484 *Journal of Electrical Engineering & Technology, Vol. 3, No. 4, pp. 484~490, 2008*

# Ungrounded System Fault Section Detection Method by Comparison of Phase Angle of Zero-Sequence Current

**Xia Yang†, Myeon-Song Choi*, Seung-Jae Lee*, Il-Hyung Lim***
**and Seong-Il Lim****

**Abstract** – In this paper, an integrated fault section detection and isolation strategy is proposed based on the application of the Distribution Automation System (DAS) utilizing advanced IT and communication technologies. The Feeder Remote Terminal Unit (FRTU) has been widely used to collect data in the Korean distribution system. The achieved data is adopted in this method for detecting multiple fault types. Especially in the case of single phase-to-ground fault, the fault section is detected by comparison of the zero-sequence current phase angle. The test results have verified the effectiveness of the proposed method in a radial distribution system through extensive simulations in Matlab/Simulink. Furthermore, a communication-based demo system identical to the simulation model has been developed, and it can be applied as an online monitoring and control program for fault section detection and isolation.

**Keywords:** DAS, Distribution System, Fault Section Detection, FRTU, Ungrounded System

## 1. Introduction

The ungrounded system can be defined as a system having no intentional ground connection between the phase conductors and ground. In reality, the ungrounded system is actually capacitively grounded as a result of the capacitance coupling between the energized components of the distribution system and ground [1]. Unlike solidly-grounded systems, ungrounded power systems can be used to keep a high continuity of service and minimize costly production process interruptions. Because there is no return path for fault current when a single phase-to-ground fault occurs, due to the capacitive coupling there is usually very little current flowing, especially in the case of low voltage distribution systems, so equipment damage is minimal and it is not necessarily essential to isolate the faulted area rapidly.

In some countries such as China and Japan, many medium voltage distribution networks employ an ungrounded system to reduce outages caused by single phase-to-ground fault. However, the detection of single phase-to-ground fault in the ungrounded system is very difficult. So far some techniques have been put forward with a focus on this issue, but there are still certain deficiencies on them. In [2], a fault section detection method using fault generated transient zero-sequence current is presented. This method requires detecting and comparing peak value of the transient current. Nevertheless, the peak value cannot make full use of the transient signal and is subject to influence of noise although transient true RMS value is adopted to ensure the detection reliability. Recently, a specialized frequency signal injection method has been adopted to detect the fault section [3], however it requires many manual operations to be carried out, which cannot meet the requirements of the DAS application.

The proposed algorithm is dedicated in presenting an integrated fault section detection and isolation strategy based on the DAS application utilizing advanced IT and communication technologies. So far FRTU has been widely spread to collect data in the Korean distribution system. In this method, the achieved data is used for detecting multiple fault types such as single phase-to-ground fault, phase-to-phase fault, as well as open-circuit fault. Furthermore, according to our previous studies [4, 5], a demo system based on the same simulation model has been developed using the Manufacturing Message Specification (MMS) communication in the IEC 61850 standard. Therefore, it demonstrates that the proposed method can be applied as an online monitoring and control program.

The remainder of the paper is organized in three sections. Section 2 elaborates the criteria of the faulted feeder selection and the fault section detection with consideration of multiple fault types and also takes into account all of the procedures of fault section detection and isolation that have been proposed. Section 3 provides extensive case studies to verify its effectiveness. The conclusion is given in Section 4.

---

† Corresponding author: Dept. of Electrical Engineering, Myongji University, Korea. (xiayang@mju.ac.kr)

* Dept. of Electrical Engineering, Myongji University, Korea. (mschoi@mju.ac.kr, sjlee@mju.ac.kr, sojoo2jan@mju.ac.kr)

** Dept. of Electrical and Electronic Engineering, KyungNam University, Korea. (slim@kyungnam.ac.kr)

Received 2 November, 2007; Accepted 13 June, 2008

## 2. Proposed Algorithm

Fig. 1 shows a typical ungrounded distribution feeder. When a single phase-to-ground fault occurs, all phase-to-phase distributed capacitances are short. The phase-to-ground distributed capacitances primarily determine ground fault current magnitude that is relatively small.

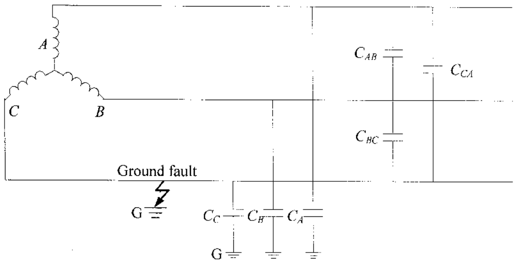


**Fig. 1.** Single phase-to-ground fault in the ungrounded system

But the phase-to-neutral voltages at the healthy phases increase essentially by $\sqrt{3}$, thus the ungrounded system requires the insulation capability in a phase-to-phase voltage level. Moreover, both the magnitude and phase angle of phase-to-phase voltages ($V_{AB}$, $V_{BC}$, and $V_{CA}$) do not change in both pre-fault and post-fault condition [6].

### 2.1 Faulted Feeder Selection

Although some approaches have been put forward for faulted line selection, there are still unsolved problems with them. In [7-9], Wavelets technology has been widely used, but it is very difficult to select the suitable Wavelet bases when analyzing the determinate signal. Another method comparing the similitude power of the lines has been adopted [10] as well. However, the analysis of the signal is complex and the calculation is very intricate. Therefore, in this paper a conventional and simple method is introduced according to the angular relationship between zero-sequence current of the feeder and zero-sequence voltage of the system.

Fig. 2 illustrates an ungrounded power system with a solid $C$ phase-to-ground fault at Feeder 3. In this case, zero-sequence voltage of the system is equal to the phase-to-neutral voltage at the normal condition. If zero-sequence current at each feeder is in phase, then the fault occurs in the busbar; if zero-sequence current at each feeder is reverse in polarity, then the fault occurs at one of the feeders. In addition, zero-sequence current of the faulted feeder is equivalent to the sum of capacitance current of the whole network excluding the faulted feeder, while zero-sequence current of the healthy feeder is the sum of its own three-phase currents. Zero-sequence current of the faulted feeder flows from the fault point to the busbar, while that of the healthy feeder flows from the busbar to the other end of the feeder. Hence, zero-sequence current of the faulted feeder is higher than that of the healthy feeder in magnitude.

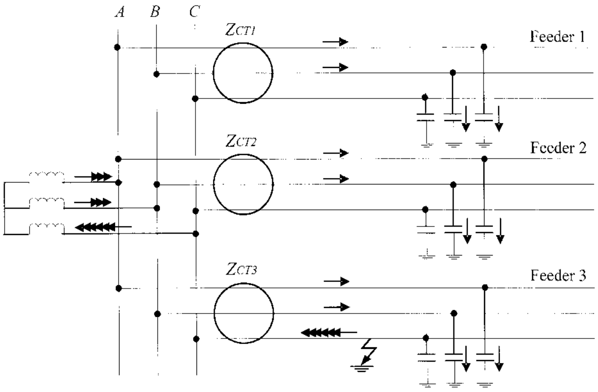


**Fig. 2.** A multi-feeder ungrounded system

Fig. 3 depicts the criterion of the faulted feeder selection: zero-sequence current of the healthy feeder leads zero-sequence voltage of the system by 90°, while zero-sequence current of the faulted feeder lags zero-sequence voltage of the system by 90°.

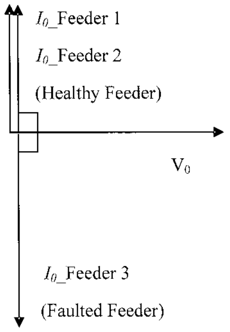


**Fig. 3.** Criterion of faulted feeder selection

### 2.2 Fault Section Detection

In the Korean distribution system, zero-sequence voltage can be measured by Grounding Potential Transformer (GPT) in the substation, and zero-sequence current can be achieved by FRTU. Note that the data should be obtained synchronously in the network. The proposed fault section detection method is based on the analysis of the phasor relationship between phase-to-phase voltage and zero-sequence current at each node. Fig. 4 shows the direction of zero-sequence current at each feeder when a single phase-to-ground fault occurs in an ungrounded system. At the faulted feeder, the direction of zero-sequence current at the upstream nodes of the fault point is in reverse with that at the downstream nodes of the fault point. Note that the upstream side is from the fault point up to the busbar, and the downstream side is from the fault point down to the receiving-end of the feeder.

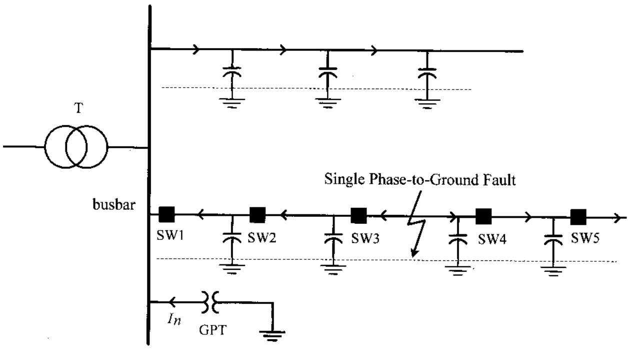


**Fig. 4.** Direction of zero-sequence current in the feeders

Due to the aforementioned discussion, the magnitude and phase angle of the phase-to-phase voltages are not changed in both pre-fault and post-fault condition, so any one of the phase-to-phase voltages can be adopted as a standard reference, which is used to compare with the phase angle of zero-sequence current.

Assume that $\theta^k$ is the phase angle difference between phase-to-phase voltage and zero-sequence current at node *k*.

$$\theta^k = \angle V_{LL}^k - \angle I_0^k \tag{1}$$

$\theta_{Diff}^k$ is the difference between $\theta^{k-1}$ and $\theta^k$.

$$\theta_{Diff}^k = \theta^{k-1} - \theta^k \tag{2}$$

If $\theta_{Diff}^k$ is 180° between node (*k*-1) and node *k*, then it indicates the single phase-to-ground fault occurs between the two nodes.

In practice, the measurement error of phase-to-phase voltage and zero-sequence current should be taken into account, so an amendment value $\beta$ will be compensated into $\theta_{Diff}^k$, which turns $180° \pm \beta$. Fig. 5 shows the criterion for the operation area and non-operation area.

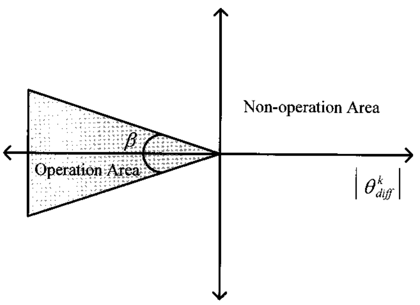


**Fig. 5.** Criterion of fault section detection

Phase-to-phase fault and open-circuit fault have also been analyzed.

Fig. 6 depicts that phase *B* to phase *C* short-circuit fault occurs in an ungrounded system.

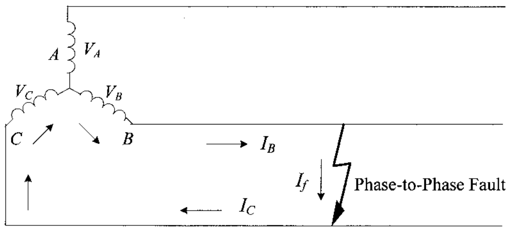


**Fig. 6.** Phase-to-phase fault in ungrounded system

Since both the fault point and the generator neutral are not grounded, there is no zero-sequence current in the system. However, the current magnitude at phases *B* and *C* significantly increase to a value as shown in (3), which is based on unsymmetrical fault calculations [11].

$$I_B = -I_C = \frac{-j\sqrt{3}V_A}{Z_1 + Z_2 + Z_f} \tag{3}$$

Where, $Z_1$, $Z_2$ are positive, negative-sequence impedances, respectively, and $Z_f$ is fault impedance. So if at node *k* the current magnitudes at any two phases are the same as (3), and at node (*k*+1) the current magnitude at the two phases is less than its normal-state value, then it demonstrates that the fault section is between node *k* and node (*k*+1). In practice, the overcurrent protective relays at phase *B* and phase *C* will trip due to the significant current magnitude.

In Fig. 7, an open-circuit fault occurs in phase *C*. The magnitudes of phase-to-phase voltages ($V_{BC}$ and $V_{CA}$) would be decreased to the magnitude of phase-to-neutral voltage if they are seen from the downstream side of the fault point. In general, if the magnitudes of any two phase-to-phase voltages are decreased to phase-to-neutral voltage magnitude at node *k*, it demonstrates that the fault section is between node (*k*-1) and node *k*.

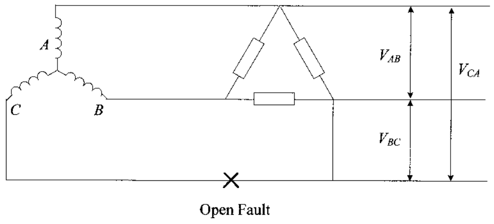


**Fig. 7.** Open-circuit fault in ungrounded system

## 2.3 Proposed Procedures in DAS

The DAS enables an electric utility to monitor, coordinate, and operate distribution components in a real-time mode from the distribution control center (DCC). The

DAS is based on an integrated technology, which involves collecting data, analyzing information to make control decisions, and implementing the appropriate control decisions in the field.

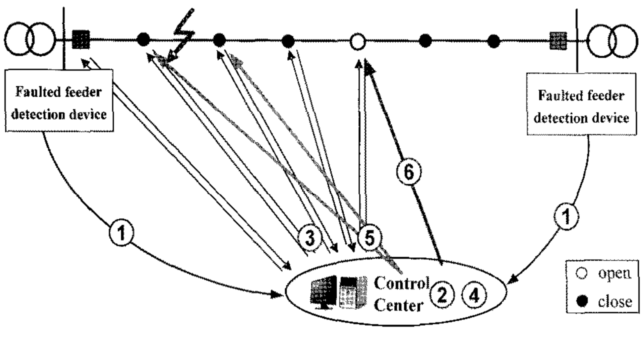


**Fig. 8.** Proposed Procedures in DAS

Fig. 8 shows a simple distribution system where each node is connected with one FRTU, respectively; the faulted feeder detection device is installed at the beginning end of the feeders; and the control center can communicate with each FRTU to collect data.

In the case of a single phase-to-ground fault, the following procedure is proposed:

(1) Faulted feeder selection through faulted feeder detection devices;
(2) System topology searching in the faulted feeder;
(3) Control center requests the data from FRTUs;
(4) Detect fault section based on the proposed algorithm;
(5) Open the switches to isolate the faulted area;
(6) Start up the restoration program.

As for phase-to-phase fault detection based on the same DAS topology and communication system, the control center requests the data of the phase current magnitude from FRTU at each node periodically. Once it indicates that a fault has occurred in the system through the data analysis, the fault section can be found according to the criterion. At the same time, the control center also keeps requesting the data of the phase-to-phase voltage magnitudes from FRTU at each node periodically in order to detect open-circuit fault. Compared with the single phase-to-ground fault detection procedure, phase-to-phase fault and open-circuit fault detection procedure starts from the third step. To sum up, the communication-based proposed method can be applied as an online monitoring and control program to isolate the fault section while taking into account multiple fault types.

## 3. Case Study

A simulation model is demonstrated in Fig. 9. This radial distribution system consists of four feeders, in which there are four circuit breakers and five switches. Moreover, a control center has been developed in the demo system.

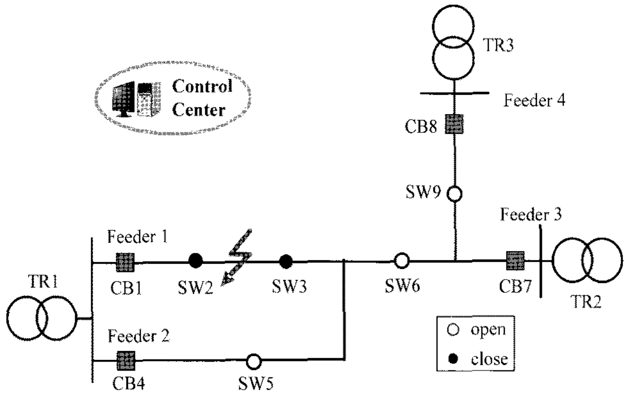


**Fig. 9.** Demo System

In Matlab/Simulink simulations, assume that a fault occurs between SW2 and SW3 in the system based on 10kV/50Hz; the total simulation time is 0.2s and the fault starts at 0.1s. The measured data at each node can be achieved. In practice, those circuit breakers (CB) and the switches are supposed to connect with the FRTU at each node. In the test demonstrations, each FRTU is simulated by a PC. The communication system is based on the application of MMS in the IEC 61850 standard. The control center can communicate with all FRTUs synchronously to collect the data and then analyze the achieved data to detect fault section. Afterwards, the control center downloads the corresponding restoration program and carries it out.

### 3.1 Test for Single Phase-to-Ground Fault

Phase $C$ to ground fault occurs between SW2 and SW3. Table 1 shows the data at the time of 0.126s since there is significant transient oscillation during the first cycle (0.02s) after a fault occurs at 0.1s. Note that the proposed method requires steady state post-fault voltage and current data. The data in Table 1 can be analyzed to determine the faulted feeder. The magnitude of zero-sequence voltage $V_0$ at Feeder 1 and Feeder 2 is 8114.3V, which is close to the phase-to-neutral voltage of the normal condition. It indicates that a single phase-to-ground fault occurs. The phase angle of $V_0$ at Feeder 1 and Feeder 2 is -30.311°, but the magnitude of $V_0$ at Feeder 3 and Feeder 4 is almost near 0, so its phase angle is meaningless. As such it can determine that fault occurs at either Feeder 1 or Feeder 2. Further, zero-sequence current $I_0$ at Feeder 2 leads $V_0$ by 91.006°, while $I_0$ at Feeder 1 lags $V_0$ by 88.989°. Therefore, Feeder 1 is the faulted feeder.

**Table 1.** Simulation results for faulted feeder selection

| Data type | Feeder (CB) | Magnitude | Phase Angle |
|---|---|---|---|
| $V_0$ | Feeder 1(CB1) | 8114.3V | -30.311° |
| | Feeder 2(CB4) | 8114.3V | -30.311° |
| | Feeder 3(CB7) | 1.85e-9 | - |
| | Feeder 4(CB8) | 8.75e-10 | - |
| $I_0$ | Feeder 1(CB1) | 0.030 A | -119.3° |
| | Feeder 2(CB4) | 0.030 A | 60.695° |
| | Feeder 3(CB7) | 3.74e-15 | - |
| | Feeder 4(CB8) | 3.89e-16 | - |

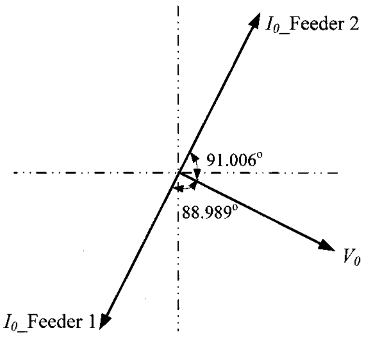


**Fig. 10.** Phasor diagram for faulted feeder selection

**Table 2.** Simulation results for fault section detection

| SW(CB)<br>Angle | CB1 | SW2 | SW3 |
|---|---|---|---|
| $V_{AB}^k$ | 60° | 59.768° | 59.601° |
| $I_0^k$ | -119.3° | -119.39° | 60.494° |
| $\theta^k = V_{AB}^k - I_0^k$ | 179.3° | 179.158° | -0.89° |
| $\theta_{Diff}^k = \theta^{k-1} - \theta^k$ | - | 0.142° | 180.048° |

As shown in Table 2, the phase angle difference between node 2 and node 3 is 180.048°, so it can be determined that the fault section is between SW2 and SW3 due to the fault section detection criterion. Note that although the phase-to-phase voltage $V_{AB}$ is chosen as a standard reference here, the other phase-to-phase voltage, $V_{BC}$ or $V_{CA}$, can be chosen as a standard reference as well and it will achieve the same result.

### 3.2 Test for Phase-to-Phase Fault

In the demonstration, phase $B$ to phase $C$ short-circuit fault occurs between SW2 and SW3. The fault current magnitude can be pre-estimated by (3). In this case, the estimated value is 5700 A, which is the boundary value.

**Table 3.** Simulation results for phase-to-phase fault

| Data Type | CB1 | SW2 | SW3 |
|---|---|---|---|
| $I_A$(A) | 63.294 | 45.15 | 27.07 |
| $I_B$(A) | 5679.2 | 5669.3 | 13.623 |
| $I_C$(A) | 5638.2 | 5640.1 | 13.447 |

The simulation results are listed in Table 3. At node 1 and node 2, the current magnitude at phase $B$ and $C$ nearly increases to the boundary value, while at node 3 the current magnitudes at phase $B$ and $C$ significantly reduce. Therefore, it demonstrates that the fault section is between SW2 and SW3.

### 3.3 Test for Open-Circuit Fault

In the demonstration, an open-circuit fault in phase $C$ occurs between SW2 and SW3. As shown in Table 4, the magnitudes of phase-to-phase voltages, $V_{BC}$ and $V_{CA}$, at node 3 nearly decrease to the phase-to-neutral voltage, while $V_{BC}$ and $V_{CA}$ at node 1 and node 2 are almost unchanged. Therefore, the fault section is between SW2 and SW3.

**Table 4.** Simulation results for open-circuit fault

| Data Type | CB1 | SW2 | SW3 |
|---|---|---|---|
| $V_{AB}$(V) | 14142 | 14072 | 14022 |
| $V_{BC}$(V) | 14142 | 14092 | 7006.1 |
| $V_{CA}$(V) | 14142 | 14127 | 7015.4 |

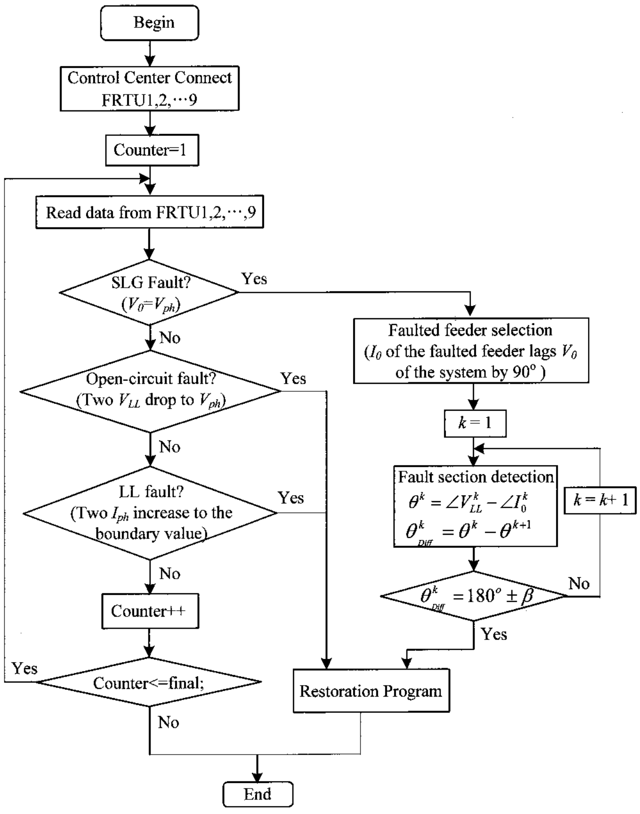


**Fig. 11.** Flowchart

Fig. 11 indicates the flowchart of the entire procedures based on the developed demo system. The final result is demonstrated in Fig. 12. The control center keeps requesting data from the FRTU at each node periodically.

As long as the data analysis indicates that a fault has occurred, the fault section detection method will be carried out. Afterwards, the restoration program will be performed. As shown in the demo system, SW2 and SW3 are open, and SW5 is closed. Moreover, a monitoring system has been developed to detect the status of the circuit break or the switch at each node.

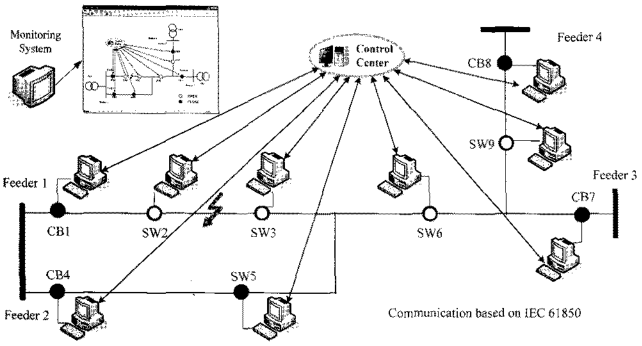


**Fig. 12.** The demo system with a monitoring system after fault section isolation

## 4. Conclusion

A communication-based fault section detection and isolation method is proposed for an ungrounded system. The FRTU plays an important role in DAS to collect data that is adopted in the proposed method for detecting multiple fault types. The extensive simulation results have verified its effectiveness. The developed demo system shows its great capability to be used as an online monitoring and control program for fault section detection and isolation, which helps to improve grid operation and maintenance of the distribution network.

## Acknowledgements

This work was supported by the ERC program of MOST/KOSEF (Next-generation Power Technology Center) and the Ministry of Commerce, Industry and Energy for their support through the development program of the Intelligent Distribution Management System.

## References

[1] Raymond O. D. Whitt, "Trends and practices in grounding and ground fault protection using static devices", *IEEE Transactions on Industry Applications*, Vol. IA-9, Issue 2, March, 1973.

[2] Bingyin Xu, Yongduan Xue, Jing Li, Yu Chen, "Single phase fault detection technique based on transient current and its application in non-solid grounded network", *IEE conference in Developments in Power System Protection*, No. 479, 2001.

[3] Pan Zhengcun, Zhang Huifen, Zhang Fan and Sang Zaizhong, "Analysis and Modification of Signal Injection Based Fault Line Selection Protection", *Automation of Electric Power Systems*, Vol. 31 No. 4, Feb. 25, 2007.

[4] Xia Yang, Seong-Il Lim, Seung-Jae Lee, Myeon-Song Choi, "Communication-based Fault Handling Scheme for Ungrounded Distribution System", *Energy and Power Systems (EPS2006)*, March, 2006.

[5] Qiang Guan, Myeon-Song Choi and Seung-Soo Han, "IEC61850 Based FRTU Development Scheme", *KIEE summer conference*, July 2007.

[6] J. Lewis Blackburn, Thomas J. Domin, *Protective Relaying: Principles and Applications, Third Edition (Power Engineering)*, pp. 191-195, CRC, 2006.

[7] Hong-chun Shu, Bai Xiao, "A novel fault line selection algorithm of single-phase ground faults in ungrounded neutral system using wavelets transform", *PowerCon 2002*, Vol. 4, pp. 2532-2536, Oct. 2002.

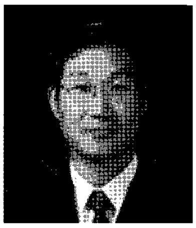
[8] Qianli Su, Xinzhou Dong, Shenxing Shi, Bin Su, Jiali He, "A new principle of fault line selection for distribution", *IEE Seventh International Conference on Developments in Power System Protection*, pp. 379-382, April 2001.

[9] Zheng Qi, Yihan Yang, "Study on line selection in non-effectively grounded system based on wavelet transform and Wiener filter", *IEEE Power Engineering Society General Meeting*, Vol.1, pp. 89-93, June 2004.

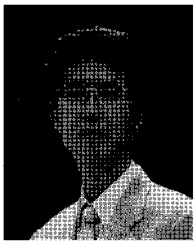
[10] Chengyong Zhao, Yanfen Guo, Gengyin Li, "The similitude power detection on singlephase-to-ground fault in the non-solidly grounded system", *IEEE/PES Transmission and Distribution Conference & Exhibition: Asia and Pacific Dalian, China*, 2005.

[11] J. C. Das, *Power System Analysis - Short-Circuit Load Flow and Harmonics*, pp. 42-43, Marcel Dekker, Inc. 2002.

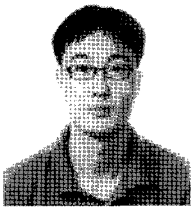
**Xia Yang**
She received her B.S. in Information Science and Engineering from Northeastern University, Shenyang, China in 2002 and her M.S. in Electrical Engineering from Myongji University, Yongin, Korea in 2004. Currently, she is pursuing her Ph.D. degree at Myongji University. Her major research fields are power system protection, automation, and control.



**Myeon-Song Choi**
He received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from Seoul National University, Korea, in 1989, 1991, and 1996, respectively. He was a Visiting Scholar at Pennsylvania State University in 1995. Currently, he is a Professor at Myongji University. His major research fields are power system control and protection including artificial-intelligence application.



**Seung-Jae Lee**
He received his B.S. and M.S. in Electrical Engineering from Seoul National University, Korea, in 1979 and 1981, respectively, and his Ph.D. from the University of Washington, Seattle, USA, in 1988. Currently, he is a Professor at Myongji University and Director of NPTC (Next-generation Power Technology Center). His major research fields are protective relaying, distribution automation, and AI applications to power systems.



**Il Hyung Lim**
He was born in Seoul, Korea, in 1979. He received his B.S., and M.S. degrees in Electrical Engineering from Myongji University, Yongin, Korea in 2007. He is now working towards his Ph.D. at Myongji University. His research interests are power system control and protective relaying, including artificial intelligence application.

**Seong-Il Lim**
He received his B.S., M.S. and Ph.D. degrees in Electrical Engineering from Myongji University, Korea in 1994, 1996, and 2004, respectively. He worked for the Korea Electric Power Research Institute, Daejeon, Korea for 6 years. He is currently an Assistant Professor in the Department of Electrical Engineering, Kyungnam University, Korea. His main research areas are protective relaying and power system automation.