

AN ACCURATE FAULT LOCATION USING SYNCHRONIZED
SAMPLING AT TWO ENDS OF A TRANSMISSION LINE

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Abstract— This paper presents a new approach in solving the problem of fault location on a transmission line in time domain. It uses synchronized samples of transient, post-fault voltages and currents taken at all ends of the transmission line. Starting from a theoretical formulation of a general concept, an exact fault location algorithm for a short, two-terminal transmission line is derived. A thorough evaluation of the algorithm performances is done, through a number of EMTP generated fault test cases. The test results show the high accuracy of the proposed method while the computational burden is moderate. The developed algorithm is robust, i.e., it is not affected by the fault type, fault resistance, nor incidence angle.

Keywords: Surges and Fault Location, Electromagnetic Transients, Synchronized Sampling

INTRODUCTION

A continuous and reliable electrical energy supply is the objective of any power system. Nevertheless, faults do inevitably occur in the power system. A transmission line is a part of the power system where the faults are most likely to happen. An accurate and fast location of the fault is a need for the efficient and cost effective repair of the mechanical damage, usually associated with the fault occurrence. Enabling the fast and effective recovery of the faulted transmission line, the fault location algorithms contribute to the economic operation of the overall power system.

The nature of the fault location on the transmission line requires voltages and currents of all line ends to be considered. Still, such approach has not been fully explored until few years ago. There are many reasons for that. The fault location algorithms were implemented as a part of existing protection devices, where only the single end voltages and currents are available. To use all ends data, synchronized information from line ends have to be communicated to one location, shortly after the fault occurrence. It is just recently that the particular hardware to support this need (GPS, optical communication links, etc.) has become readily available for a low cost [1,2].

There are not many fault location algorithms developed using all line ends information. One of the first algorithms to consider both ends data of the two-terminal transmission line, was proposed by Eriksson et. al [3]. It did not use both ends data explicitly, but the influence of the remote-end in-feed was taken into account. Even though the error obtained by this algorithm was large (3%), this result is important since the algorithm was implemented as the actual fault locator, and tested using the field data.

Fault location algorithms using all/both ends line infor-

mation have one characteristic in common. They use post-fault steady state values to calculate the fault location. Some of them filter the post-fault data (voltages and currents) to extract the fundamental frequency components of the signals [3-7]. The others use various numerical methods to estimate the post-fault steady-state values of voltages and currents [8,9]. Since the post-fault steady state values are not readily available, a processing of transient data is needed to obtain these values. This preprocessing introduces an error in determining the post-fault steady state values. Also, it influences the execution time of the algorithms. In contrast, the algorithm presented here uses recorded, transient data directly utilizing the time domain approach.

Most of the algorithms have some constraints on the transmission line configuration. The algorithms given in [3-6] assume the transposed transmission lines. The earlier developed ones [4,5] are sensitive to the fault location and fault type, while the recent ones [8,9] are not. Overall, the obtained error is in the range from 4% [5] to 0.05% [9] at the best.

In this paper, a new approach to the fault location using the synchronized data from both ends of transmission line is proposed. The synchronized phase voltages and currents, taken during the transient, post-fault state of the faulted line, are used to determine the location of the fault. This approach does not involve preprocessing of sampled data. No assumptions on the geometry of the line (transposed, or untransposed) are needed. The method is not influenced by type of the fault, fault resistance, nor changes in the incidence angle. Its accuracy depends strongly on the accuracy of line model. Also, it depends on the numerical method used for solving the system of fault location equations which is closely related to the data sampling rate.

Here, the new approach will be applied to an electrically short transmission line. First, the general concept of the fault location technique will be given. Secondly, the fault location equation and the algorithm for short transmission line will be derived. At the end, its performance evaluation will be presented.

FAULT LOCATION TECHNIQUE

General Concept

In this section, the principles of the technique using the synchronized phase voltage and current samples at both ends of the transmission line to calculate the location of the fault on any line are described.

Consider the arbitrary, faultless three-phase system depicted in Figure 1.

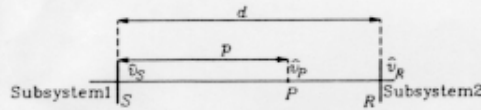


Fig. 1. Unfaulted Three-Phase System

Two ends of the transmission line of interest are denoted with S as the sending end and R as the receiving end. The transmission line of interest connects two parts of the system denoted with *Subsystem1* and *Subsystem2*. The length of the transmission line is d . The main idea of the fault location concept is based on the following characteristic of any transmission line. At any location P along a homogeneous, unfaulted transmission line, the instantaneous values of voltage and current signals are related to:

- instantaneous values of the corresponding voltage and current signals of both ends of the line;
- distance between that particular location and each of the line ends;
- line parameters;

Above stated relations can be expressed as:

$$\tilde{v}_P = L^* \{ \tilde{v}_S, \tilde{i}_S, x \} \quad (1)$$

$$\tilde{i}_P = L^i \{ \tilde{v}_S, \tilde{i}_S, x \} \quad (2)$$

where \tilde{v}_P and \tilde{i}_P are vectors of the instantaneous phase voltages ($v_{aP}(t), v_{bP}(t), v_{cP}(t)$) and currents ($i_{aP}(t), i_{bP}(t), i_{cP}(t)$) at the point P , at the distance p from the line end S , defined as:

$$\tilde{v}_P^t = [v_{aP}(t), v_{bP}(t), v_{cP}(t)] \quad (3)$$

$$\tilde{i}_P^t = [i_{aP}(t), i_{bP}(t), i_{cP}(t)] \quad (4)$$

while \tilde{v}_S^t and \tilde{i}_S^t are vectors of the instantaneous phase voltages and currents at the end S of the line, defined as:

$$\tilde{v}_S^t = [v_{aS}(t), v_{bS}(t), v_{cS}(t)] \quad (5)$$

$$\tilde{i}_S^t = [i_{aS}(t), i_{bS}(t), i_{cS}(t)] \quad (6)$$

Similarly,

$$\tilde{v}_P = L^* \{ \tilde{v}_R, \tilde{i}_R, d - x \} \quad (7)$$

$$\tilde{i}_P = L^i \{ \tilde{v}_R, \tilde{i}_R, d - x \} \quad (8)$$

where \tilde{v}_R^t and \tilde{i}_R^t are vectors of the instantaneous phase voltages and currents at the end R of the line, defined as

$$\tilde{v}_R^t = [v_{aR}(t), v_{bR}(t), v_{cR}(t)] \quad (9)$$

$$\tilde{i}_R^t = [i_{aR}(t), i_{bR}(t), i_{cR}(t)] \quad (10)$$

L^* and L^i are linear operators in respect to the vector of voltages \tilde{v} and vector of currents \tilde{i} . Still, these operators do not necessarily have to be linear in respect to the distance x . Operators L^* and L^i are related to the line parameters. However, these relations are the function of the line length.

Now, consider the faulted three-phase system depicted in Figure 2. The fault point is denoted with F , and it is at the distance x from the line end S .

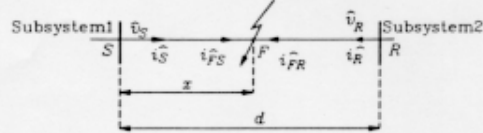


Fig. 2. Faulted Three-Phase System

Due to the fault occurrence at the point F , the transmission line is divided into two homogeneous parts, one being from the end S to the fault point F , and the other one from the end R to F . Now, the fault point F of the faulted transmission line is the only point on the line at which the voltages and currents can be expressed in terms of voltages and currents at both ends of the line. Voltages and currents of any point on the line between end S and F can be expressed in terms of the end S voltages and currents, only. Similarly, voltages and currents of any point on the line between end R and F can be expressed in terms of the end R voltages and currents, only. The fault point F phase voltages and currents are related to the line end S phase voltages and currents given by equations (1) and (2) as:

$$\tilde{v}_{FS} = L^* \{ \tilde{v}_S, \tilde{i}_S, x \} \quad (11)$$

$$\tilde{i}_{FS} = L^i \{ \tilde{v}_S, \tilde{i}_S, x \} \quad (12)$$

Similarly, the phase voltages and currents at the fault point F are related to the line end R phase voltages and currents given by equations (7) and (8) as:

$$\tilde{v}_{FR} = L^* \{ \tilde{v}_R, \tilde{i}_R, d - x \} \quad (13)$$

$$\tilde{i}_{FR} = L^i \{ \tilde{v}_R, \tilde{i}_R, d - x \} \quad (14)$$

where \tilde{v}_R^t and \tilde{i}_R^t are vectors of the instantaneous phase voltages and currents at the end R of the line. Here, $d - x$ is the distance between the fault point F and line end R .

Because of the continuity of the voltage along the transmission line, the equations (11) and (13) can be combined leading to:

$$\tilde{v}_{FS} = \tilde{v}_{FR} \\ L^* \{ \tilde{v}_S, \tilde{i}_S, x \} = L^* \{ \tilde{v}_R, \tilde{i}_R, d - x \} \quad (15)$$

Linearity of operators L^* , L^i enables expression (15) to be rewritten as:

$$\tilde{L}^v \{ \tilde{v}_R - \tilde{v}_S, \tilde{i}_R - \tilde{i}_S, x, d \} = 0 \quad (16)$$

where \tilde{L}^v is a new operator of the same type as L^v is.

The equation (16) is the *generic fault location equation*. It relates the unknown distance x to the fault point F (from the line end S) and to the phase voltages and currents at both transmission line ends. For different types of transmission lines, this generic equation have different forms. Next, the derivation of the fault location equation for the short transmission line will be given.

Derivation of the Fault Location Equation for the Short Transmission line

This section gives detailed derivation of the fault location equation for the short line using the generic equation (16). Now, consider the short three-phase transmission line depicted in Figure 3.

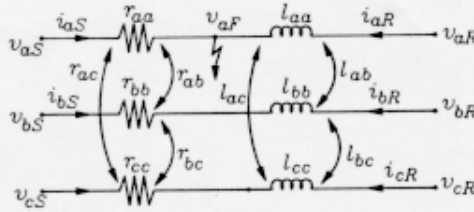


Fig. 3. Faulted Short Three-Phase Line

For the purpose of the simplicity, let us assume that the line is homogeneous in its whole length, characterized with constant, per-length parameters:

- self (phase) resistivity: r_{aa}, r_{bb}, r_{cc} ,
- mutual resistivity: r_{ab}, r_{ac}, r_{bc} ,
- self (phase) inductivity: l_{aa}, l_{bb}, l_{cc} ,
- mutual inductivity: l_{ab}, l_{ac}, l_{bc} .

In spite of the assumption made, the general concept holds for any transmission line being a combination of homogeneous parts. Also, no other assumptions about the transmission line are needed.

In case of short transmission line, relation between the fault point F and the line end S phase voltages and currents [eq. (11)] has the following form:

$$v_{mF}(t) = v_{mS}(t) - x \sum_{p=a,b,c} \left[r_{mp} i_{pS}(t) + l_{mp} \frac{di_{pS}(t)}{dt} \right] \quad (17)$$

$m = a, b, c$

Similarly, relation between the fault point F and the line end R phase voltages and currents [(eq. (13))] becomes:

$$v_{mF}(t) = v_{mR}(t) - (d-x) \sum_{p=a,b,c} \left[r_{mp} i_{pR}(t) + l_{mp} \frac{di_{pR}(t)}{dt} \right] \quad (18)$$

$m = a, b, c$

Now, combining the equations (17) and (18) the fault location equation for the short transmission line is obtained as follows:

$$v_{mR}(t) - v_{mS}(t) - d \sum_{p=a,b,c} \left[r_{mp} i_{pR}(t) + l_{mp} \frac{di_{pR}(t)}{dt} \right] + x \sum_{p=a,b,c} \left[r_{mp} i_{pR}(t) + r_{mp} i_{pS}(t) + l_{mp} \frac{di_{pR}(t)}{dt} + l_{mp} \frac{di_{pS}(t)}{dt} \right] = 0 \quad (19)$$

$m = a, b, c$

Since the signals of the voltage and current, at both ends of the line, are available in the sampled form, system of fault location equations (19) can be rewritten in the *discrete* form as:

$$A_m(k) + B_m(k)x = 0 \quad (20)$$

$m = a, b, c$
 $k = 1, \dots, N$

where $A_m(k)$ and $B_m(k)$, for $m = a, b, c$, and $k = 1, \dots, N$, are defined as:

$$A_m(k) = v_{mR}(k) - v_{mS}(k) - d \sum_{p=a,b,c} \left[\left(r_{mp} + \frac{l_{mp}}{\Delta t} \right) i_{pR}(k) - \frac{l_{mp}}{\Delta t} i_{pR}(k-1) \right] \quad (21)$$

$$B_m(k) = \sum_{p=a,b,c} \left\{ \left(r_{mp} + \frac{l_{mp}}{\Delta t} \right) [i_{pR}(k) + i_{pS}(k)] - \frac{l_{mp}}{\Delta t} [i_{pR}(k-1) + i_{pS}(k-1)] \right\} \quad (22)$$

In above equations, $v_{mS}(k)$, $v_{mR}(k)$ are phase ($m = a, b, c$) voltage samples at the time instants $t = k\Delta t$ ($k = 1, \dots, N$) at the line end S , and at the line end R , respectively. Similarly, $i_{mS}(k)$, $i_{mR}(k)$ are phase current samples at the line end S , and at the line end R . Here, Δt is the sampling step and N is the total number of samples.

The system of equations given in expression (20) is over-specified since it has just one unknown variable, distance to the fault point x . Thus, x is determined using the *least square estimate* for all three phases together:

$$x = \frac{-\sum_{m=a,b,c} \sum_{k=1}^N A_m(k) B_m(k)}{\sum_{m=a,b,c} \sum_{k=1}^N B_m^2(k)} \quad (23)$$

The expression (23) is the explicit fault location equation that defines the fault location algorithm for the short three-phase transmission line.

PERFORMANCE EVALUATION

Description of the Performed Tests

Based on the derived fault location equation for the short transmission line [eq. (23)], the fault location algorithm was developed. The performances of the algorithm were evaluated using the EMTP generated data. The test system, modeled

using the EMTP, is an actual, 161kV power system. The transmission lines considered are fully transposed, and 13.35 and 30.56 miles long. The EMTP model of the test system as well as the system parameters are given in the Appendix. The transmission lines of interest are one between busses 2 and 3 (13.35 mi) and the other between busses 1 and 2 (30.56 mi).

A number of EMTP simulations of various fault events were performed for testing of the proposed algorithm. The total time of the simulation was $T_{tot} = 0.032s$, starting from the instant of the fault occurrence. Since the available window of samples is limited, the largest number of samples is obtained using high sampling frequency. Besides, the high sampling frequency enables as close as possible approximation of derivatives from the equation (23). Therefore, the value of the sampling time step used is $\Delta t = 41.667\mu s$.

These test cases were generated by varying four, most important parameters of the fault event:

- fault location
- type of the fault
- fault resistance
- incidence angle of the fault occurrence

Each of these simulation parameters were varied in the range of their lower and upper physically meaningful boundaries to enable the extensive coverage of possible real fault events. Three values for the fault location were considered: 0.1, 0.5, 0.8, where the location 1.0 corresponds to the whole length of the transmission line. Four typical fault types were simulated: single line to ground (phase a to ground), two phase (phase b to phase c), two phase to ground (phase b to phase c to ground), and three phase to ground fault. For the fault resistance, values of $R_f = 3\Omega$ and $R_f = 50\Omega$ were considered, while for the incidence angle, values of 0 and 90 degrees were used.

The results of the algorithm testing are presented and discussed in the following section.

Test Results

For the variety of the fault cases, described in the above section, the error of the fault location algorithm was observed. The results of the test are given in the following six tables. For the particular line, they are organized by the type of the fault: first four tables correspond to the 13.35 miles long line while the other two correspond to the 30.56 miles long line. The error (%) of the fault location algorithm is defined as:

$$\text{error} = \frac{|\text{actual fault loc.} - \text{calculated fault loc.}|}{\text{total line length}} \cdot 100\% \quad (24)$$

Comparing the two rows of each table, it can be seen that the variation in the error is very small. Thus, the algorithm is not affected by the value of the fault resistance R_f . Also, the variation of the incidence angle is of no influence on the error. Comparing the corresponding entries of different tables, the small variation in the error is noticed, due to the different fault types. Considering different line lengths, not a significant variation of the error is found. The highest variation of the error is due to the location of the fault. This result is the consequence of the particular configuration of the system used in the study. Still, it should be noted that in case of small error, the relative variation of the error seems to be more significant than in case of large error. Nevertheless, for the wide range of cases, obtained error is in the order of 0.1%, being smaller than 0.5% in most of the cases. The numerical method used for solving the

fault location equations influences the error significantly. The sampling time step Δt has the major impact on the error. A small Δt provides more accurate derivative approximation and decreases the error, but it increases the computational burden.

Results obtained in this study are of the same order as the best ones obtained using the steady state post-fault data [9]. However, the algorithm presented here does not require preprocessing of the input data but uses the transient data as recorded. This makes the algorithm computationally simple. These properties are considered unique performance features of this algorithm.

Table I. Error in % for Phase a to Ground Fault, 13.35 mi line

Simulation Parameter	Phase A to Ground Fault					
	0.1		0.5		0.8	
Location of the Fault						
Incidence Angle	0 deg.	90 deg.	0 deg.	90 deg.	0 deg.	90 deg.
$R_f = 3\Omega$	0.4344	0.4346	0.2091	0.2093	0.0388	0.8390
$R_f = 50\Omega$	0.4576	0.4549	0.2237	0.2229	0.0464	0.0472

Table II. Error in % for Three Phase to Ground Fault, 13.35 mi line

Simulation Parameter	Three Phase to Ground Fault					
	0.1		0.5		0.8	
Location of the Fault						
Incidence Angle	0 deg.	90 deg.	0 deg.	90 deg.	0 deg.	90 deg.
$R_f = 3\Omega$	0.7084	0.7084	0.3658	0.3658	0.1066	0.1066
$R_f = 50\Omega$	0.7084	0.6991	0.3658	0.3612	0.1066	0.1052

Table III. Error in % for Phase B to Phase C Fault, 13.35 mi line

Simulation Parameter	Phase B to Phase C Fault					
	0.1		0.5		0.8	
Location of the Fault						
Incidence Angle	0 deg.	90 deg.	0 deg.	90 deg.	0 deg.	90 deg.
$R_f = 3\Omega$	0.7075	0.7166	0.3658	0.3707	0.01075	0.1091
$R_f = 50\Omega$	0.7428	0.7283	0.3915	0.3855	0.1241	0.1262

Table IV. Error in % for Phase B to Phase C to Ground Fault, 13.35 mi line

Simulation Parameter	Phase B to Phase C to Ground Fault					
	0.1		0.5		0.8	
Location of the Fault						
Incidence Angle	0 deg.	90 deg.	0 deg.	90 deg.	0 deg.	90 deg.
$R_f = 3\Omega$	0.5938	0.5912	0.3159	0.3143	0.0900	0.0885
$R_f = 50\Omega$	0.7036	0.7067	0.3635	0.3654	0.1060	0.1066

Table VI. Error in % for Three Phase to Ground Fault, 30.56 mi line

Simulation Parameter	Phase B to Phase C to Ground Fault					
	0.1		0.5		0.8	
Location of the Fault	0 deg.	90 deg.	0 deg.	90 deg.	0 deg.	90 deg.
$R_f = 3\Omega$	0.5238	0.5412	0.4559	0.4143	0.4800	0.4885
$R_f = 50\Omega$	0.6036	0.6167	0.4335	0.4054	0.4997	0.4966

Table V. Error in % for Phase A to Ground Fault, 30.56 mi line

Simulation Parameter	Phase B to Phase C to Ground Fault					
	0.1		0.5		0.8	
Location of the Fault	0 deg.	90 deg.	0 deg.	90 deg.	0 deg.	90 deg.
$R_f = 3\Omega$	0.3842	0.3887	0.3059	0.3043	0.0988	0.9885
$R_f = 50\Omega$	0.3698	0.3723	0.3615	0.3655	0.1068	0.1066

CONCLUSION

This paper presents a new approach in solving the problem of fault location on the transmission line. This approach uses synchronized samples of faulted voltages and currents at both ends of the transmission line. Starting from the theoretical formulation of the general approach, the exact fault location equation for the short transmission line was derived. This simple equation relates the samples of the phase voltages and currents during the transient, post-fault period, and the distance to the fault x .

The algorithm developed based on this equation does not require any approximation, filtering of sampled signals, or estimation of the post-fault steady state values. Besides, the fault location equation is defined for each phase in the time domain. Therefore, no processing of the sampled data for the transformations such as phase to sequence, or time to phasor domain, is performed. Such approach contributes to the computational simplicity and execution speed of the algorithm. Also, it offers the possibility of algorithm's usage in the on-line protective devices.

Evaluation of the algorithm, obtained through the number of EMTP generated tests, has shown that the obtained error is less than 0.5% in most of the cases. This error depends on the choice of Δt and numerical method used. The value of Δt used in this study does not match available data acquisition equipment. Therefore, further studies are planned to find the value for Δt that would meet the practical requirements for the on-line implementation of the algorithm. The algorithm has shown a robustness, since it is not significantly affected by the type of the fault, nor fault resistance. The changes in the incidence angle have not been the source of the error, neither.

It should be noted that no pre-fault steady state values of the system variables, nor the fault classification are required by

the algorithm. The only assumption imposed by the algorithm is the transmission line homogeneity, on its whole length or on its parts.

The thorough testing of the algorithm has revealed its additional useful characteristics. There are indications that the algorithm can be used for the fault identification and fault classification, besides its main function. This is the subject of our future work, as well as the development of the algorithm for the long transmission line, based on the same, general approach.

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APPENDIX

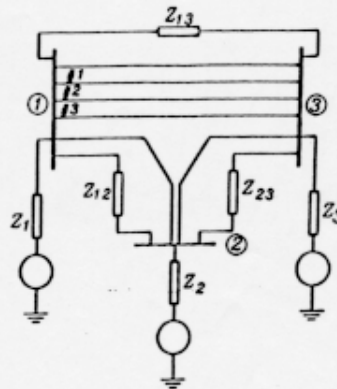


Fig. A-1. EMTP Model of the System

Table A-I. Source Impedances

Bus Name	Per-Unit Value (Ω)	Real Value (Ω)	
1	Z_0	$0.58 + j 6.32$	$1.503 + j 16.382$
	Z_1	$0.58 + j 11.41$	$1.503 + j 29576$
2	Z_0	$0.07 + j 1.07$	$0.181 + j 2.774$
	Z_1	$0.04 + j 0.73$	$1.1044 + j 1.892$
3	Z_0	$0.75 + j 407$	$1.944 + j 10.550$
	Z_1	$0.31 + j 3.04$	$0.804 + j 7.880$

Table A-II. System Equivalents

Terminal Buses	Per-Unit Value (Ω)	Real Value (Ω)	
1-3	Z_0	$119.69 + j 188.93$	$310.248 + j 489.725$
	Z_1	$1.80 + j 11.44$	$4.666 + j 29.654$
2-3	Z_0	∞	∞
	Z_1	$12.58 + j 74.00$	$32.609 + j 191.815$
1-2	Z_0	$39.79 + j 100.63$	$103.140 + j 260.843$
	Z_1	$2.75 + j 18.32$	$7.128 + j 47.487$

Table A-III. Self Impedances of Transmission Lines

Terminal Buses		Per-Unit Value (Ω)	Real Value (Ω)
1-3	Z_0	$8.94 + j 28.34$	$23.1734 + j 73.4601$
	Z_1	$1.52 + j 9.06$	$3.9400 + j 23.4844$
1-3	Z_0	$8.52 + j 29.23$	$22.0847 + j 75.7671$
	Z_1	$1.38 + j 8.80$	$3.5771 + j 22.8105$
1-3	Z_0	$8.40 + j 29.37$	$21.7736 + j 76.1300$
	Z_1	$1.34 + j 8.73$	$3.4734 + j 22.6290$
1-2	Z_0	$8.42 + j 26.74$	$21.8255 + j 69.3128$
	Z_1	$1.50 + j 8.47$	$3.8882 + j 21.9551$
2-3	Z_0	$3.67 + j 12.38$	$9.5130 + j 32.0902$
	Z_1	$0.67 + j 3.92$	$1.7367 + j 10.1610$

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