} 1 & -sB_{xy} \\ sC_{xy} & -1 \end{bmatrix} \begin{bmatrix} V_x \\ I_{xf} \end{bmatrix} \quad (4)$$

where, s is the per unit distance to node F from node x .

The sequence voltages and currents at nodes N and F during the fault are related by the following equation

$$\begin{bmatrix} V_n \\ -I_n \end{bmatrix} = \begin{bmatrix} D_e & -B_e \\ C_e & -A_e \end{bmatrix} \begin{bmatrix} 1 & -(1-s)B_{xy} \\ -(1-s)C_{xy} & 1 \end{bmatrix} \begin{bmatrix} V_f \\ I_{fn} \end{bmatrix}, \quad (5)$$

where, A_e, B_e, C_e and D_e are the equivalent constants of the cascaded sections between nodes $x+1(=y)$ and N .

The currents at node F are related by:

$$I_{fn} = -I_{fx} - I_f. \quad (6)$$

The following equation is obtained by further substitutions from (4) and (6) and from an equation involving pre-fault voltages and currents in (5) and, neglecting the second and higher order terms in s .

$$\begin{bmatrix} V_n \\ I_f \end{bmatrix} = \frac{1}{K_v + sK_w} \begin{bmatrix} K_m + sK_n & sK_p \\ K_q + sK_r & K_v + sK_u \end{bmatrix} \begin{bmatrix} V_x \\ I_{xf} \end{bmatrix} \quad (7)$$

where, $K_m, K_n, K_p, K_q, K_r, K_u, K_v$ and K_w are complex parameters and are computed using $Y_n, B_{xy}, C_{xy}, A_e, B_e, C_e$ and D_e respectively.

The sequence voltages at nodes F and N and sequence currents at node F are obtained by using (4) and (7) and various parameters.

E. Estimating the Location of the Fault

The distance to the fault node F from node x , s , expressed as a fraction of the length from node x and node $x+1(=y)$, is estimated from the voltage-current relationships at the fault and the resistive nature of the fault impedance. For an A-phase-to-ground fault,

$$\frac{V_{af}}{I_{af}} = \frac{V_{0f} + V_{1f} + V_{2f}}{I_{0f} + I_{1f} + I_{2f}} = Z_f \quad (8)$$

where: V_{0f}, V_{1f}, V_{2f} and I_{0f}, I_{1f}, I_{2f} are zero, positive and negative sequence voltage and current phasors at fault F and, Z_f is the fault impedance.

Equating imaginary parts of both sides of (8), substituting the sequence voltages and currents at fault from (4) and (7), neglecting the second and higher order terms in s and rationalizing, the following equation is obtained.

$$\text{Im} \left(\frac{K_A + sK_B}{K_C + sK_D} \right) = 0, \quad (9)$$

where: $K_A - K_D$ are complex parameters.

The complex parameters K_A, K_B, K_C and K_D are expressed into real and imaginary parts as $K_A = K_{AR} + jK_{AI}$ and so on and, substituted in (9). Rationalizing the resulting equation, neglecting higher order terms in s and rearranging the following equation is obtained.

$$s = \frac{K_{AR}K_{CI} - K_{AI}K_{CR}}{(K_{CR}K_{BI} - K_{CI}K_{BR}) + (K_{DR}K_{AI} - K_{DI}K_{AR})} \quad (10)$$

An iterative solution of s is obtained using the pre-fault admittance of the consolidated load at node N and some of the above mentioned equations.

Two more estimates of the distance are obtained by considering that the fault is either located between node $x-1$ and node x or is located between nodes $x+1$ and $x+2$ respectively. Most plausible solution is selected and the location of the fault from the relay location, node M , is estimated.

F. Converting Multiple Estimates to Single Estimate

The fault location technique could provide multiple estimates if the line has 'laterals'. The number of estimates, for a fault, depends on the system configuration and the location of the fault. Software-based fault indicators, like those commercially available, are developed for this purpose. They detect downstream faults irrespective of their location. Information from the fault indicators is combined with multiple estimates, to arrive at a single estimate for the location of a fault.

Test Results

The fault location technique described above was tested using simulated fault data on a 37 km long 25 kV radial circuit of SaskPower. Simulations were performed using the PSCAD/EMTDC. The fault locations were estimated by the proposed technique for single-phase-to-ground faults, using fault resistances of 5.0 and 50.0 ohms. Results indicate that for a 5.0 ohm fault resistance, maximum error by the

proposed technique is less than 1.7%. For a 50 ohm fault resistance, the maximum error is less than 2.2%.

Algorithm of Saha et al. [9]

Reference [9] suggested an algorithm that uses the fundamental frequency voltages and currents measured at a line terminal before and during the fault. Current can be also measured at a supplying transformer if only one centralized type of DFR is installed at the substation. A distance to fault is estimated based on the topology principle. The proposed method is devoted for estimating the location of faults on radial MV system, which can include many intermediate load taps. In the method non-homogeneity of the feeder sections is also taken into account. A distribution utility MV networks are used as an example.

A. Algorithm for calculating the fault impedance

In the proposed method the calculation of fault-location consists of two steps. First, the fault-loop impedance is calculated by utilising the measured voltages and currents obtained before and during the fault. Second, the impedance along the feeder is calculated by assuming the faults at each successive section. By comparing the measured impedance with the calculated feeder impedance, an indication of the fault-location can be obtained.

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, as shown in Figure 4.

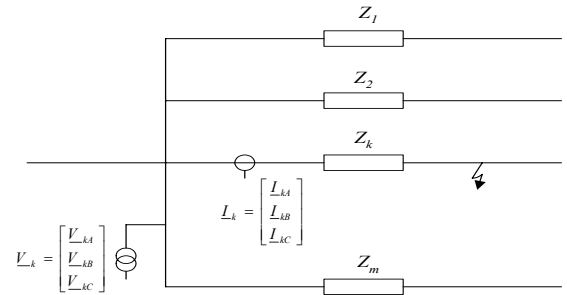


Figure 4. Diagram of the network: measurements are taken in the faulty feeder.

Measurements at the substation level

Let us consider a radial network, where a faulty feeder, as for example, k has the pre-fault equivalent impedance \underline{Z}_{Lk} . The remaining parallel connected feeders are represented by an equivalent branch with the impedance \underline{Z}_L . 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 remains unchanged during a fault. The following equation is valid for the pre-fault state:

$$\underline{Z}_{pre} = \frac{V_{pre}}{I_{pre}} = \frac{\underline{Z}_L \underline{Z}_{Lk}}{\underline{Z}_L + \underline{Z}_{Lk}} \quad (11)$$

where, V_{pre}, I_{pre} - are pre-fault voltages and currents, respectively.

Two post-fault cases are considered, namely:

Phase-phase fault-loop: The positive sequence impedance seen from the substation is obtained from the equation:

$$\underline{Z} = \frac{V_{pp}}{I_{pp}} = \frac{\underline{Z}_L \underline{Z}_k}{\underline{Z}_L + \underline{Z}_k} \quad (12)$$

where, V_{pp} - phase-phase fault-loop voltage taken at the substation,

Combining equation (11) and equation (12) yields:

$$\underline{Z}_k = \frac{\underline{Z} \underline{Z}_{pre}}{\underline{Z}_{pre} - \underline{Z}(1 - k_{zk})} \quad (13)$$

$$\text{where: } k_{zk} = \frac{\underline{Z}_{pre}}{\underline{Z}_{Lk}} = \frac{\underline{S}_{Lk}}{\underline{S}_\Sigma} \quad (14)$$

\underline{S}_{Lk} - the power in the faulty line in pre-fault condition, \underline{S}_Σ - the power in all the lines in pre-fault conditions.

Combining equation (11) and equation (14) one also obtains

$$k_{zk} = \frac{\underline{Z}_L}{\underline{Z}_L + \underline{Z}_{Lk}} \quad (15)$$

The coefficient k_{zk} for each line is estimated on the basis of the pre-fault steady-state conditions. From equation (13) one can calculate the fault-loop impedance using the measurements from the substation. Dividing numerator and denominator of equation (13) by \underline{Z}_{pre} and substituting equation (12) for \underline{Z} , equation (13) can be rewritten in a more convenient form:

$$\underline{Z}_k = \frac{V_{pp}}{I_{pp} - (1 - k_{zk}) \frac{V_{pp}}{\underline{Z}_{pre}}} \quad (16)$$

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 in a classical way. One can observe that as only a single phase-to-ground fault is considered, the zero sequence current measured in the substation contains the faulty feeder current I_{kN} and zero-sequence current flows through capacitance of the healthy feeders. 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

$$\underline{Z}_k = \frac{\underline{Z}_g \underline{Z}_{pre}}{\underline{Z}_{pre} - \underline{Z}_g (1 - k_{zk}) (1 - \frac{V_0}{V_{ph}})} \quad (17)$$

$$\text{where: } \underline{Z}_g = \frac{V_{ph}}{I_{ph} + k_{kN} I_{kN}} \quad (18)$$

$$V_0 = (V_A + V_B + V_C)/3.$$

The above equations define fault-loop impedance for phase-to-ground fault in terms of positive-sequence impedance.

B. Estimation of distance to fault

Based on the measured fault-loop impedance and the cable parameters it is possible to estimate the distance to a fault. The algorithm for phase-to-phase fault is discussed below in details.

Algorithm for phase-to-phase fault

Let us consider the equivalent positive-sequence scheme of the fault-loop. 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 i th node to the fault point one obtains the following recursive form (Figure 5).

$$\underline{Z}_{fi} = \frac{\underline{Z}_{pi} (\underline{Z}_{fi-1} - \underline{Z}_{si-1})}{\underline{Z}_{pi} - \underline{Z}_{fi-1} + \underline{Z}_{si-1}} = R_{fi} + X_{fi} \quad (19)$$

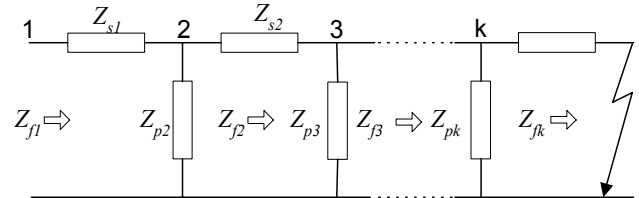


Figure 5. Equivalent positive-sequence diagram of the faulty cable.

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. Value of this impedance is estimated from the steady-state condition of the network. One can see that impedance obtained in the following steps tends toward zero

$$|\underline{Z}_{fi-1}| > |\underline{Z}_{fi}| \quad (20)$$

and the impedance of the faulty section is

$$\underline{Z}_{fk} = I_{fk-1} \underline{Z}_{sk-1} + R_f \quad (21)$$

where: l_{fk} - p.u. distance from node k to the fault point (total length of the faulty segment is assumed to be 1), Z_{sk-1} - impedance of the cable segment between nodes $k-1$ and k ($Z_{sk-1} = R_{sk-1} + jX_{sk-1}$), R_f - fault resistance.

C. EMTP/ATP simulations and staged fault tests

A 10 kV substation is supplied from 150 kV system. The network contains of rings and sub-rings, containing several 10/0.4 kV transformer-houses. Example of the analysed network is presented in Figure 6.

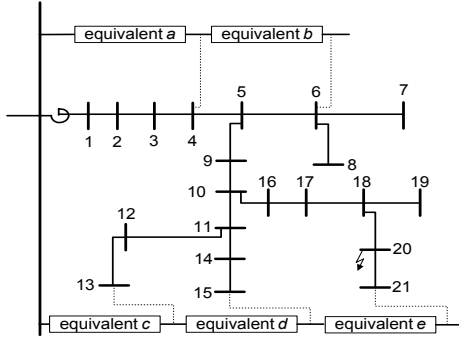


Figure 6. Idea of the feeder model representation; dotted lines are for grounding system connection.

For verification of the proposed algorithm, a series of field tests have been made in the considered network. The DFRs were installed at the substation and in the faulty feeder. For example, a double phase fault was initiated during field tests at node 20 (Figure 6). The estimated distance to fault was obtained at a distance 227 m from node 18 (for measurement in the feeder) and 64 m from node 18 (for measurement at the substation). From the EMTP/ATP simulation the estimated distance to fault for same fault was obtained at a distance 266 m from node 18. The actual fault position is 308 m from node 18.

Conclusions

Some experiences with fault location in distribution networks have been discussed. Proposed methods vary, depending on available measurements and network information, as well as different types of networks and applications. The fault location problem can be divided into several sub-problems related to both network type and fault type. From the solution point of view the two approaches can be separated: local/device solution and system solution. The former may also be 'system solution' in SA (Substation Automation) level, but the term 'local' means that there is no need for topology and advanced network modeling, which are the key factors in system solution.

As shown in this paper, by having more data and a better network model, more accurate fault locating is possible. For example, the more elaborate methods in sections IV and V

(requiring more information about the network) will be more accurate than the method in section III. In conclusion, users have a choice to select methods that best suit their needs and infrastructure.

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