An Improved Technique for Fault Location Estimation Considering Shunt Capacitance on Transmission Line

Hyun-Houng Kim*, Yun-Won Jeong*, Chan-Joo Lee†, Jong-Bae Park* and Joong-Rin Shin*

Abstract - This paper presents a new two-terminal numerical algorithm for fault location estimation using the synchronized phasor in time-domain. The proposed algorithm is also based on the synchronized voltage and current phasor measured from the PMUs (Phasor Measurement Units) installed at both ends of the transmission lines. In this paper, the algorithm is given without shunt capacitance and with shunt capacitance using Π -model and estimated using DFT (Discrete Fourier Transform) and LES (Least Error Squares Method). The algorithm uses a very short data window and classification for real-time transmission line protection. To verify the validity of the proposed algorithm, the Electro-Magnetic Transient Program (EMTP) and MATLAB are used.

Keywords: Fault location, Numerical algorithms, Protection, Time-domain, With/Without shunt capacitance

1. Introduction

The fault location estimation on transmission lines is a very important problem from the viewpoint of economics and quality of a power system. The occurrence of fault on the transmission line not only incurs economical losses and social problems but also affects a serious problem to the entire power system. Following the occurrence of a fault, the utility tries to restore the supply of power as soon as possible, and rapid restoration of service reduces customer complaints, outage time, loss of revenue, and etc. Therefore, in order to provide service continuity to the customers and minimize the damage to the system and equipments when the fault is occurring on transmission lines, development of an accurate and efficient numerical algorithm is needed.

Most one-terminal algorithms for the fault location estimation were based on the analysis of voltage and current data at the one end of the transmission line [1-3]. However, since the data from another end are required for more precise computation, these algorithms make it difficult to estimate the fault location accurately. In additional, most of the one-end algorithms were based on the estimation of voltage and current phasors.

Recently, the progress of high technology such as GPS (Global Positioning System) helps us to provide more accurate computations. Over the past few years, many studies for a fault location technique using GPS have been done [4-6]. The GPS in power systems is applied to many parts such as PMUs (Phasor Measurement Units), state estimation, prediction of instability, adaptive relaying, and control/monitoring [7-8].

In this paper, a new two-terminal algorithm for fault location estimation is derived in time domain. The proposed numerical algorithms are divided into two steps as follows:

- First Step : without shut capacitance
- Second Step : with shut capacitance

The proposed numerical algorithms are based on the only use of voltage and current samples that are synchronously taken from assumed PMUs installed at both ends of a transmission line.

2. Algorithm of Fault distance calculation

2.1 First Step: without shut capacitance

To derive the algorithm, it assumes that a -phase arcing ground fault occurs on the transmission lines at ℓ way from sending end. A faulted three-phase system considering the lumped line parameter is shown in Fig. 1.

The line parameters of phase A can be divided into two homogeneous sections owing to the fault. Therefore, the fault point is the only point on the line where the voltage and current can be expressed as a function of the voltages and currents from both line ends. The series parameters are only modeled in the algorithm as a lumped line resistance and inductance. Since Equation (1) is written for three-phase over a number of sampling instants, and the only

† Corresponding Author: Dept. of Electrical Engineering, Konkuk University, Korea. (jubily@konkuk.ac.kr)

* Dept. of Electrical Engineering, Konkuk University, Korea. (hhblue@konkuk.ac.kr)

Received: December 10, 2005 ; Accepted: March 16, 2006

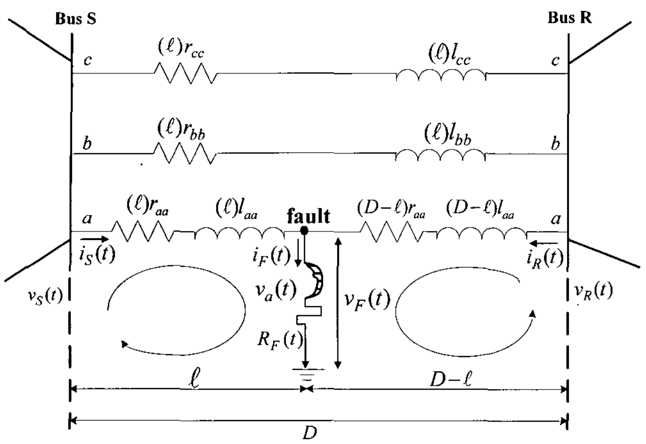


Fig. 1. Three phase transmission line with phase-a to ground fault

unknown variable is distance ℓ to the point, the unknown distance ℓ is determined using the Least Square Estimation for all three phases of the line [9]:

$$\ell = \frac{\sum_{n=a,b,c}\sum_{k=1}^{N} A_n(k)}{\sum_{n=a,b,c}\sum_{k=1}^{N} B_n(k)} \quad (1)$$

where $A_n(k)$ and $B_n(k)$ for $n=a,b,c$ and $k=1,2,....,N$ are defined as follows:

$$A_n(k)=v_{nS}(k)-v_{nR}(k)-d\sum_{p=a,b,c}\left\{\left(r_{np}+l_{np}\frac{1}{\Delta t}\right)i_{pR}(k)-l_{np}\frac{1}{\Delta t}i_{pR}(k-1)\right\} \quad (2)$$

$$B_n(k)=\sum_{p=a,b,c}\left\{\left(r_{np}+l_{np}\frac{1}{\Delta t}\right)(i_{pS}(k)+i_{pR}(k))-\frac{l_{np}}{\Delta t}(i_{pS}(k-1)+i_{pR}(k-1))\right\} \quad (3)$$

Equation (1) is the explicit fault location equation that defines the fault location algorithm for the three-phase transmission line.

2.2 Second Step: with shut capacitance

If the fault location algorithm does not compensate for shunt capacitance in the long line model, error may be increased to the longer lines on higher voltage levels. In this step, the distributed line model is used to develop the fault location algorithm for long line application. The line Π model may be corresponded to the distributed *ABCD* model. The line Π model is shown in Fig. 2. Here, unknown parameter ℓ^* is the fault distance away from sending end considering the shunt capacitance and y is shunt admittance capacitance.

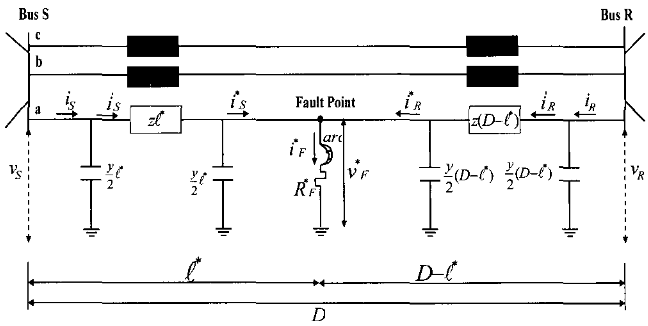


Fig. 2. Schematic diagram line of the faulted system with shunt

In the previous step the fault location algorithm derived without shunt capacitance is approximately expressed as Equation (1). From Fig. 2, the phase current at both terminals of the lines can be obtained as follows:

$$i'_S(t) = i_S(t) - \frac{Y}{2}\ell\, v_S(t) \quad (4)$$

$$i'_R(t) = i_R(t) - \frac{Y}{2}(D-\ell)\, v_R(t) \quad (5)$$

where i'_S, i'_R are the phase current in the series impedance at the sending and receiving ends, respectively.

From KVL, the phase voltage at sending and receiving end is given by:

$$v_S(t) = i'_S(t)\frac{Y}{2}\ell^* + v_F^*(t) \quad (6)$$

$$v_R(t) = i'_R(t)\frac{Y}{2}(D-\ell^*) + v_F^*(t) \quad (7)$$

Subtracting equation (7) from (6), one equation can be obtained:

$$v_S(k) - v_R(k) = i'_S(k)\frac{Y}{2}\ell^* - i'_R(k)\frac{Y}{2}(D-\ell^*) \quad (8)$$

The fault distance ℓ^* from equation (8) can be calculated as follows:

$$\ell^* = \frac{v_S(k) - v_R(k) + i'_R(k)\frac{Y}{2}D}{\left(i'_S(k)\frac{Y}{2} + i'_R(k)\frac{Y}{2}\right)} \quad (9)$$

Equation (9) is the explicit fault location expression in the long line model for a-phase arcing ground fault on transmission lines.

Without shunt capacitances at the fault distance are known, with shunt capacitance considering fault distance can be easily obtained.

3. Computer Simulated Tests

3.1 Case 1: Without Shunt Capacitance

The tests have been done using the Electromagnetic Transient Program (EMTP) and MATLAB. The schematic diagram of the 400[kV] power system on which the tests are based as shown in Fig. 3. In this chapter the synchronized test power system is used to verify the synchronized time fault analysis.

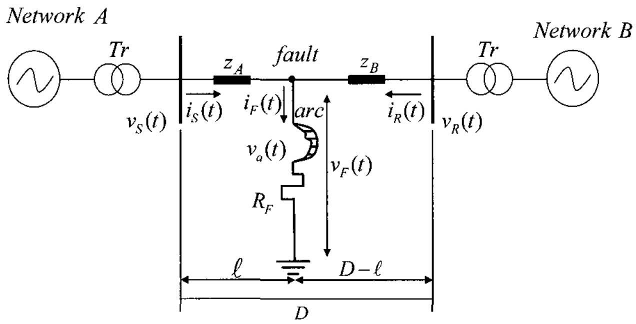


Fig. 3. Schematic of the test power system (without shunt capacitance)

Here, $v_{S,R}(t), i_{S,R}(t)$ are the digitized voltages and currents, and D is the line length. The line parameters are D =100[km], r=0.0325 [Ω/km] , x=0.36 [Ω/km] , r_0 =0.0975 [Ω/km] , and x_0 =1.08 [Ω/km] . Data for network A are: R_A =1 [Ω], L_A =0.064[H], R_{A0} =2 [Ω], and L_{A0} =0.128[H]. Data for network B are: R_B =0.5 [Ω] , L_B =0.032[H], R_{B0} =1 [Ω] , and L_{B0} =0.064[H]. The equivalent electromotive forces of networks A and B are E_A=400[kV] and E_B=395[kV], respectively. Here, network A and B are equivalent power systems connected to the sending and receiving end of the transmission line. Single-phase to ground faults are simulated at different points on the transmission line. The left line terminal voltages and currents are sampled with the sampling frequency f_S =3840Hz (64 $samples/T_0$). The arc voltage used by EMTP is assumed to be of square wave with amplitude of V_a =4.5[kV], corrupted by the random noise. Typical waveforms of arc voltage obtained through computer simulation are depicted in Fig. 4, where the instant of the fault inception is 33ms.

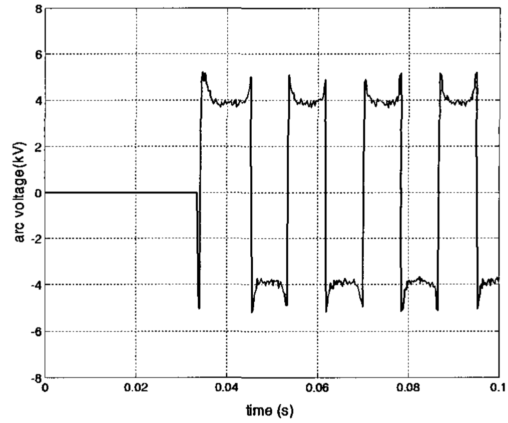


Fig. 4. Arc voltage shape used by EMTP

Input phase voltages and line currents, measurable at relay loaction, calculated by EMTP for selected case studies are plotted in Fig. 5 and 6, respectively.

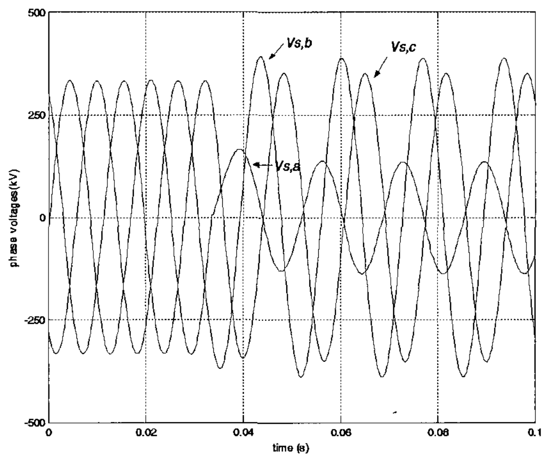


Fig. 5. Distorted input voltages generated by EMTP.

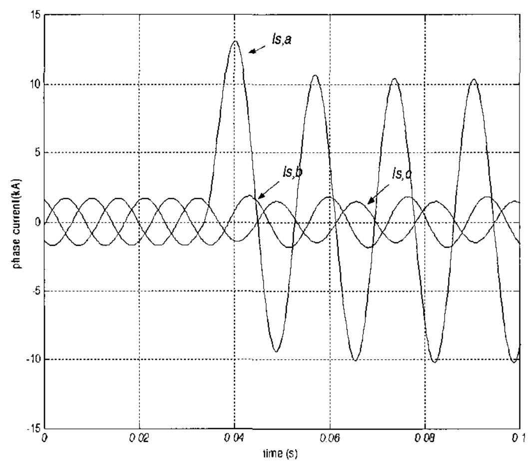


Fig. 6. Distorted input currents generated by EMTP.

The calculated fault distances according to the fault location variation are plotted in Fig. 7. The tested fault locations are $\ell = 10$, 20, 30, 80 away from Bus S, respectively.

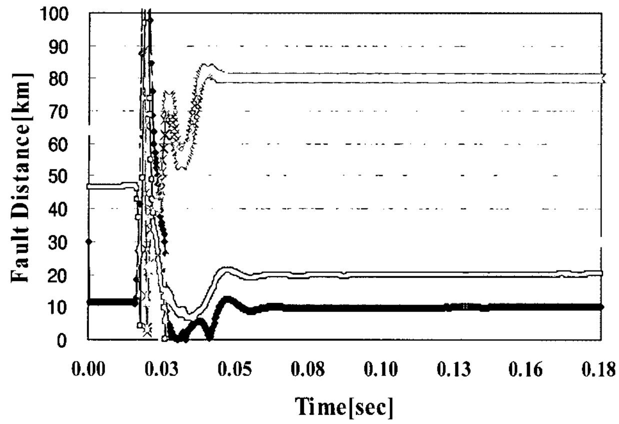


Fig. 7. Calculated fault distance obtained by changing the fault location

As seen in Fig. 7, the proposed algorithm is not affected by different fault locations. Fig. 8 shows the errors of estimated fault location.

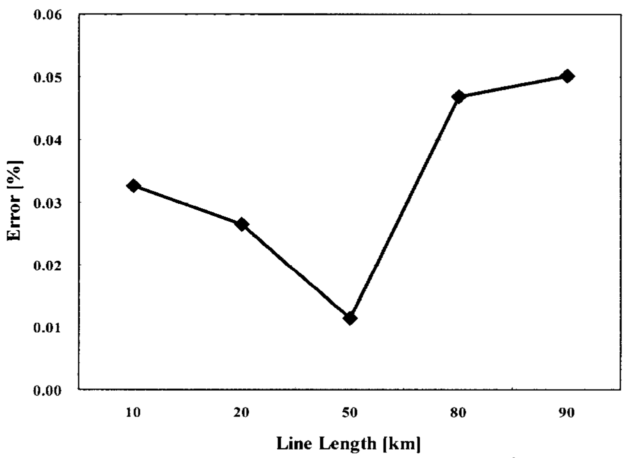


Fig. 8. Errors of estimated fault location

As shown in Fig. 8, the relative errors obtained by changing the fault location are less than 0.1%.

The fault location error to evaluate the algorithm accuracy in percentage terms is calculated using the following equation:

$$error[\%] = \left| \frac{\ell_c - \ell_a}{D} \right| \times 100 \quad (15)$$

where ℓ_a and ℓ_c represent the actual fault location and the calculated fault location, and D denotes the whole line length.

Fig. 9 shows the faulted a-phase currents obtained by changing the fault distance and fault resistance.

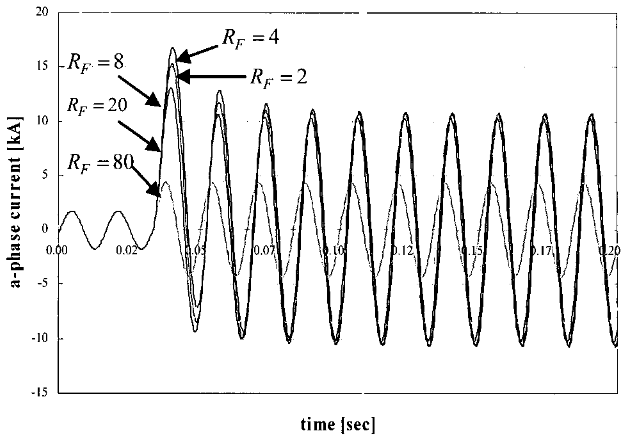


Fig. 9. Faulted a-phase currents (i_S)

Table 1 and Fig. 10 show the fault location error for various values of actual fault distance and resistance.

Table 1. Fault location error for various values of fault resistance

Fault Resistance R_F [Ω]	Error of Fault Location [%]				
	10 [km]	20 [km]	50 [km]	80 [km]	90 [km]
2	0.0151	0.0124	0.0034	0.0061	0.0092
4	0.0166	0.0133	0.0035	0.0065	0.0098
8	0.0169	0.0134	0.0036	0.0065	0.0101
20	0.0181	0.0145	0.0035	0.0071	0.0107
80	0.0160	0.0125	0.0023	0.0078	0.0113

In Table 1, the maximum and minimum error obtained by calculating the different location and resistance are approximately 0.01 and 0.003%, respectively.

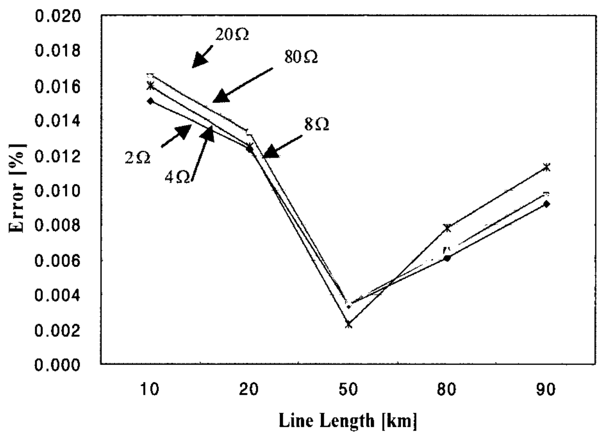


Fig. 10. Fault location error for various values of fault resistance

As shown in Table 1 and Fig. 10, the error increases in small fault resistance cases. However, the calculated results are sufficiently accurate for most tested cases.

From Table 1 and Fig. 10, it is evident that, for different fault location and resistance, the calculated fault distances are very accurate.

3.2 Case 2: With Shunt Capacitance

The line parameters for this case are: r =0.1 $[\Omega/km]$, x=0.36 $[\Omega/km]$, r_0 =0.25 $[\Omega/km]$, x_0 =0.6 $[\Omega/km]$, c =3.0 $[\mu F]$, and c_0 =2.0 $[\mu F]$. Sequence impedance of network A are: Z_{Ap} =5+j13Ω, Z_{An} =4+j10Ω, and Z_{A0} = 3+j6Ω. Sequence impedance of network B are: Z_{Bp} =5+j18Ω, Z_{Bn} = 4+j14Ω, and Z_{B0} = 3+j19Ω. The equivalent electromotive forces of networks A and B are E_A = 133 kV and E_B = 100 kV, respectively.

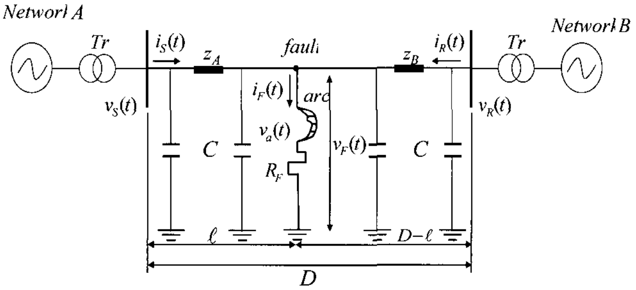


Fig. 11. Schematic of the test power system (with shunt capacitance)

For the transmission line (200, 300km), the results of the new two-terminal algorithm for different fault points are shown in Tables 2 and 3. Here, the first column of the table specifies the fault location in percent from bus S. The second and last column are the results of the two-terminal algorithm estimated using a simple impedance model (i.e., without shunt capacitance) and a Π line model (i.e., with shunt capacitance).

Table 2. Calculated fault distance for the different fault point on the line (D=200km)

Fault Point [km]	Without Shunt		With Shunt	
	Estimated [km]	Error [%]	Estimated [km]	Error [%]
20	18.4806	0.7597	20.085	0.0426
50	48.5588	0.7206	50.064	0.0320
100	100.168	0.0840	99.9191	0.0404
150	152.179	1.0895	149.713	0.1435
180	182.740	1.3700	179.613	0.1935

Table 3. Calculated fault distance for the different fault point on the line (D=300km)

Fault Point [km]	Without Shunt		With Shunt	
	Estimated [km]	Error [%]	Estimated [km]	Error [%]
10	6.75676	1.0811	10.1896	0.0632
20	16.0836	1.3055	20.1773	0.0591
50	45.1420	1.6193	50.1411	0.0470
100	96.6154	1.1282	100.011	0.00377
150	150.588	0.1960	149.730	0.0900
200	205.118	1.7060	199.325	0.2250
250	257.858	2.6193	248.956	0.3480
280	287.575	2.5247	278.886	0.3713

Tables 2 and 3 show that the maximum and minimum error calculated for cases without and with shunt capacitance are approximately 0.3 and 0.003%, respectively.

The errors of estimated fault location with long line are shown in Fig. 12.

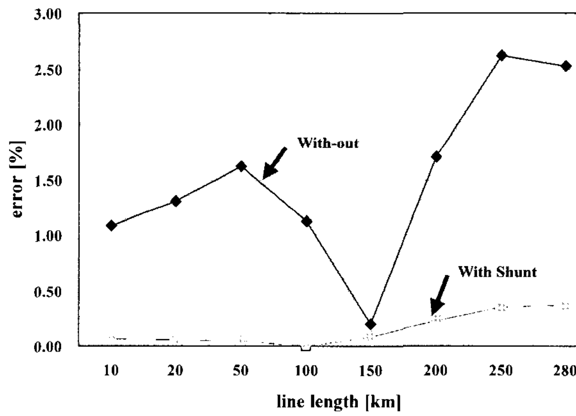


Fig. 12. Errors of estimated fault location

From the results presented in Table 2, 3 and Fig. 12, accurate compensation for long lines should be considered to develop fault algorithm. Through the analysis for the various case studies, the errors of fault location estimation are reduced when the shunt capacitance is considered.

4. Conclusion

This paper presents a new numerical algorithm for fault distance calculation. The proposed two-terminal algorithms use the synchronized phasor information measured from the assumed PMUs installed at two terminals of the transmission lines. The fault distance can also be solved by using a Π parameter line model and simple impedance model. Without shunt capacitances at the fault distance are known, with shunt capacitance considering fault distance can be easily obtained. In this paper, the proposed algorithm is based on direct solution of a set of differential equations, and therefore, provides accurate results. In the case of a long line model, in order to obtain the more accurate result, shunt capacitance is considered in this algorithm.

From the algorithm speed and accuracy point of view, the results obtained confirm that the algorithm is useful for the application to real transmission line protection.

Acknowledgement

This work is supported by the Korea Ministry of Commerce, Industry and Energy (MOCIE) and Korea Electric Power Research Instituted (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, 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 Tran. On the PAS*, Vol. PAS-104, No. 2, pp.424-436, Feb. 1985.

[3] M. Sant and Y. Paithankar, "One Line Digital Fault Locator for Overhead Transmission Line", *IEE Preceedings*, 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 1: Theory and Algorithm", *IEEE Trans. On Power Deliver*, 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 2: Performance Evaluation", *IEEE Trans. on Power Deliver*, Vol. 19, No. 4, pp. 1587-1593, Oct. 2004.

[6] J. G. McNeff, "The Global Positioning System", *Microwave theory and Techniques, IEEE Transaction on*. Vol. 50, Issue 3, pp. 645-652, March 2002.

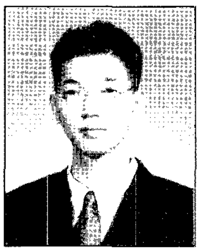
[7] R.O. Burnett, M.M. Butts, and P.S. Sterlina, " Power System Applications for Phasor Measurement Units", *IEEE Computer Applications in Power*, Vol. 7, No. 1, pp. 8-13, 1994.

[8] H. Lee, A.M. Mousa, "GPS traveling wave fault locator system investigation into the anomalous measurements related to lightning strikes", *IEEE Transaction on Power Delivery*, Vol. 11, Issue 3, pp.1214-1223, July 1996.

[9] C.J. Lee, H.H. Kim, J.B Park, J.R. Shin, Zoran Radojevic, "An Improved Two-Terminal Numerical Algorithm of Fault Location Estimation and Arcing Fault Detection for Adaptive AutoReclosure", *Trans KIEE*, Vol. 54A, No. 11, pp.525-532, Nov, 2005.

Hyun-Houng Kim
He received his B.E. degree from Jeonju University, South Korea, in 2004, and his M.S. degree from Konkuk University, South Korea, in 2006, respectively. He is currently working toward his Ph.D. degree in Electrical Engineering from Konkuk University.

Yun-Won Jeong
He received his B.E. degree from Konkuk University, South Korea, in 2002, and his M.S. degree from Konkuk University, South Korea, in 2004, respectively. He is currently working toward his Ph.D. degree in Electrical Engineering from Konkuk University.



Chan-Joo Lee
He received his B.E. degree from Anyang University, South Korea, in 2000, and his M.S. and Ph. D. degree from Konkuk University, South Korea, in 2002 and 2006, respectively. Since 2006 he has worked as a market analyst in the power trading team at K-Power, Korea. His research interests are economics studies and power system planning.

Jong-Bae Park

He received his B.E., M.S. and Ph.D. degrees in Electrical Engineering from Seoul National University, South Korea, in 1987, 1989, and 1998, respectively. From 1989-1988, he worked as a researcher at Korea Electric Power Corporation (KEPCO), and since 2001 he has been an assistant professor at Konkuk University, Korea. His research interests are power system planning and economic studies.

Joong-Rin Shin

He received his B.E., M.S., and Ph.D. in Electrical Engineering from Seoul National University, South Korea, in 1977, 1984, and 1989, respectively. Since 1990, he has been with the Department of Electrical Engineering, Konkuk University in Seoul, Korea, where he is currently a professor. His major research fields are power system analysis, power system planning and reliability evaluation.