J Electr Eng Technol Vol. 8, No. 5: 969-974, 2013
http://dx.doi.org/10.5370/JEET.2013.8.5.969

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Automatic Protection Schemes for Distribution System with Open and Closed-loop

Kang-le Guan*, Seung-Jae Lee* and Myeon-Song Choi†

Abstract – Protection issues in distribution systems which are to be operated in open and closed-loop modes in a smart grid are studied and a generalized protection setting method is proposed to meet the new requirements. The developed setting method assumes a conventional over-current protection scheme for the system with reclosers and over-current relays. In a closed-loop mode, it identifies protective devices that have to be sacrificed in order to maximize protection coordination for bi-directional fault current flow. The proposed setting method has been tested on many systems with different complexity and is proved effective.

Keywords: On-line system analysis, Over-current protection, Closed-loop distribution system

1. Introduction

With the rapid development of modern industry, nowadays the power system is expected to provide higher reliability to avoid the losses caused by even a temporary power outage. One way to ensure the reliability, which is popular and being extensively studied by the electrical engineers, is to connect the current radial distribution system, as well as integrating DG sources to realize closed-loop operation distribution system [1, 2]. And thus the concept of smart grid was proposed to describe it.

Apparently, besides the reliability improvement there are more benefits that we can obtain from the smart grid. In smart grid, more renewable power can be utilized, higher energy efficiency can be achieved and more advanced IT technologies would be adopted and so forth. The smart grid including the corresponding protection techniques have been widely studying nowadays [3, 4]. To be simple and specific, in this paper, only the new protection issues of the distribution systems with open and closed-loop rather than the actual smart grid will be discussed.

The conventional protection theories have been well studied in the past [5], but in the distribution systems with open and closed-loop, some new issues appear and should be considered carefully [6-8].

In this paper, new protection issues in the distribution system with open and closed-loop will be discussed in detail. And to realize the generalized coordination setting method, the solutions for each problem will be proposed. Section 2 describes the new systems briefly with a sample system. Section 3 presents the new protection problems and proposes the solutions. Section 4 introduces the generalized setting method. Section 5 gives a case study as well as the result verification and at last section 6 comes up with conclusions.

2. Distribution System with Open/Closed-loops

A typical distribution system with loops is shown in Fig. 1. It is realized by connecting several conventional radial feeders and allowing open and closed-loop operation mode.

In the example system, the original radial feeders supported by substations S/S #1, S/S #2 and S/S #3 separately are connected by tie switches T1, T2, and T3 to improve service reliability. Relay1, 2 and 3 are the over-current relays combining with circuit breakers (OC(G)R/CB) which are used to protect the substations. The devices P1 to P7 denote the protective devices (OC(G)R or recloser) in the feeder.

These devices sectionalize the feeder into several parts. And by selecting the right ones to clear the fault, the outage area can be limited to a minimal zone while faults appear. Each device shall coordinate with its backup devices satisfying the requirements between their operating curves (inverse-time curve) in both direction (except Relay 1, 2 and 3), thus the directional unit is necessary [9].

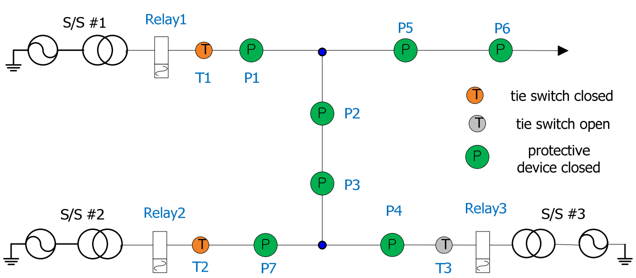

Fig. 1. A typical closed-loop distribution system

† Corresponding Author: Dept. of Electrical and Electronic Engineering, Myong-Ji University, Korea. (mschoi@mju.ac.kr)
* Dept. of Electrical and Electronic Engineering, Myong-Ji University, Korea. (kleguan@hotmail.com, sjlee@mju.ac.kr)
Received: April 30, 2012; Accepted: April 3, 2013

Based on the over current protection theories [2, 3], the protection objective of such a system would be: (1) selectivity: limiting the outage area to be minimal when faults occur, (2) speed: clearing the fault as fast as possible, (3) sensitivity: detecting any prospective fault in its protection zone, and (4) reliability: no maloperation for the faults in the overlap zone.

In the distribution systems as shown in Fig. 1, the relay protection system faces new problems. Some important aspects that should be taken into account are summarized as following: (1) load increases when system runs from closed-loop mode to open mode after the tripping of protective devices, (2) fault current goes through the primary and backup devices may have marked difference, (3) coordination time interval is insufficient for too many protection devices in series, (4) one device coordinates with two or more backups, and (5) bi-directional load current and fault current. All of these mentioned problems will be analyzed in more details in the next section.

3. New Protection Problems and Solutions

To realize the protection system of the distribution systems with open and closed-loop, the new problems of the important aspects of the protection theory are studied carefully, and for every problem, a corresponding solution is proposed.

3.1 Bidirectional load current and fault current

The multiple source in the system will bring in bidirectional load current and fault current, thus the directional element for each protective device is necessary to guarantee that the protective devices will not operate while a normally load current or a reverse fault current goes through.

In order to cope with the fault current that may flow in both directions, the devices in the loop setting path should have two sets of setting. Only the excessive current in the tripping direction will start up the relay.

3.2 Maximum load current

After the radial systems are connected and the closed-loop is put into practice, the loads will be shared by the sources which are in service. And when the system operates normally, the load current passes each protective device is similar with the current under open loop operation mode. However, if fault occurs, it can change significantly and the protective devices should be capable of enduring such a condition.

For instance, if there is a short-circuit fault between Relay1 and P1 (the most severely condition) in Fig. 1, both Relay1 and P1 will trip to isolate the fault. Before a new closed-loop operating scheme has been carried out, all the loads will be carried by S/S #2 only, that means the load current will increase sharply. Therefore, the maximum load current that may go through a protective device in the closed-loop distribution systems should be the sum of all its downstream loads without regarding to the load sharing by the source in the other sides. This maximum load current is used to determine the lower limit of the pickup current of the relevant protective devices.

$$I_{pick\_up} \geq K_{\max\_load} \times I_{\max\_load} \qquad (1)$$

Here $K_{\max\_load}$ is the safety factor, and generally it is no less than 1.5 for phase fault and around 0.3 for phase-ground fault.

3.3 Fault current distribution

To assure that the protective devices will see all of the faults, the pickup current should be less than the possible minimum fault current that may happen in the protection zone. So one of the upper limits determined by the minimum fault current is:

$$I_{pick\_up} \leq K_{\min\_f} \times I_{\min\_f} \qquad (2)$$

Here $K_{\min\_f}$ is the safety factor, and generally it is 1.0 for phase fault and around 0.5 for phase-ground fault.

Usually the protection will extend into adjacent lines. But to set a protective devices which acts as the backup of the other one, the fault current goes through the backup and primary devices may differs significantly. In Fig. 2, P1 and P2 will back up for P5, the minimum fault current that should be detected by P1 and P2 has high possibility to occur at the end of the line after P5. However when we are setting P2, if Z2 >> Z1, the upper limit for P2 would be less than the lower limit determined by formula (1) and then P2 cannot be set. Such a situation is inevitable in the closed-loop distribution system so we cannot simply take it as a setting failure case.

To solve this problem, the minimal fault is assumed to be the fault current flowing through P2 when P1 is open. That is to say, when there is a fault in the primary protection zone of P5 and unfortunately, P5 fails to clear the fault due to some unpredictable reasons, P2 can start up after P1 tripped if it cannot detect the fault at the beginning. Distribution factor like $Z_2/(Z_1+Z_2)$ and $Z_1/(Z_1+Z_2)$ is

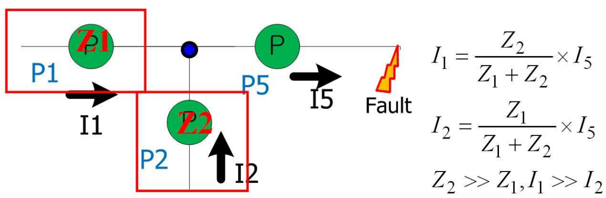

Fig. 2. Fault current distribution

necessary in calculating the fault current going through the backup ones with the fault current passing the primary one.

3.3 CTI Insufficient and devices sacrificing

In the distribution system, in order to insure the safety of the substation, generally the OC(G)R/CBs at the substation are required to clear the maximum short-circuit fault in no more than 30 cycles. Together with the coordination time interval (CTI) threshold between backup and primary devices, it is natural to understand that the CTI is insufficient for the protection devices in series.

And for automatic reclosers in series, the situation is more definite. A recloser has many groups of available curves [10], but usually it is difficult to achieve coordination if the backup and primary ones configured with the same curve. Generally if we select a group of the TCCs, we can coordinate at most three reclosers in series (with the upstream OC(G)R/CB protecting the substation). Taking KH-ESV (one type of reclosers) as an example, the possible setting series of curves and sequences if N1, N2, N3 and N4 are selected are listed in Table 1. In the table, F and D denote the fast and delay sequence respectively.

To set all the protective devices in series even if the CTI interval is insufficient, the proposed method is choosing the prior ones to set firstly and then set the ones of less priority by copying the setting of the previously set ones. At present there are two similar rules to determine the priority of the devices: (1) a higher load capacity generates higher priority; (2) the device along the feeder which is near the 50% point of the total load has a highest the priority, and then the 50% point of the two halves. In this paper we choose the first rule to realize the sacrificing strategy.

Table 1. Coordinating recloser (KH-ESV) in series

Depth	1		2		3	
Setting	Curve	Seq.	Curve	Seq.	Curve	Seq.
Series 1	N2N4	1F3D	N2N4	1F2D	N1N3	1F1D
Series 2	N2N4	2F2D	N1N3	2F1D	N1	2F
Series 3	N2N4	2F2D	N1N3	2F1D	\	\
Series 4	N2N4	2F1D	N1	2F	\	\
Series 5	N1N4	2F2D	\	\	\	\

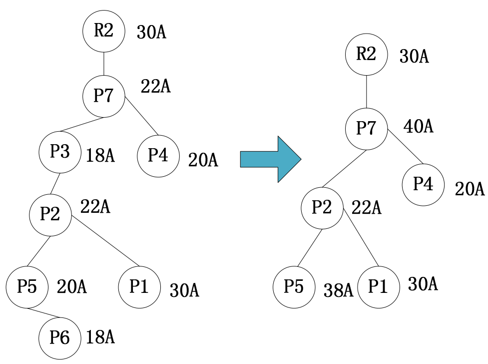

Fig. 3. Recloser sacrificing process

Take the system in Fig.1 as the example, with the section load given, the sacrificing procedure from S/S #2 is shown in Fig. 3.

3.4 Multi Backups for one protective device

As depicted in Fig. 4, in a closed-loop system, some devices like P5 would have more than one backups (here are P1 and P2), and with one set of setting it should be capable of coordinating with all its backups. In such a case, the primary device will be set according to every backup respectively. And then, remain the setting of the backups unchanged, but the fastest operating setting of the primary protective device will be searched and reloaded to it as the final setting. In this way, the CTI requirements between the primary and backup devices are all ensured.

In Fig. 4, Setting 1 is obtained by coordinating P5 with P1 (set previously), and Setting 2 is obtained by coordinating P5 and P2 (set previously). Then the two sets of setting will be compared and the faster one will be chosen.

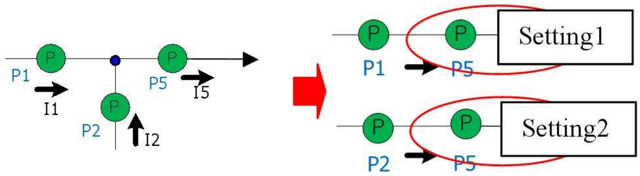

Fig. 4. Fastest setting selection

4. The Generalized Setting Method for ComputErized Automation

The system in Fig. 1 is referred to illustrate the algorithm. To be brief, the basic concepts of protection theories are omitted, and the protective devices in the systems are assumed to be OC(G)Rs and automatic circuit reclosers (Rec) only. The general processing flow of the setting method is shown by the flowchart in Fig. 5. All the procedures will handle with phase fault and ground fault respectively. And some vital procedures are discussed subsequently.

4.1 Setting paths analysis

A setting path uses a list to store the protective devices in sequence of connection. Each device is represented by a node which stores the information of it in the setting path, including its identifier, direction, and load current and so on.

The proposed protection scheme will first take each feeder in the system as radial feeders equivalently. From every substation which is in service, by traversing the system network, all the setting paths will be searched and stored separately. The setting paths are stored taking

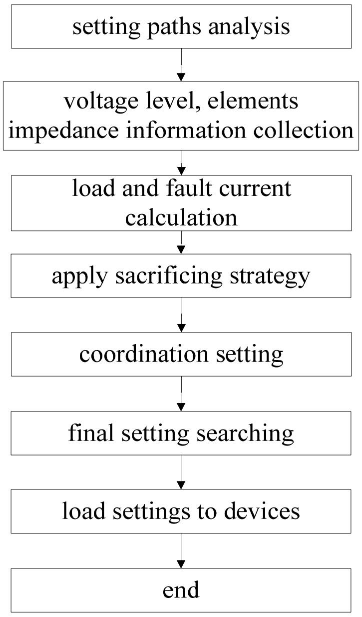

Fig. 5. The processing flow of the protection scheme

Table 2. The node in a setting path

Item	Contents
Flags	Identifier, head node etc.
Device data	Devices type, transformer ratio etc.
Measured data	Maximum load current fault currents etc.
Settings	Pickup current, operation curve etc.
Network data	Downstream nodes next node etc.

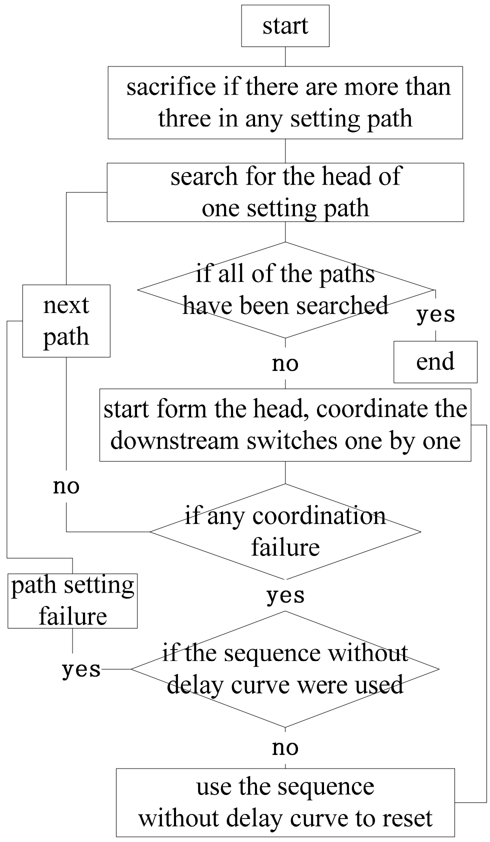

Fig. 6. The processing flow of setting reclosers

advantage of the tree data structure which is easy to be processed. And the node is actually an object of the protective device which contains necessary information for setting. Table 2 illustrates the contents of a node.

4.2 Current calculation

Refer to the theory discussed in Section 3.1 and 3.2, the load and fault current for one same protective device but in different direction is different. To calculate the load and fault current of each device in a setting path, the system is analyzed including the system configuration, voltage level, source impedances, and line impedances and so on. The maximum load which may go through the device is computed by summing all the downstream loads and fault current is calculated or measured.

4.3 Coordination setting

After all the setting paths are stored, the system is taken as a group of radial feeders, and each feeder is sectionalized by several protective devices. And then with the equivalent current data, the over-current based protection scheme for each feeder can be achieved.

In realizing an automatic setting program, to reduce the complexity and get the optimizing setting (selectivity and speed), the setting process will traverse every setting path twice. Taking use of the setting paths, for the first traverse, the coordination setting begins with a OC(G)R and one of its downstream reclosers, and then set the following downstream ones until the last one in the path is set. At this step, the maximum possible pickup which can offer maximal CTI margin is found for every protection device. For the second traverse, from the last ones in every setting path, reset them with the minimum possible operating value (less than the upper limit found in the previous step) to make the fault can be cleared as fast as possible.

The first traverse is vital because it determines whether the protection system can be coordinated successfully or not. The process of it for setting recloser in series is shown in Fig. 6. Here the setting sequences shown in Table 1 are used to set the reclosers. The last recloser in the series can have no delay curve if in the worst situation. In that case, if there is a fault occurred in the protection zone of the last recloser, after two fast operations (trip and reclose), the recloser will be locked out to clear the fault.

For instance, the setting order of the system shown in Fig. 1 would be: (1) first traverse, relay1, P1, P2, P3 and P4, P5, P6 and then P7, (2) second traverse, P7, P6, P5, P4 and P3, P2 and then P1. And so does the setting path from Relay2.

5. Case Study and Result Verification

The proposed setting method is realized using C++ program in this study. The input data of the program is documents specifying system configuration information and the necessary parameters of the devices and the outputs for each protective device are the setting values such as pickup and operating curve and so on.

A test on the system shown in Fig. 1 is demonstrated to verify the setting method. The recloser in the system is assumed to KH-ESV, which is one of the automatic reclosers produced by ABB. For such a type of recloser, operating curve (N1, N2, N3 and N4), sequence (fast (F) and delay (D)) and pickup all need to be set. Generally the popular automatic reclosers in the distribution system have same or similar time characteristic curves, so the setting procedure and result actual depend on the system configuration.

From S/S #1, assuming that the maximum load of each section is shown in Table 3. The section is the load connected to the line right after the protective device. The range of the fault current for each device determines the scope of its curve in the time-current coordinate system which can be seen from result verification figure (Fig. 7).

The setting result for each protective device not sacrificed is displayed in Table 4. Here HD denotes the head node which is used to mark the direction, Seq is the abbreviation of operating sequence, Ip,_fp and Ip,_fg denote the pickup current (A) for phase and ground fault respectively.

To verify the settings, the coordination curves of the devices in one path which are expected to coordinate with each other are plotted using MATLAB (Fig. 7).

Table 3. Section load of the protective devices

Protective Device	Section load(A)
Relay1	30
P1	22
P2	18
P3	22
P4	20
P5	20
P6	18
P7	30

Table 4. The setting result of the sample case

Device ID	HD	curve	Seq	Ip_fp	Ip_fg
R1(OCR)	10	\	\	480.0	90.0
P1(Rec)	1	N2N4	2F2D	432.0	81.0
P3(Rec)	3	N1N3	2F1D	280.8	72.9
P4(Rec)	4	N1	2F	77.2	65.6
P7(Rec)	4	N1	2F	119.3	65.6
P5(Rec)	2	N1	2F	71.3	65.6
R2(OCR)	11	\	\	480.0	90.0
P7(Rec)	8	N2N4	2F2D	432.0	81.0
P2(Rec)	3	N1N3	2F1D	356.4	72.9
P1(Rec)	2	N1	2F	71.3	65.6

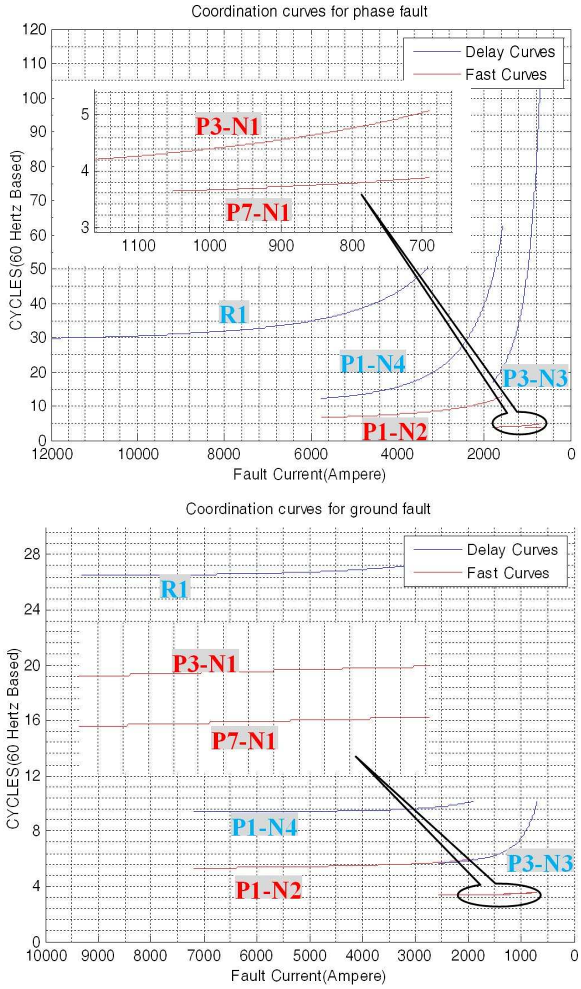

Fig. 7. Setting result verification

As depicted in Fig. 7, R1, P1, P2, P3 and P7 are in series around the loop. From S/S #1, P2 is sacrificed and all of the other reclosers were configured to coordinate with its backup. On the condition that the pickup of each device can see all the faults belong to its protection zone and less than the maximum normal current, as we can see from Fig. 7, the coordination can be achieved even the most severe situation is encountered. When the fault is in the overlapping zone, the primary device and backup may start up at the same time. But the former has a short time delay and will clear the fault several cycles (which is greater than the CTI limit) before the latter. If the primary device fails to clear the fault, then the backup will trip after a longer time delay.

For a permanent fault, the system configuration will be changed and the program can set the new system again with the new system information.

6. Conclusion

A generalized setting method of over current protection devices for distribution system with open and closed-loop is studied in this paper. The method takes account of all the basic factors in the over current protection theory, and analyzed the differences of these factors between the traditional distribution systems and the one with open and closed-loop. The method provides a generalized setting process of the distribution systems with open and closed-loop which is adaptive, reliable and easy to use. What is more, the clearance time of fault and the setting time are limited to the minimum level.

Acknowledgements

This work is supported by the Power Generation & Electricity Delivery of Korea Institute of Energy Technology and Planning (KETEP) grant funded by Korea government Ministry of Knowledge Economy (No. 2009T100200067).

References

[1] Wei-Tzer Huang and Shyi-Wen Wang, Ling-Yi Hong, "Nature and Operation Schemes of Normally Closed-loop Distribution Systems", *Control, Automation, Robotics and Vision*, 2008 10th International Conf.

[2] Ali Saidian and Davar Mirabbasi, "The Effect of Size of DG on Voltage Flicker and Voltage Sag in Closed-loop Distribution System", *Industrial Electronics and Applications (ICIEA)*, 2010 the 5th IEEE Conf.

[3] Yi Lv, Dahai You, Ke Wang and Liang Wang, "Study on Wide-area Backup Protection System for the Smart Grid", *Electric Utility Deregulation and Restructuring and Power Technologies (DRPT),* 2011 4th International Conf.

[4] Eric Sortomme and S.S. Venkata, "Microgrid Protection Using Communication-Assisted Digital Relays", *IEEE Transactions on Power Delivery,* Vol. 25, No. 4, 2010.

[5] J.Lewis Blackburn, *Protective Relaying-Principles and Applications*, 1987, pp. 390-422.

[6] Kun-Yuan Shen and Jyh-Cherng Gu, "Protection Coordination Analysis of Closed-Loop Distribution System", *PowerCon 2002 International Conference,* Vol. 2, pp.702-706.

[7] Bin Li, Xuan Yu and Zhiqian Bo, "Protecion schemes for closed loop distribution network with distributed generator", *Sustainable Power Generation and Supply,* 2009, International Conf.

[8] Ferry A. Viawan and Daniel Karlsson, "Various Protection Schemes for Closed Loop Feeders with Synchronous Machine Based Distributed Generation and Their Impacts on Reliability", *Power Tech, 2007 IEEE Lansanne,* pp. 1170-1175.

[9] Guibin Zou, Houlei Gao, Feng Zhu, "Realization scheme of directional unit protection based on travelling wave integral", *Electric Utility Deregulation and Restructuring and Power Technologies(DRPT),* 2011 4th International Conference.

[10] Charles V. Walker, *Electrical Distribution System Protection*, pp. 125-132.

Kang-Le Guan He received B.S. degree in Electrical Engineering and Automation from Huazhong University of Science & Technology, China in 2010. He received M.S. degree from Myongji University, Korea in 2012, majoring in power system in Electrical Engineering department. His research interests are power system relay protection and automation.

Seung-Jae Lee He is with the department of Electrical Engineering, Myongji University as a Professor since 1988. He is a Director of Next-Generation Power Technology Center. He received BS and MS degree from Seoul National University, Korea in 1979 and 1981 respectively and Ph.D. from University of Washington, Seattle, USA in 1988. His main research areas are protective relaying, distribution automation and AI applications to power systems.

Myeon-Song Choi He is a professor at Myongji University, Korea. He received the B.S., M.S. and Ph.D. degrees from Seoul National University, Korea in 1989, 1991 and 1996, respectively. He was a visiting fellow at Pennsylvania State University in 1995. His research interest is on power system control and protection.