Synchronized Sampling Improves Fault Location

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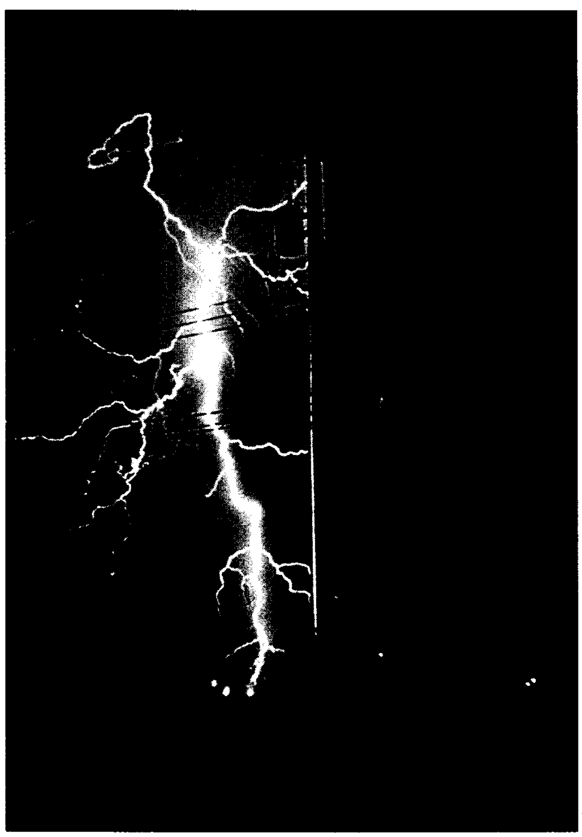
Transmission line faults must be located accurately to allow maintenance crews to arrive at the scene and repair the faulted section as soon as possible. Rugged terrain and geographical layout cause some sections of power transmission lines to be difficult to reach. Therefore, robustness of the accurate fault location determination under a variety of power system operating constraints and fault conditions is an important requirement.

This unique concept of high-speed fault location can be implemented either as a simple add-on to DFRs or as a new stand-alone relaying function

In the past, a variety of fault location algorithms were introduced as either an add-on feature in protective relays or stand-alone implementation in fault locators. In both cases, the measurements of current and voltages were taken at one terminal of a transmission line only. Under such conditions, it may become difficult to determine the fault location accurately, since data from other transmission line ends are required for more precise computations. In the absence of data from the other end, existing algorithms have accuracy problems under several circumstances, such as varying switching and loading conditions, fault infeed from the other end, and random value of fault resistance. In addition, most of the one-end algorithms were based on estimation of voltage and current phasors. The need to estimate phasors introduces additional difficulty in high-speed tripping situations where the algorithms may not be fast enough in determining fault location accurately before the current signals disappear due to the relay operation and breaker opening. The following is a summary of different fault location implementation approaches to various design properties:

- Data acquisition location: one-end, two (all) ends
- Equipment used for implementation of the fault location algorithm: digital relays, digital fault recorders, RTU of SCADA, fault locators
- Data sampling frequency: low (≤ 1 *kHz*), high (≥ 5 *kHz*)
- Techniques for synchronization at two (all) ends: GPS receiver, rotation of samples for phasors
- Signal processing requirements: direct use of samples, computation of phasors.



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Most recently, several new algorithms for fault location were introduced to provide more accurate computations. This article introduces a unique concept of high-speed fault location that can be implemented either as a simple add-on to the digital fault recorders (DFRs) or as a stand-alone new relaying function. This advanced concept is based on the use of voltage and current samples that are synchronously taken at both ends of a transmission line. This sampling technique can be made readily available in some new DFR designs incorporating receivers for accurate sampling clock synchronization using the satellite Global Positioning System (GPS).

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The new fault location algorithm provides major improvements over the existing ones regarding several critical application criteria:

- Offers increased accuracy under a variety of operating and fault conditions
- Very robust, since it is virtually transparent to any changing power system conditions outside of the transmission line of interest
- Not affected by the fault resistance and can even provide accurate fault location determination for a time varying fault impedance
- Can easily be applied to the three terminal as well as parallel lines with strong mutual coupling.

The algorithm uses a very short data window and enables fast fault detection and classification. This makes the algorithm a good candidate for future considerations for applications in protective relaying as well.

Fault Location Based on Synchronized Sampling

To simplify introduction of the new concept, a two-terminal transmission line is considered using a lumped parameter model where the line conductance and capacitance are neglected. The one line representation of the three-phase system is used. The fault location set-up is shown in Figure 1, where "S" and "R" are the sending and receiving ends, CT is the current transformer, CCVT is the capacitor coupling voltage transformer, CB is the circuit breaker, DFR is the digital fault recorder, F is the location of the fault, d is the transmission line length, and x is the distance to the fault.

For the transmission line given in Figure 1, the following two vectors can be defined, where $V_S(t)$ and $V_R(t)$ are the vectors of phase voltage samples; $I_S(t)$, $I_R(t)$, and $I_F(t)$ are the vectors of phase current samples; *"S"* and *"R"* are the transmission line ends; and R and L are the matrices of self and mutual line parameters:

$$\Delta I(t) = I_S(t) + I_R(t) \quad [1]$$

$$\Delta V(t) = V_S(t) - V_R(t) + d\left[RI_R(t) + L\frac{dI_R(t)}{dt}\right] \quad [2]$$

In normal operating conditions, the fault current $I_F(t)$ is zero. As a consequence of Kirchoff's current and voltage laws, the above vectors are equal to zero.

$$\Delta I(t) = 0 \quad [3]$$

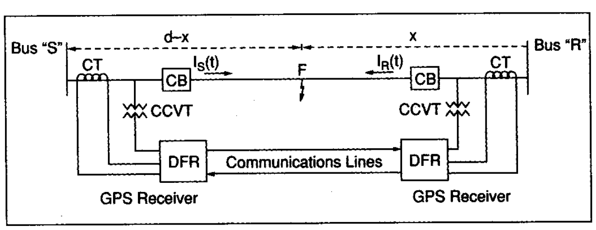

Figure 1. Fault location system

$$\Delta V(t) = 0 \quad [4]$$

If the line is faulted, the values of these vectors are:

$$\Delta I(t) = I_F(t) \quad [5]$$

$$\Delta V(t) = x\left[RI_F(t) + L\frac{dI_F(t)}{dt}\right] \quad [6]$$

where $I_F(t)$ is the phase vector of samples of fault current. The fault current does not have to be measured since it may be eliminated from equations 5 and 6 leading to:

$$\Delta V(t) - x\left[R\Delta I(t) + L\frac{d}{dt}\Delta I(t)\right] = 0 \quad [7]$$

Equation 7 can be used directly to find the fault location x.

The values of the vectors $\Delta V(t)$ and $\Delta I(t)$ at times n/f_s, where f_s is the sampling frequency, can be calculated from current and voltage samples:

$$\Delta I_n = I_{Sn} + I_{Rn} \quad [8]$$

$$\Delta V_n = V_{Sn} - V_{Rn} + d\left[RI_{Rn} + f_s L(I_{Rn} - I_{Rn-1})\right] \quad [9]$$

Here, V_{Sn}, V_{Rn}, I_{Sn}, and I_{Rn} denote vectors of samples taken synchronously at moments n/f_s. It should be noted that the expression for ΔV_n is an approximate one, since the current derivative can not be measured. The derivative is approximated with "backward" approximation.

Derivation of the fault location equation given in this section is based on the short-line model. Further details of the fault location for short lines are discussed next.

Short-Line Application

The short transmission line model is presented in Figure 2.

It is assumed that the line is homogeneous on its whole length, and that it has constant per-length parameters (Figure 2):

- Self (phase) resistance: r_{aa}, r_{bb}, r_{cc}
- Mutual resistance: r_{ab}, r_{ac}, r_{bc}
- Self (phase) inductance: l_{aa}, l_{bb}, l_{cc}
- Mutual inductance: l_{ab}, l_{ac}, l_{bc}.

No other assumptions about the transmission line are needed.

In the case of such a transmission line, the generic fault location equation becomes a system of three equations:

$$v_{mS}(t) - v_{mR}(t) - d\sum_{p=a,b,c}\left[r_{mp}i_{pS}(t) + l_{mp}\frac{di_{pS}(t)}{dt}\right]$$
$$+x\sum_{p=a,b,c}\left[r_{mp}i_{pR}(t) + r_{mp}i_{pS}(t) + l_{mp}\frac{di_{pR}(t)}{dt} + L_{mp}\frac{di_{pS}(t)}{dt}\right] = 0$$
$$m = a,b,c \quad [10]$$

Since the phase voltage and the current at both ends of the line are available in the sampled form, the system of fault location in equation 10 can be rewritten in the discrete form as:

$$A_m(k) + B_m(k)x = 0$$
$$m = a, b, c$$
$$k = 1, 2, \ldots, N \quad [11]$$

where $A_m(k)$ and $B_m(k)$ for $m = a, b, c$, and $k = 1, 2, \ldots, N$ are defined as:

$$A_m(k) = v_{mS}(k) - v_{mR}(k) - d\sum_{p=a,b,c}\left[\left(r_{mp} + \frac{l_{mp}}{\Delta t}\right)i_{pS}(k) - \frac{l_{mp}}{\Delta t}i_{pS}(k-1)\right] \quad [12]$$

$$B_m(k) = \sum_{p=a,b,c}\left\{\left(r_{mp} + \frac{l_{mp}}{\Delta t}\right)\left[i_{pR}(k) + i_{pS}(k)\right] - \frac{l_{mp}}{\Delta t}\left[i_{pR}(k-1) + i_{pS}(k-1)\right]\right\} \quad [13]$$

In the equations 12 and 13, $v_{mS}(k)$ and $v_{mR}(k)$ are phase ($m = a, b, c$) voltage samples taken at the time instant $t = \Delta t$ ($k = 1, 2, \ldots, N$), at the line ends "S" and "R," respectively. Similarly, $i_{mS}(k)$ and $i_{mR}(k)$ are phase current samples taken at the time $t = k\Delta t$, at the line ends "S" and "R." The sampling step is Δt, and N is the total number of samples considered.

The system of fault location equations given by the expression 11 is over specified, since it has just one unknown variable, distance x to the fault point. Therefore, the unknown distance x is determined using the *least square estimate* for all three phases of the line together:

$$x = -\frac{\sum_{m=a,b,c}\sum_{k=1}^{N} A_m(k)B_m(k)}{\sum_{m=a,b,c}\sum_{k=1}^{N} B_m^2(k)} \quad [14]$$

Expression 14 is the fault location equation that defines the fault location algorithm for the short three-phase transmission line.

Long-Line Application

To simplify the presentation, only a lossless, single-phase, long transmission line is considered, as described by the following equations:

$$\frac{\partial v(x,t)}{\partial x} = -l\frac{\partial i(x,t)}{\partial t}$$
$$\frac{\partial i(x,t)}{\partial x} = -c\frac{\partial v(x,t)}{\partial t} \quad [15]$$

Using the traveling wave approach, Bergeron's solution of equation 15 is:

$$v_R(t) = \frac{z}{2}\left[i_S(t-\tau) - i_S(t+\tau)\right] + \frac{1}{2}\left[v_S(t-\tau) + v_S(t+\tau)\right]$$
$$i_R(t) = -\frac{1}{2}\left[i_S(t-\tau) + i_S(t+\tau)\right] - \frac{1}{2z}\left[v_S(t-\tau) - v_S(t+\tau)\right] \quad [16]$$

where $v_R(t)$ and $i_R(t)$ correspond to the "R" end of the line, and $v_S(t)$ and $i_S(t)$ correspond to the "S" end of the line. The surge impedance of the line is z, and τ is the surge traveling time, defined as:

$$z = \sqrt{\frac{l}{c}} \quad [17]$$

$$\tau = d\sqrt{lc} \quad [18]$$

It can be seen that, in equation 16, the distance does not appear explicitly; it is hidden in the surge traveling time τ. Furthermore, τ does not appear as the variable of equation 16, but as the value that the voltage and current depend on. Physically, equation 16 has the following meaning: to calculate the voltage and current at any point of the line, the "forward" and "backward" waveforms of the current and voltage at the other end are needed, and they are the function of the distance. Therefore, an explicit fault location equation for the long transmission line can not be derived out of the generic fault location equation. Instead, an indirect method is used for solving the fault location equation in this case. A procedure has been developed for finding the solution x by systematically changing the parameter τ. (Details of this procedure are published in a paper listed in For Further Reading.)

Accuracy and Performance

The fault location algorithms for short and long transmission lines were extensively tested using the Electromagnetic Transient Program (EMTP) models of sections of actual power systems. Table 1 shows typical test results for a:

- Short, 161-kV line with strong mutual coupling with several adjacent lines; the transmission line considered is fully transposed and 13.35 miles long.
- Long, 345-kV line that runs in parallel with another line; the transmission line considered is untrans-

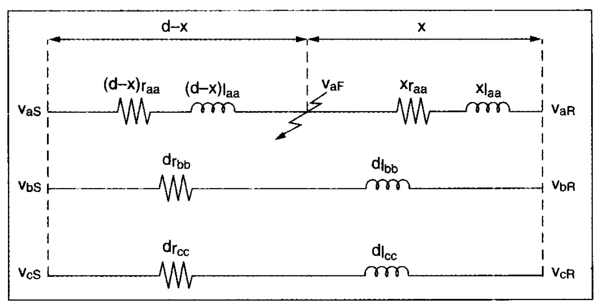

Figure 2. Faulted short three-phase transmission line

Table 1. Short-line fault location algorithm error percent for a phase A to ground fault

Location of Fault	0.1		0.5		0.8	
Incidence Angle (deg)	**0**	**90**	**0**	**90**	**0**	**90**
Short line						
$R_f = 3\Omega$	0.4344	0.4346	0.2901	0.2093	0.0388	0.0390
$R_f = 50\Omega$	0.4576	0.4549	0.2237	0.2229	0.0464	0.0472
Long line						
$R_f = 3\Omega$	0.4283	0.4212	0.3912	0.3966	0.4783	0.4152
$R_f = 50\Omega$	0.4301	0.4832	0.3991	0.4003	0.4853	0.4765

Table 2. Error (percent) for the fault location 10 percent of the line with time variable resistance RF, as shown in Figure 3

Type of Fault	Sampling Frequency (kHz) 24	12	6
a-g	0.1330	0.6969	2.2398
b-c	0.2736	0.4380	1.5619
b-c-g	0.2537	0.2880	0.1832
a-b-c-g	0.2719	0.2441	0.1615

posed and 195 miles long.

The error of the fault location algorithm is calculated as follows:

$$error(\%) = \frac{|actual\ fault\ loc. - calculated\ fault\ loc.|}{total\ line\ length} \times 100 \quad [19]$$

The worst case errors were close to 0.7 percent for the line-to-line faults, but, for most cases, the errors were not exceeding 0.5 percent. This accuracy is quite remarkable, considering the different models used as well as the range of operating and fault conditions considered.

Algorithm Robustness

The fact that a very small number of constraints is imposed on the algorithm derivation reveals that the synchronized sampling algorithm is very robust, since it is not affected by the conditions that would affect most of the other algorithms. For example:

- Fault location, type, and incidence angle have very little effect on the accuracy.
- Taking synchronized sampling at two ends of a line makes the algorithm transparent to the model characteristic and operating conditions of the rest of the power system.
- The algorithm can easily cope with any level of mutual coupling, and it is applicable to multiterminal lines.
- Operating conditions on the line of interest can be highly unbalanced, including even the cases where some phases may be de-energized, and it can operate accurately on both transposed and untransposed lines.
- The fault impedance may contain an inductive component, the fault resistance may be variable in time, and the algorithm will still preserve the high accuracy.

The last point with the time variable resistance is illustrated in Figure 3. This case is commonly found in applications in which the arc resistance is established in bursts, or in the cases when a foreign object, such as a tree limb, touches the line repeatedly at given time intervals.

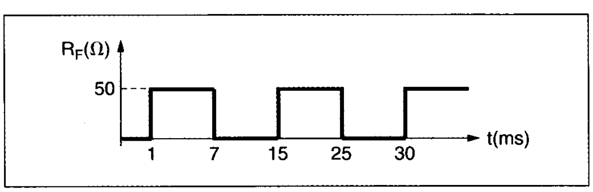

Figure 3. Variable resistance R_F

For this difficult application case, the algorithm requires a higher sampling rate than otherwise needed, but the accuracy achieved is still comparable with the overall accuracy discussed earlier. Typical test results for the time variable fault resistance are shown in Table 2.

Fault Location Improvements

The use of synchronized sampling in the fault location algorithm provides the following additional benefits not found in the previous solutions:

- The algorithm is based on direct solution of a set of differential equations, and therefore, provides accurate results for almost any type of a transmission line as long as a model of this line is available.
- The algorithm is extremely robust, giving accurate results for a fault on a transmission line under a number of different operating and fault conditions such as different loading, change in the switching conditions in the rest of the system, time varying fault resistance, multiterminal lines and mutually coupled lines.
- The algorithm is extremely fast, with a data window of one cycle, and is capable of performing both fault detection and classification that makes it a promising candidate for an ultimate protective relaying algorithm using an accurate fault location as the relaying principle.

For Further Reading

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Biographies

Mladen Kezunovic received his Dipl. Ing. degree from the University of Sarajevo, Yugoslavia, the MS and PhD degrees from the University of Kansas, all in electrical engineering in 1974, 1977, and 1980, respectively. He has been with Texas A&M University since 1987. He is an IEEE senior member, member of the IEEE PES Power System Relaying Committee, and chair of the Working Group on Intelligent System Applications in Protection Engineering and the Working Group on Digital Simulators for Relay Testing. He is a registered professional engineer in Texas.

Branislava Perunicic-Drazenovic received her BSEE and MSEE from the University of Belgrade, Yugoslavia, and PhDs in electrical engineering from the Academy of Science of USSR, Moscow, and the University of Sarajevo. She is currently a professor at Lamar University, Beaumont, Texas. She was with the Energoinvest Company, Sarajevo from 1960-1992, and has extensive academic and research experience, starting in 1964.