Two Terminals Numerical Algorithm for Distance Protection, Fault Location and Acing Faults Recognition Based on Synchronized Phasors

Chan-Joo Lee† **, Jong-Bae Park*, Joong-Rin Shin* and Zoran Radojević***

Abstract - This paper presents a new numerical algorithm for fault location estimation and for faults recognition based on the synchronized phasors. The proposed algorithm is based on the synchronized phasor measured from the synchronized PMUs installed at two-terminals of the transmission lines. In order to discriminate the fault type, the arc voltage wave shape is modeled numerically on the basis of a great number of arc voltage records obtained by transient recorder. From the calculated arc voltage amplitude it can make a decision whether the fault is permanent or transient. The results of the proposed algorithm testing through computer simulation are given.

Keywords: Arc resistance, Fault location, Protection, PMUs (Phasor Measurement Units), Spectral analysis, Transmission lines

1. Introduction

In the competitive electricity market, a rapid fault restoration on a transmission line is faced with the quality of the utility's power service. Most of the faults on transmission lines are transient and the remaining faults are permanent ones. The reasons for the transient faults are lightning, swing wires, temporary contact with foreign objects, and etc. These transient faults frequently take place in power systems and pose a risk to the stability of the power system as well as lower the quality of the utility's power service. Therefore, following the occurrence of a fault, the utility tries to restore power as quickly as possible and rapid restoration of service reduces customer complaints, outage time, loss of revenue, and crew repair costs. To aid in rapid and efficient service restoration, an accurate fault location estimation and fault discrimination technique are needed.

Many studies regarding transmission line protection have been done in the last decade. Most of the one-terminal algorithms have been based on the analysis of voltage and current data at the end of the transmission lines [1-3]. While these algorithms provide accurate results, certain error will remain due to the inherent assumptions that are required in the algorithms. The rapid progress in technology helps us to solve these problems.

The GPS (Global Positioning System) is a system with the ability to provide time synchronization to $\pm 1\mu s$ accuracy over a wide area as covered by a power system network. Recently, many studies for a fault location/ detection technique using the GPS have been done [4-6]. The GPS in the power system is applied for many parts such as PMUs (Phasor Measurement Units), state estimation, prediction of instability, adaptive relaying, and control/monitoring.

This paper presents a new numerical spectral domain algorithm devoted to blocking unsuccessful automatic reclosing onto permanent faults and fault location calculation. The proposed algorithm only uses the synchronized phasor measured from the synchronized PMUs installed at two-terminals of the transmission lines. In order to discriminate the accurate fault type, the arc voltage wave shape is modeled numerically on the basis of a great number of arc voltage records obtained by transient recorder. The calculated arc voltage amplitude can make a decision as to whether the fault is permanent or transient. In this paper the proposed algorithm for arcing faults discrimination and fault location estimation using DFT (Discrete Fourier Technique) is given.

2. The Fault Model

2.1 Synchronized Phasors

The GPS is a space-based positioning, navigation, and timing system and consists of 24 satellites that constantly revolve around the earth. Since a GPS receiver provides time synchronization to $\pm 1\mu s$ accuracy, the PMUs using

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Received July 9, 2005 ; Accepted November 1, 2005

GPS techniques in the power system are mainly applied for the fault location and protection of the EHV transmission line. When a fault occurs on any transmission line, each detector detects the fault generated high frequency transients and records the instance when the initial traveling wave generated by the fault arrives. The GPS is used to synchronize the clocks of the detectors through the receiver unit. Comparison between the arriving time of the fault transient signals at each busbar can be used to determine the accurate fault location.

For two-terminal fault location estimation based on samples, a measurement unit at each end of the transmission line is required. Two synchronized sampling units at each end of the transmission line are shown in Fig. 1.

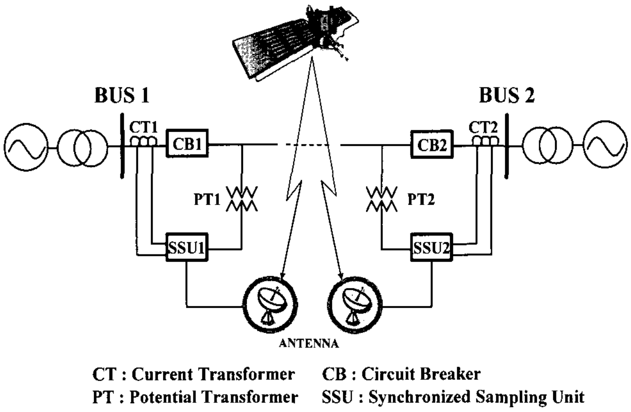


Fig. 1 Synchronized sampling arrangement

In Fig. 1 the synchronized sampling units constantly acquire voltage and current data from the PT and CT at the end of each line. The voltage and current data collected from the synchronized sampling units are sent to a central control computer. These synchronized voltage and current data from a central control computer can be applied to many parts of a power system.

2.2 Characteristics of a Long Electric Arc [7]

The long electric arc in free air is a plasma discharge and has a nonlinear variation. A nonlinear characteristic of the arcing fault on the transmission line causes the distortion of a voltage and current waveform at each end of the transmission line. In [8] the arc voltage is modeled by a nonlinear arc resistance. Also, the arc voltage in [9] is modeled by the piecewise arc voltage-current characteristics.

The typical arc voltage wave shape can be approximated into a near square waveform as indicated in Fig. 2. The arc voltage model in Fig. 2 gives a normalized cycle of the arc voltage model with arc voltage amplitude $V_a = 1.0[p.u.]$.

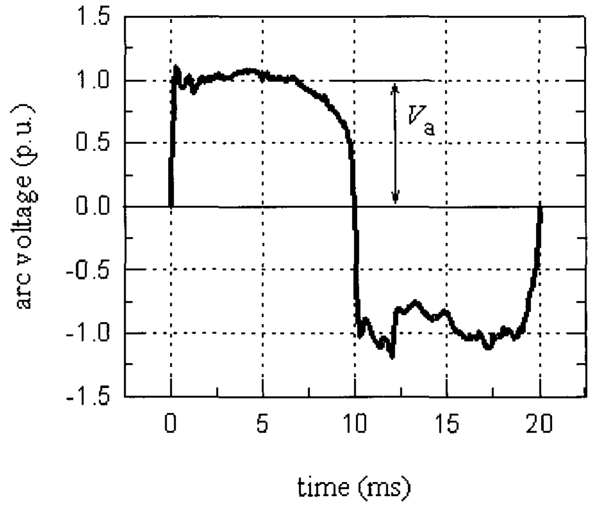


Fig. 2 The accepted arc voltage wave shape

The arc model in Fig. 2 can be numerically represented by Fourier series containing odd sine components only and the coefficients($k^{(h)}$) of the h -th harmonic are obtained to use the DFT algorithm as shown in Table 1.

$$v_a(t) = \sum_{h=1,3,5,..}^{\infty} v_a^{(h)}(t) = \sum_{h=1,3,,5,..}^{\infty} k^{(h)} V_a \sin(h\omega t) \quad (1)$$

Table 1 Coefficient of the h-th harmonics of the arc voltage

h	1	3	5	7
$k^{(h)}$	1.23	0.393	0.213	0.135

where $h = 1, 3, 5, 7, \ldots$ is the odd harmonic order, $v_a^{(h)}(t)$ is the h-th harmonic of arc voltage, V_a is a scalar, ω is the fundamental radian frequency and $k^{(h)}$ is the coefficient of the h-th harmonic.

The advantage of the arc voltage presentation through the sequence of numerical values is its flexibility. One can create various waveform shapes and calculate the corresponding coefficients $k^{(h)}$, depending on the modeling application.

2.3 Derivation of Arcing Fault Location Estimation Algorithm

Faults on overhead lines are divided into two types. About 70-90% of faults on most overhead lines are transient faults and the remaining 10-30% of faults are permanent faults. In this paper, it is considered that a-phase arcing ground fault occurs on transmission lines. The representation of a-phase arcing ground fault in spectrum domain is shown in Fig. 3 [7].

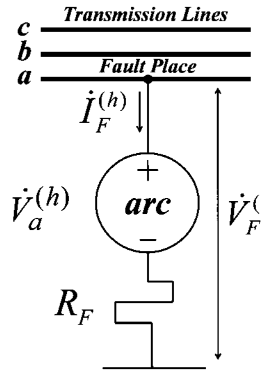


Fig. 3 *a*-phase arcing ground fault model

The arcing fault in Fig. 3 is modeled as a serial connection of arc voltage and fault resistance R_F. From Fig. 3 the *h*-th harmonic of the fault voltage is given in (2).

$$\dot V_F^{(h)} = \dot V_a^{(h)} + R_F \dot I_F^{(h)} \tag{2}$$

where $\dot V_a^{(h)}$ is the *h*-th harmonic of the arc voltage and $\dot I_F^{(h)}$ is the *h*-th harmonic of the fault current.

This paper presents a new two-terminal fault location estimation algorithm using the synchronized sampling technique. To demonstrate the proposed algorithm, assume that an *a*-phase arcing ground fault occurs on the transmission lines at ℓ away from the sending end as shown in Fig. 4. Due to the shortness of the line, the shunt capacitance and the shunt conductance of the transmission line will be neglected. In Fig. 4, all variables have radian frequency and all line parameters are calculated in terms of ($h\omega$). The fault point is denoted by *F* at a distance ℓ from the sending end (*S*).

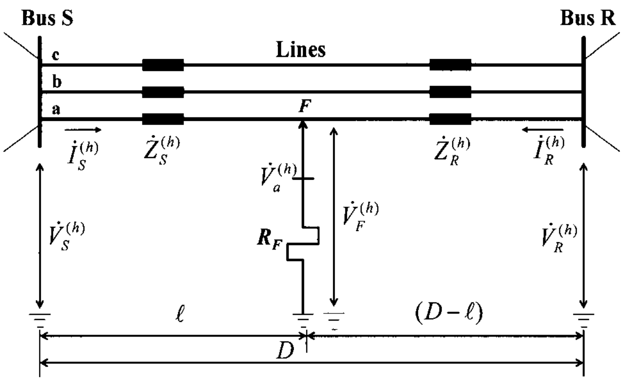


Fig. 4 Single phase to ground arcing fault on three phase overhead line

where index *h* denotes the order of harmonic, *D* is line length, and subscripts *S* and *R* denote the sending- and receiving end of the line, respectively.

The three phase circuit from Fig. 4 can be presented by the three single-phase equivalent sequence circuits of the faulted lines as indicated in Fig. 5. The three single-phase equivalent circuits are positive (*p*), negative (*n*), and zero (*0*) sequence circuits, respectively.

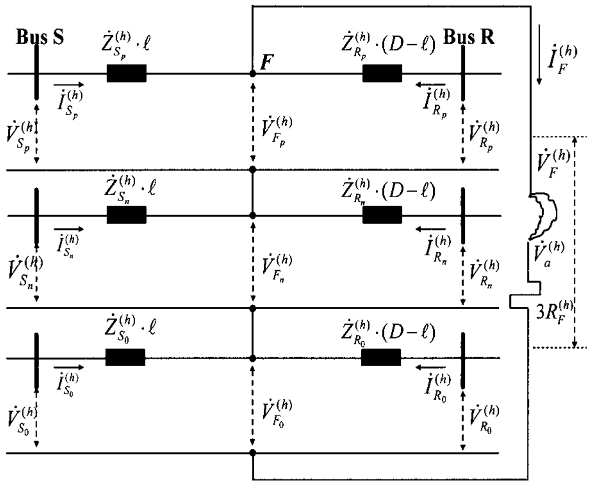


Fig. 5 Equivalent sequence network connection of faulted lines

For the equivalent sequence network depicted in Fig. 5 the following equations can be written:

$$\dot V_{S_p}^{(h)} = \dot z^{(h)} \, \ell \, \dot I_{S_p}^{(h)} + \dot V_{F_p}^{(h)} \tag{3}$$

$$\dot V_{S_n}^{(h)} = \dot z^{(h)} \, \ell \, \dot I_{S_n}^{(h)} + \dot V_{F_n}^{(h)} \tag{4}$$

$$\dot V_{S_0}^{(h)} = \dot z_0{}^{(h)} \, \ell \, \dot I_{S_0}^{(h)} + \dot V_{F_0}^{(h)} \tag{5}$$

$$\dot V_{R_p}^{(h)} = \dot z^{(h)} \, (D-\ell) \, \dot I_{R_p}^{(h)} + \dot V_{F_p}^{(h)} \tag{6}$$

$$\dot V_{R_n}^{(h)} = \dot z^{(h)} \, (D-\ell) \, \dot I_{R_n}^{(h)} + \dot V_{F_n}^{(h)} \tag{7}$$

$$\dot V_{R_0}^{(h)} = \dot z_0{}^{(h)} \, (D-\ell) \, \dot I_{R_0}^{(h)} + \dot V_{F_0}^{(h)} \tag{8}$$

where,

$\dot V_{S_{p,n,0}}^{(h)}, \dot V_{R_{p,n,0}}^{(h)}$: the *h*-th harmonic of positive-, negative-, and zero sequence phase voltage at both ends of the lines;

$\dot I_{S_{p,n,0}}^{(h)}, \dot I_{R_{p,n,0}}^{(h)}$: the *h*-th harmonic of positive-, negative-, and zero sequence phase current at both ends of the lines;

$\dot{V}^{(h)}_{F_{p,n,0}}$: the h-th harmonic of positive-, negative-, and zero sequence faulted phase voltage at the fault point;

$\dot{z}^{(h)}$: positive- or negative sequence line impedance.

By adding the above equations and using the basic symmetrical component equations, the h-th harmonic of phase voltage and current at both ends of the lines can be obtained:

$$\dot{V}^{(h)}_{S} = \dot{V}^{(h)}_{S_p} + \dot{V}^{(h)}_{S_n} + \dot{V}^{(h)}_{S_0} \tag{9}$$

$$\dot{I}^{(h)}_{S} = \dot{I}^{(h)}_{S_p} + \dot{I}^{(h)}_{S_n} + \dot{I}^{(h)}_{S_0} \tag{10}$$

$$\dot{V}^{(h)}_{R} = \dot{V}^{(h)}_{R_p} + \dot{V}^{(h)}_{R_n} + \dot{V}^{(h)}_{R_0} \tag{11}$$

$$\dot{I}^{(h)}_{R} = \dot{I}^{(h)}_{R_p} + \dot{I}^{(h)}_{R_n} + \dot{I}^{(h)}_{R_0} \tag{12}$$

and

$$\dot{V}^{(h)}_{F} = \dot{V}^{(h)}_{F_p} + \dot{V}^{(h)}_{F_n} + \dot{V}^{(h)}_{F_0} \tag{13}$$

The h-th harmonic of phase voltage of the sending- and receiving end is given by:

$$\dot{V}^{(h)}_{S} = \dot{z}^{(h)}\,(\dot{I}^{(h)}_{S} + \dot{k}^{(h)}_{z}\,\dot{I}^{(h)}_{S_0})\ell + \dot{V}^{(h)}_{F} \tag{14}$$

$$\dot{V}^{(h)}_{R} = \dot{z}^{(h)}\,(\dot{I}^{(h)}_{R} + \dot{k}^{(h)}_{z}\,\dot{I}^{(h)}_{R_0})(D-\ell) + \dot{V}^{(h)}_{F} \tag{15}$$

where $\dot{k}^{(h)}_{z} = (\dot{z}^{(h)}_{0} - \dot{z}^{(h)})/\dot{z}^{(h)}$ is the zero sequence compensation factor, which can be calculated in advance.

Subtracting equation (15) from (14), one equation for the fundamental harmonic can be obtained:

$$\dot{V}^{(1)}_{S} - \dot{V}^{(1)}_{R} = \dot{z}^{(1)}(\dot{I}^{(1)}_{S} + \dot{k}^{(1)}_{z}\dot{I}^{(1)}_{S_0})\ell - \dot{z}^{(1)}(\dot{I}^{(1)}_{R} + \dot{k}^{(1)}_{z}\dot{I}^{(1)}_{R_0})(D-\ell) \tag{16}$$

The fault location ℓ from equation (16) can be calculated as follows:

$$\ell = \frac{\dot{V}^{(1)}_{S} - \dot{V}^{(1)}_{R} + \dot{z}^{(1)}(\dot{I}^{(1)}_{R} + \dot{k}^{(1)}_{z}\dot{I}^{(1)}_{R_0})D}{\dot{z}^{(1)}[\dot{I}^{(1)}_{S} + \dot{I}^{(1)}_{R} + \dot{k}^{(1)}_{z}(\dot{I}^{(1)}_{S_0} + \dot{I}^{(1)}_{R_0})]} \tag{17}$$

Equation (17) is the explicit fault location expression for the short three-phase transmission line. Unknown parameter ℓ from equation (17) can be calculated by using the faulted loop equation from the synchronized voltage and current data at both transmission line terminals.

After calculating the fault distance ℓ, the third harmonic of fault voltage from equation (14) can be calculated. The fault resistance R_F from equation (2) can be expressed as follows:

$$R_F = \frac{\dot{V}^{(3)}_{F} - \dot{k}^{(3)}V_a}{\dot{I}^{(3)}_{F}} \tag{18}$$

$$\dot{k}^{(3)} = \frac{4}{\pi}\frac{1}{3}\angle 3\varphi_1$$

where $\dot{k}^{(3)}$ is the coefficient of the third harmonic and φ_1 is the phase angle of the fundamental harmonic.

Since the fault resistance is a scalar, equation (18) is expressed as follows:

$$\operatorname{Im}\{R_F\} = \operatorname{Im}\left\{\frac{\dot{V}^{(3)}_{F} - \dot{k}^{(3)}V_a}{\dot{I}^{(3)}_{F}}\right\} = 0 \tag{19}$$

$$\operatorname{Im}\left\{\frac{\dot{V}^{(3)}_{F}}{\dot{I}^{(3)}_{F}}\right\} - \operatorname{Im}\left\{\frac{\dot{k}^{(3)}}{\dot{I}^{(3)}_{F}}\right\}V_a = 0 \tag{20}$$

The unknown arc voltage amplitude from equation (20) is calculated as follows.

$$V_a = \frac{\operatorname{Im}\left\{\dfrac{\dot{V}^{(3)}_{F}}{\dot{I}^{(3)}_{F}}\right\}}{\operatorname{Im}\left\{\dfrac{\dot{k}^{(3)}}{\dot{I}^{(3)}_{F}}\right\}} \tag{21}$$

The calculated arc voltage amplitude is used to decide a fault type. The fault is classified as an arcing transient fault if the calculated value of arc voltage amplitude is greater than the product of arc voltage gradient and the length of the arc path, which is equal to or greater than the flashover length of a suspension insulator string. The average arc voltage gradient lies between 12 and 15 V/cm [10].

3. Computer Simulated Tests

The EMTP (Electromagnetic Transient Program) is used to test the validity of the proposed algorithm. The schematic diagram of the 400kV power system is shown in Fig. 6. Shunt capacitance and conductance on transmission line will be neglected.

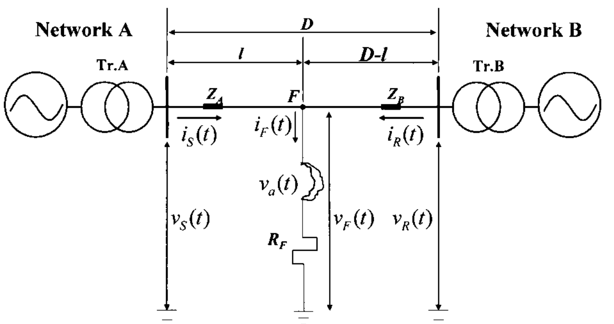


Fig. 6 Schematic of the test power system

Here, $v_{S,R}(t)$, $i_{S,R}(t)$ are the digitized voltages and currents, and the line parameters that are calculated via a line constant program were D = 100 [km], r = 0.0325 [Ω/km], x = 0.3 [Ω/km], r_0 = 0.0975 [Ω/km], and x_0 = 0.9 [Ω/km]. Network data is shown in Table 2. The equivalent electromotive force of networks A and B are E_A and E_B, respectively.

Table 2 Network data

	R[Ω]	L[H]	R_0[Ω]	L_0[H]
Network A	1	0.064	2	0.128
Network B	0.5	0.032	1	0.064

Single-phase to ground faults are simulated at different points on the transmission line. The pre-fault load is present on the line. A synchronization error of 0 degrees was added to the test input data.

Figs. 7, 8, 9, and 10 show the faulted phase voltages and currents at each end of the transmission line, sampled with the sampling frequency $f_s = 3840\ Hz(64\ \text{sample}/T_0)$ for the single phase to ground fault with arc. The fault is initiated at 10% of the line.

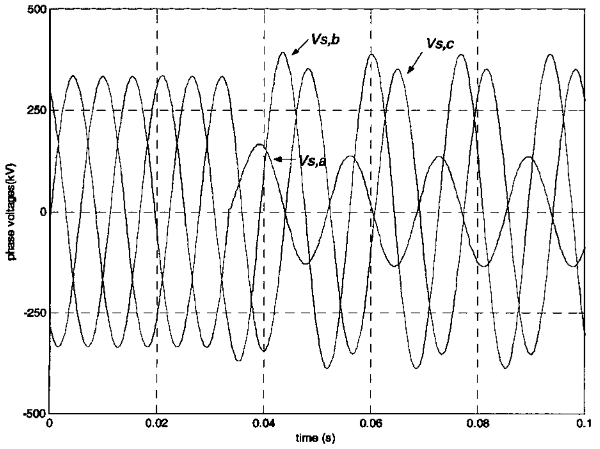


Fig. 7 Faulted phase voltages at the sending end

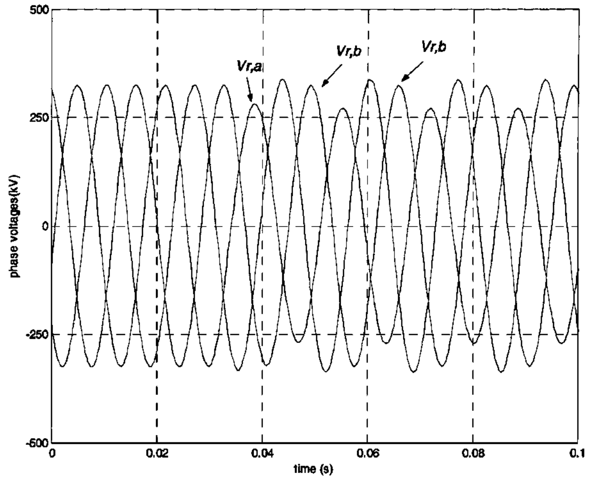


Fig. 8 Faulted phase voltages at the receiving end

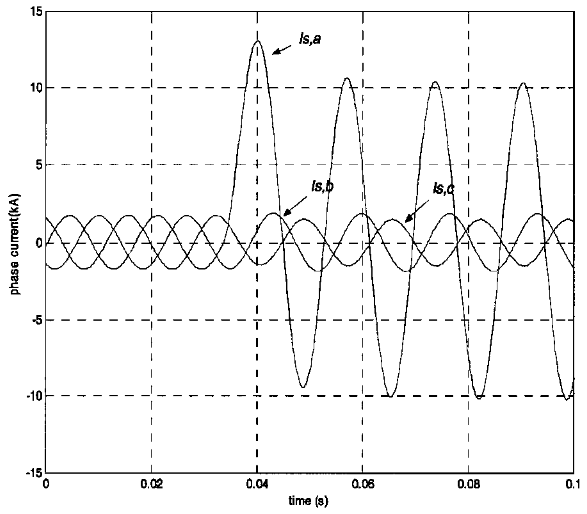


Fig. 9 Faulted phase currents at the sending end

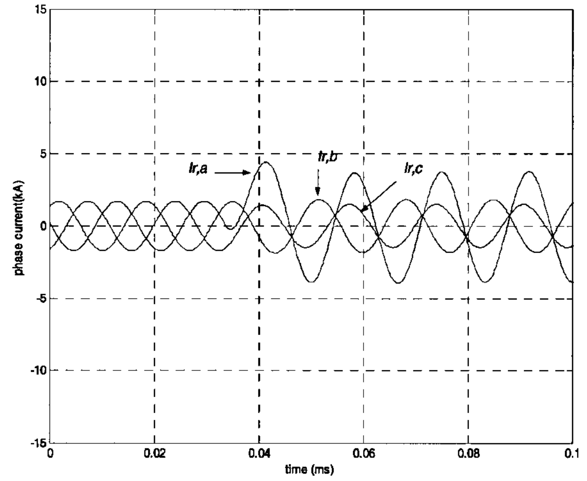


Fig. 10 Faulted phase currents at the receiving end

The arc voltage waveform and amplitude are assumed to be of square wave shape with amplitude of V_a =4.5 [kV] as shown in Fig. 11. The fault inception is 33 [ms] and fault resistance is R_F = 8 [Ω].

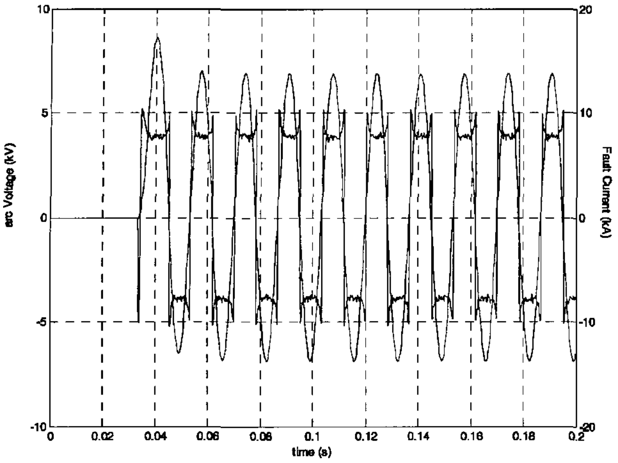


Fig. 11 Arc voltage and fault current

Fig. 12 depicts the estimated fault location and arc voltage amplitude using the proposed two-terminal algorithm. From the estimated values the fault on the transmission line occurred at about 10 km away from sending end. Since the estimated arc voltage amplitude converges to about 4.5 kV, the type of fault is the transient fault.

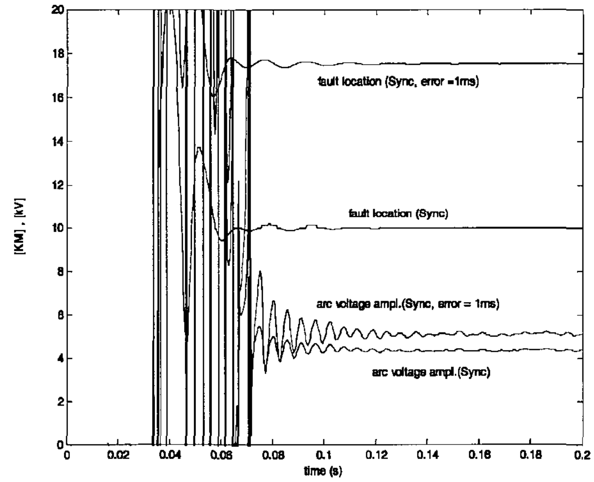


Fig. 12 Estimated fault location (exact value used by EMTP was 10 km) and arc voltage amplitude (exact value used by EMTP was 4.5 kV)

In Fig. 12 while the fault location and arc voltage amplitude with synchronization error of 1 [ms] are both inaccurate and unstable, the estimated values at the arc voltage amplitude using the proposed algorithm are accurate, fast and stable.

4. Conclusions

This paper presents a two-terminal approach for fault location estimation and for faults recognition using the synchronized sampling technique. The proposed algorithm is also based on the synchronized phasor measured from the synchronized PMUs installed at two-terminals of the transmission lines. Only the fundamental and third harmonic phasors calculated by DFT (Discrete Fourier Transform) are needed to estimate the unknown parameters such as the fault location and the arc voltage amplitude. The fault location can be used for distance protection and the arc voltage amplitude can be used for blocking reclosing of the transmission line with permanent faults. Also, the validity of the proposed algorithm was proven for the computer simulation.

By knowing the fault location and the fault type more accurately, utilities should be able to reduce outage time and improve the quality of power service.

Acknowledgement

This work is supported by the Korea Ministry of Commerce, Industry and Energy (MOCIE) and the Korea Electric Power Research Institute (KEPRI) through the IERC program.

Reference

[1] T. Takagi, et al., “Development of a New Fault Locator Using the One-Terminal Voltage and Current Data”, IEEE Trans. on PAS, Vol. PAS-101, No. 8, pp. 2892-2898, August 1982.

[2] L. Eriksson, M. Saha, and G.D. Rockfeller, “An Accurate Fault Locator with Compensation for Apparent Reactance in the Fault Resistance Resulting from Remote-End Infeed”, IEE Trans. on PAS, Vol. PAS-104, No. 2, pp. 424-436, Feb. 1985.

[3] M. Sant and Y. Paithankar, “On Line Digital Fault Locator for Overhead Transmission Line”, IEE Proceedings, Vol. 126, No. 11, pp. 1181-1185, Nov. 1979.

[4] Ying-Hong Lin, Chih-Wen Liu, Ching-Shan Chen, “A New PMU-Based Fault Detection/Location Technique for Transmission Line with Consideration of Arcing Fault Discrimination-Part I: Theory and Algorithms”, IEEE Trans. on Power Delivery, Vol. 19, No. 4, pp. 1587-1593, Oct. 2004.

[5] Ying-Hong Lin, Chih-Wen Liu, Ching-Shan Chen, “A New PMU-Based Fault Detection/Location Technique for Transmission Line with Consideration of Arcing Fault Discrimination-Part II: Performance Evaluation”, IEEE Trans. on Power Delivery, Vol. 19, No. 4, pp. 1594-1601, Oct. 2004.

[6] Chi-Shan Yu, Chih-Wen Liu, Sun-Li Yu, and Joe-Air

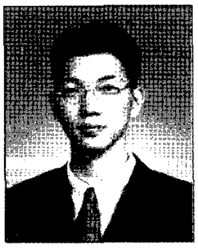
Jiang, "A New PMU-Based Fault Location Algorithm for Series Compensated Lines", IEEE Trans. on Power Delivery, Vol. 17, No. 1, pp. 33-46, Jan. 2002.

[7] Chan-Joo Lee, Zoran Radojevic, Joong-Rin Shin, Jong-Bae Park "Numerical Algorithm for Fault Location Calculation and Blocking Unsuccessful Reclosing onto Permanent Faults", IEEE Proceeding, June 2005.

[8] T. Funabashi, H. Otoguro, Y. Mizuma, L. Dube, M. Kizilcay and A. Ametani, "Influence of Fault Arc Characteristics on the Accuracy of Digital Fault Locators", IEEE Trans. on Power Delivery, Vol. 16, pp. 195-199, April 2001.

[9] A. T. Johns, R. K. Aggarwal and Y. H. Song, "Improved Technique for Modeling Fault Arc on Faulted EHV Transmission Systems", IEE Proc.-Gener. Transm. Distrib., Vol. 141, pp. 148-154, March 1994.

[10] A. S .Maikapar, "Extinction of an Open Electric Arc", Elektrichestvo, Vol. 4, pp. 64-69, 1960.



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