2005년도 대한전기학회 하계학술대회 논문집 2005. 7. 18-20

적응 자동재폐로를 위한 동기식 2 단자 사고거리 추정기법

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Synchronized Two-Terminal Fault Location Technique for Adaptive Autoreclosure

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Abstract - This paper presents a two-terminal approach for fault location estimation and for faults recognition. The proposed algorithm is also based on the synchronized phasors measured from the synchronized PMUs installed at two-terminals of the transmission lines. Also 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 permanent or transient fault. The results of the proposed algorithm testing through computer simulation are given.

1. Introduction

In the competitive electricity market, a rapid fault restoration on transmission line is faced with the quality of utility's power service. Following the occurrence of a fault, the utility tries to restore power as quickly as possible because rapid restoration of service reduces customer complaints, outage time, loss of revenue, and crew repair expensive. To aid in rapid and efficient service restoration, an accurate fault location estimation and fault discrimination technique are needed. Many studies for the transmission line protection have been done in the last decade. Most of one-terminal algorithms were 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 which are required in the algorithms. However, the rapid technology progress helps us to solve these problems.

The GPS(Global Positioning System) is a system with ability to provide time synchronization to a $\pm 1\mu s$ 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].

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. Also 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 permanent or transient fault.

2. The Fault Model

2.1 Synchronized Sampling Technology

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 a $\pm 1\mu s$ accuracy, the GPS based techniques are mainly applied for the fault location and protection for 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 travelling wave generated by the fault arrives. The GPS is used here to synchronize the clocks of the detectors through their receiver unit. Comparison between the arriving time of the fault transient signals at each busbar will be able to determine the accurate fault location.

For two-terminal fault location estimation base 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 is shown in Fig. 1.

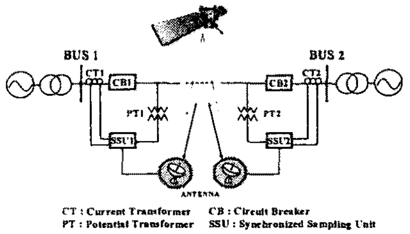

Fig. 1. Synchronized sampling arrangement

2.2 Characteristics of a Long Electric Arc[7]

The long electric arc is a plasma discharge and has a nonlinear variation. A nonlinear characteristic of the arcing fault on transmission line causes the distortion of a voltage and current waveform at the each end of the transmission line. The typical arc voltage wave shape can be approximated into a near square waveform. The arc model 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.

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

where h is the odd harmonic order, $v_a^{(h)}(t)$ is h-th harmonic of arc voltage, V_a is a scalar, w is the fundamental radian frequency and $k^{(h)}$ is the coefficient of the h-th harmonic.

2.3 Derivation of Arcing Fault Location Estimation Algorithm

Faults on overhead lines is divided into the 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 an a-phase arcing ground fault occurs on transmission lines.

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

$$V_{F(h)} = V_{a(h)} + R_F I_{F(h)} \quad (2)$$

where $V_{a(h)}$ is the h-th harmonic of the arc voltage and $I_{F(h)}$ is the h-th harmonic of the fault current.

This paper presents a new two-terminal fault location estimation and faults detection algorithm using 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.2. Due to the shortness of the line, the shunt capacitance and the shunt conductance of the transmission line will be neglected. In Fig.2 all variables have radian frequency ($h\omega$) and all line parameters are calculated in term of $h\omega$. The fault point is denoted by F at a distance ℓ from the sending end(S).

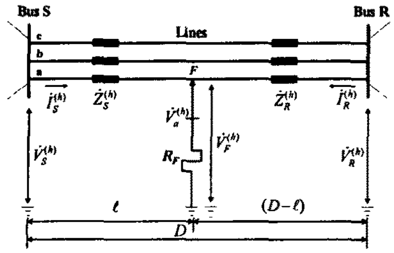

Fig. 2. Single phase to ground arcing fault on three phase overhead line

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

The three phase circuit from Fig. 2 can be presented by the three single-phase equivalent sequence circuits of the faulted lines as shown in Fig. 3. The three single-phase equivalent circuits are a positive(p), negative(n), and zero(0) sequence circuits, respectively.

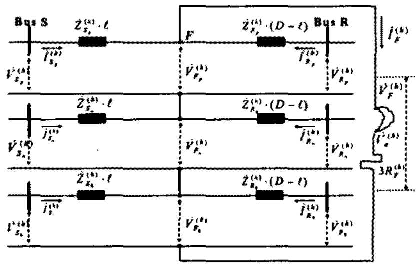

Fig. 3 Equivalent sequence network connection of faulted lines

For the equivalent sequence network depicted in Fig. 3 the following equations can be written:

$$\dot{V}_{S_p}^{(h)} = \dot{z}^{(h)} \ell \dot{I}_{S_p}^{(h)} + \dot{V}_{F_p}^{(h)} \quad (3)$$

$$\dot{V}_{S_n}^{(h)} = \dot{z}^{(h)} \ell \dot{I}_{S_n}^{(h)} + \dot{V}_{F_n}^{(h)} \quad (4)$$

$$\dot{V}_{S_0}^{(h)} = \dot{z}_0^{(h)} \ell \dot{I}_{S_0}^{(h)} + \dot{V}_{F_0}^{(h)} \quad (5)$$

$$\dot{V}_{R_p}^{(h)} = \dot{z}^{(h)} (D-\ell) \dot{I}_{R_p}^{(h)} + \dot{V}_{F_p}^{(h)} \quad (6)$$

$$\dot{V}_{R_n}^{(h)} = \dot{z}^{(h)} (D-\ell) \dot{I}_{R_n}^{(h)} + \dot{V}_{F_n}^{(h)} \quad (7)$$

$$\dot{V}_{R_0}^{(h)} = \dot{z}_0^{(h)} (D-\ell) \dot{I}_{R_0}^{(h)} + \dot{V}_{F_0}^{(h)} \quad (8)$$

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 voltage at both ends of the lines;
$\dot{V}_{F_{p,n,0}}^{(h)}$	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.

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

$$\dot{V}_S^{(h)} = \dot{z}^{(h)} (\dot{I}_S^{(h)} + \dot{k}_z^{(h)} \dot{I}_{S_0}^{(h)}) \ell + \dot{V}_F^{(h)} \quad (9)$$

$$\dot{V}_R^{(h)} = \dot{z}^{(h)} (\dot{I}_R^{(h)} + \dot{k}_z^{(h)} \dot{I}_{R_0}^{(h)})(D-\ell) + \dot{V}_F^{(h)} \quad (10)$$

where $\dot{k}_z^{(h)} = (\dot{z}_0^{(h)} - \dot{z}^{(h)}) / \dot{z}^{(h)}$ is the zero sequence compensation factor, which can be calculated in advance.

Subtracting equation (10) from (9), one equation for fundamental harmonic can be obtained:

$$\dot{V}_S^{(1)} - \dot{V}_R^{(1)} = \dot{z}^{(1)} (\dot{I}_S^{(1)} + \dot{k}_z^{(1)} \dot{I}_{S_0}^{(1)}) \ell - \dot{z}^{(1)} (\dot{I}_R^{(1)} + \dot{k}_z^{(1)} \dot{I}_{R_0}^{(1)})(D-\ell) \quad (11)$$

The fault distance ℓ from equation (11) can be calculated as follows:

$$\ell = \frac{\dot{V}_S^{(1)} - \dot{V}_R^{(1)} + \dot{z}^{(1)} (\dot{I}_R^{(1)} + \dot{k}_z^{(1)} \dot{I}_{R_0}^{(1)}) D}{\dot{z}^{(1)} [\dot{I}_S^{(1)} + \dot{I}_R^{(1)} + \dot{k}_z^{(1)} (\dot{I}_{S_0}^{(1)} + \dot{I}_{R_0}^{(1)})]} \quad (12)$$

Equation (12) is the explicit fault location expression for the short three-phase transmission line. After calculating the fault distance ℓ, the third harmonic of fault voltage from equation (9) can be calculated. The fault resistance R_F from equation (2) can be expressed as follows:

$$R_F = (\dot{V}_F^{(3)} - \dot{k}^{(3)} V_a) / \dot{I}_F^{(3)} \quad (13)$$

where $\dot{k}^{(3)}$ is the coefficient of third harmonic and ϕ_1 is the phase angle of the fundamental harmonic. Since the fault resistance is a scalar, equation (13) is expressed as follows:

$$Im\{R_F\} = Im\{(\dot{V}_F^{(3)} - \dot{k}^{(3)} V_a) / \dot{I}_F^{(3)}\} = 0 \quad (14)$$

The unknown arc voltage amplitude from equation (14) is calculated as follows.

$$V_a = Im\{\dot{V}_F^{(3)} / \dot{I}_F^{(3)}\} / Im\{\dot{k}^{(3)} / \dot{I}_F^{(3)}\} \quad (15)$$

The calculated arc voltage amplitude is used to decide a fault type. Fault is a arcing transient fault if calculated value of arc voltage amplitude is greater than product of arc voltage gradient and the length of the arc path[8].

3. Computer Simulated Tests

The EMTP(Electromagnetic Transient Program) is used to test the validity of the proposed algorithm. The schematic diagram of 400kV power system is shown in Fig. 4. Shunt capacitance and conductance on transmission line will be neglected.

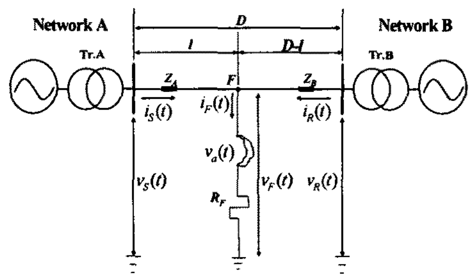

Fig. 4 Schematic of the test power system

Here, $v_{S,R}(t)$, $i_{S,R}(t)$ are the digitized voltages and currents, and the line parameters which 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 I. The equivalent electromotive force of networks A and B are E_A=400[kV] and E_B=395[kV], respectively.

Table 1 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 point on the transmission line. The pre-fault load is present on the line. A synchronization error of 0 degree was add to the test input data.

Figs. 5, 6, 7, and 8 show the faulted phase voltages and currents at the each end of the transmission line, sampled with the sampling frequency f_s=3840 Hz (64 $sample/T_0$) for the single phase to ground fault with arc. The fault is initiated at 10% of the line.

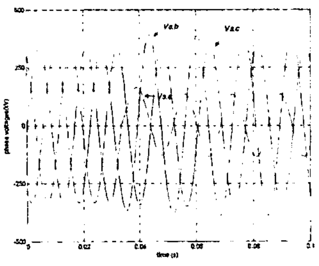

Fig. 5 Faulted phase voltages at the sending end

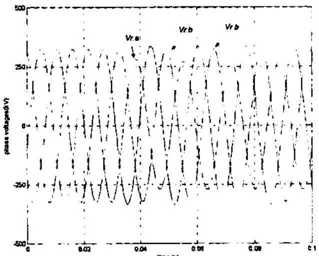

Fig. 6 Faulted phase voltages at the receiving end

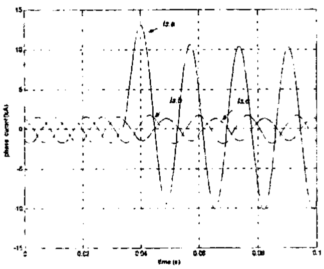

Fig. 7 Faulted phase currents at the sending end

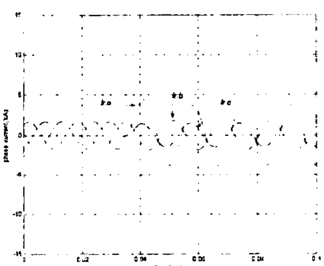

Fig. 8 Faulted phase currents at the receiving end

The arc voltage waveform and amplitude are assumed to be of square wave shape with amplitude of $V_a=5.4[kV]$ as shown in Fig. 9. The fault inception is 33[ms] and fault resistance is $R_F=8[\Omega]$.

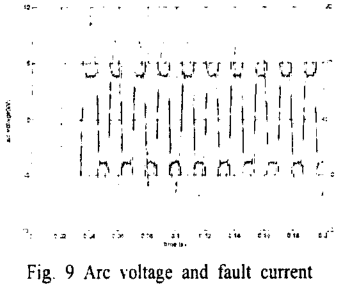

Fig. 9 Arc voltage and fault current

Fig. 10 shows the estimated fault location and arc voltage amplitude using the proposed two-terminal algorithm. From the estimated values the fault on transmission occurred at about 10 km away from sending end. Since the estimated arc voltage amplitude converges to about 5.4kV, the type of fault is the transient fault. In Fig. 9, while the fault location and arc voltage amplitude with synchronization error of 1ms are inaccuracy and unstable, the estimated values using the proposed algorithm are accuracy, fast and stable.

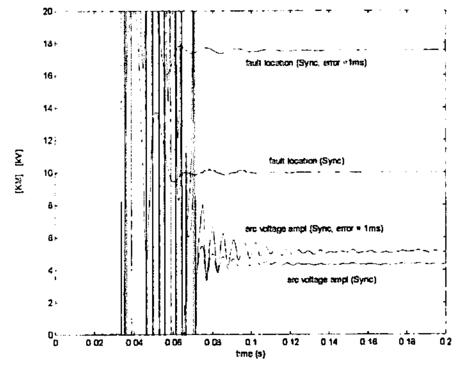

Fig. 10 Estimated fault location and arc voltage amplitude

4. Conclusions

This paper presents a two-terminal approach for fault location estimation and for arcing faults detection 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 resclosing of transmission line with permanent faults. Also, The validity of the proposed algorithm was proven by the computer simulation.

By knowing the fault location and 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, MOCIE and KEPRI through 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, August 1982, pp. 2892-2898.

[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, Feb. 1985, pp. 424-436.

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

[4] Ying-Hong Lin, Chih-Wen Liu, Ching-Shan Chen, "A New PMU-Based Fault Dectection/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, Oct. 2004, pp. 1587-1593.

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

[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, Jan. 2002, pp. 33-46.

[7] Zoran Radojevic, Joong-Rin Shin, "A New One Terminal Numerical Algorithm for Adaptive Autoreclosure and Fault Distance Calculation", Tran. KIEE, Vol. 53A, No. 8, Aug. 2004, pp. 438-445.

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