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Distribution System Reconfiguration Considering Customer and DG Reliability Cost

Sung-Min Cho*, Hee-Sang Shin*, Jin-Hyun Park and Jae-Chul Kim†**

Abstract – This paper presents a novel objective function for distribution system reconfiguration for reliability enhancement. When islanding operations of distributed generators is prohibited, faults in the feeder interrupt the operation of distributed generators. For this reason, we include the customer interruption cost as well as the distributed generator interruption cost in the objective function in the network reconfiguration algorithm. The network reconfiguration in which genetic algorithms are used is implemented by MATLAB. The effect of the proposed objective function in the network reconfiguration is analyzed and compared with existing objective functions through case studies. The network reconfiguration considering the proposed objective function is suitable for a distribution system that has a high penetration of distributed generators.

Keywords: Novel reliability cost, Distribution system reconfiguration, Composite cost, Distributed generator reliability cost

1. Introduction

Power utilities are interested in ways to improve distribution system reliability. As sensitive loads have increased in recent times, a highly reliable electrical energy supply is required. Upgrading distribution systems and adding electrical equipment are possible solutions to improve this reliability. However, these conventional solutions require additional investment in the distribution system. Optimal distribution system reconfiguration is a very effective and efficient way to enhance the distribution system reliability, improve the voltage profile, and reduce distribution system loss [1].

The process for distribution system reconfiguration involves altering the feeder topological structure by changing the open/close status of the automatic and tie switches. Many papers have dealt with optimal feeder topology by using an objective function. Previous research on distribution system reconfiguration has focused on the system minimum losses problem [2-5], improved reliability [1, 6, 7], maximized loadability [8], combinational optimization [9], and the effect of distributed generators (DGs) [10-12]. The effect of DGs on the network reconfiguration is only considered as a reduction of system loss and an improvement in system reliability. Reliability improvement by DGs is possible when intended islanding operation is allowed. However, most utilities prohibit intended islanding operation because of safety concerns for the maintenance crews and for the coordination of protective relays [13]. Therefore, if a fault occurs in a distribution line, it interrupts the electric power supply to the customer as well as to the DGs. For this reason, the DG interruption cost due to faults in the feeders should be considered in the reliability cost evaluation.

In this paper, we present a novel DG reliability cost called the distributed generator reliability cost (DGRC). The composite cost (CCOST) considering the customer interruption cost and DGRC is defined. The CCOST reduction oriented distribution network reconfiguration is presented.

Various methodologies to find the optimal reconfiguration have been developed for reconfiguration problems with acceptable constraints. We use a genetic algorithm (GA) to solve the reconfiguration problem because the GA is a simple and easy but robust method for seeking for the global reconfiguration solution [2, 4].

In section two, reliability costs such as the DGRC, expected interruption cost (ECOST), and CCOST are described for objective function calculation. The constraints of the network reconfiguration are also described for a feasible solution in an actual application. The network reconfiguration algorithm using a GA is described in section three. In section four, the CCOST oriented reconfiguration algorithm is applied to a test system. The result is compared with conventional objective functions. Finally, the paper is summarized in section five.

2. Proposed Objective Functions and Constraints

2.1 Expected interruption cost

To evaluate quantitatively the damage to customers

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† Corresponding Author: Department of Electrical Engineering, Soongsil University, Korea. (jckim@ssu.ac.kr)
* Department of Electrical Engineering, Soongsil University, Korea. (dannyone@ssu.ac.kr, shs8828@ssu.ac.kr)
** LS Industrial System Co., Ltd. Korea. (jhparkm@lsis.biz)
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caused by interruptions, the ECOST is considered in an objective function evaluation. Because the impact of an interruption is different for different customers, customers are normally classified into four types: residential, governmental and institutional, industrial, and commercial. Table 1 indicates the sector interruption cost for each customer type and interruption duration. The sector customer damage function (SCDF) can be calculated by linear interpolation of the sector interruption cost in Table 1.

Table 1. Sector interruption cost (won/kW)

User Sector	Interruption duration (Min.) and cost (won/kW)				
	1	20	60	240	480
Residential	1	93	482	4,914	15,690
Govt. & Inst.	44	369	1,492	6,558	26,040
Industrial	1,625	3,868	9,085	25,160	55,810
Commercial	381	2,969	8,552	31,320	83,010

Eq. (1) gives the ECOST that corresponds to the failure rate and average load capacity according to the SCDF.

$$ECOST = \sum_{i=1}^{K} L_i \sum_{j=1}^{N} c_{ij} \lambda_{ij} \tag{1}$$

where N is the total number of elements, K is the total number of load points in the distribution system, L_i is the average load at load point i, c_{ij} is the SCDF at load point i due to component j, and λ_{ij} is the failure rate at load point i due to component j [14, 15].

2.2 Distributed generator reliability cost

Most utilities prohibit islanding operation of DGs because of safety concerns for the maintenance crew and for the coordination of protective relays. Therefore, the DG operation is interrupted by faults in the distribution lines that lengthen the payback period of the DG owner. In addition, the DGs must wait for some minutes after the distribution system restoration for a stable interconnection [13]. In this sense, to evaluate quantitatively the damage to DGs by distribution line faults, the DGRC is proposed in this paper. We assume that the DGRC consist of two indices. The first is the expected generation interruption cost (EGIC), i.e., the cost of the energy that cannot be exported from the DGs to the distribution system. The second index is the expected trip cost (ETRC), i.e., the cost of circuit breaker (CB) operations to prohibit the DGs from islanding operation.

The EGIC and ETRC are as follows:

$$EGIC = C_{DG} \sum_{i=1}^{K} PDG_i \sum_{j=1}^{N} U_{ij} \tag{2}$$

$$ETRC = \sum_{i=1}^{K} TRC_i \sum_{j=1}^{N} \lambda_{ij} \tag{3}$$

$$DGRC = EGIC + ETRC \tag{4}$$

where C_{DG} is the energy generation cost (won/kWh), U_{ij} is the annual outage duration at load point i due to component j, PDG_i is the active power of distributed generation at load point i, and TRC_i is the operation cost of the DG interconnection circuit breakers at load point i.

Finally, the proposed objective function of network reconfiguration is the minimization of CCOST:

$$\text{Min. } (CCOST) = \text{Min. } (ECOST + DGRC) \tag{5}$$

2.3 Constraints

To apply the results of network reconfiguration to an actual system, the solution must satisfy a number of constraints. In most conventional distribution system reconfigurations, the following four constraints are considered [1-12]:

- Network topology must be radial in structure.
- Solutions must not introduce outage areas.
- Voltages at each bus must be within the permissible range.
- Currents at each line must not exceed the rated ampacity.

Eq. (6) gives the current constraint where I_l is the magnitude of the current at line l, and $I_{l,\max}$ is the rated ampacity of line l;

$$I_l \le I_{l,\max} \tag{6}$$

The voltage constraint is given in Eq. (7) where V_i is magnitude of the voltage at the i^{th} bus, and $V_{i,\min}$ and $V_{i,\max}$ are the minimum and maximum voltage limits, respectively;

$$V_{i,\min} \le V_i \le V_{i,\max} \tag{7}$$

3. Genetic Algorithm

A GA is a technique based on the theory of evolution. It is a search technique used in computing to find exact or approximate solutions to optimization and near optimization problems. It can be applied to a wide range of engineering problems. A GA has two main operators called crossover and mutation. Crossover is the principal GA operator that mixes genetic information from two different individuals (parents) to create a new individual (child). The mutation operator provides a way of introducing new information into the knowledge base and randomly changes one chromosome in the string. It is applied with a probability that has been set in the initialization phase.

The features of GAs are as follows [16]:

(1) Excellent global search ability.
(2) Simple theory and concept.
(3) Objective function and constraints are easy to change owing to high flexibility.
(4) Suitable for solving combinatorial optimization problems.
(5) Little possibility of generating infeasible solutions through crossover and mutation.
(6) Convergence speed relies on the solution candidate.

For codification of GA, the individuals are represented by a string of normally opened SW number. Accordingly, the length of the string is in accordance with the number of the loop path in the system [2].

A flow chart for the reconfiguration algorithm is shown in Fig. 1. In this paper, the elitist preserving selection, single point crossover, and mutation operators are applied to keep the feasible individuals [16].

4. Test System and Case Study

4.1 Test system

We consider two case studies in order to compare the proposed objective function with conventional objective functions. Although the test system introduced in [17] has been used in many previous studies, it is not appropriate for a reliability evaluation. Therefore, the test system is modified for the case studies. The modified test system including protective equipment is shown in Fig. 2.

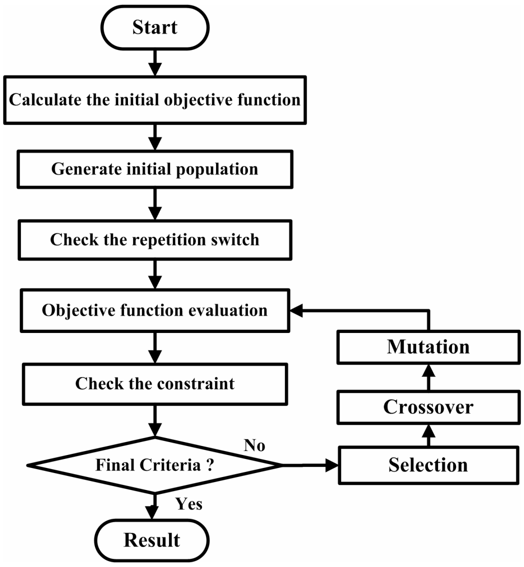


Fig. 1. Flow chart for the reconfiguration algorithm using GA

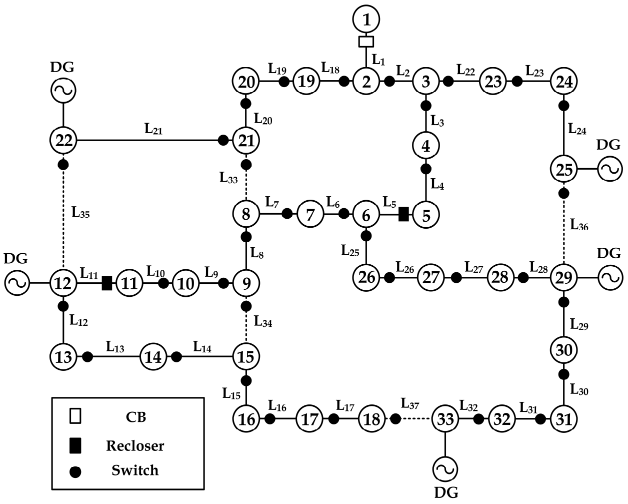


Fig. 2. Modified test system

In the test system, if fault occurs in a line, the circuit breaker (CB) or Recloser located upstream is tripped to eliminate a fault current. Automatic switches are then operated to isolate the fault. Then, the normally opened SW which is in same loop path with faulted line is closed to minimize the outage section. For example, if fault occur in line L_{14}, Recloser in L_{11} is tripped to clear fault current immediately. Then two switches in L_{14} and L_{15} are opened to isolate the fault section and the Recloser in L_{11} is closed. The loads in buses 13-14 experience short time interruption during the switches operation. We defined the switches operation time as switching time (T_{sw}) in this paper. Although the bus 12 is restored, the DG installed in bus 12 must wait some minute (T_{DGw}) for stable interconnection. Then, normally opened SW in line L_{37} is closed. The loads in bus 16-18 are restored. The time consumed in this process is defined as load transfer time (T_{lt}).

The information for the modified test system is summarized in Table 2.

Table 2. Information for modified test system

Bus	Line	Tie SW	P_{load} [MW]	Q_{load} [MVar]
33	37	5	3.7	2.3

The information about the DGs in the modified test system is shown in Table 3. The operation mode of all DGs is constant active power output and constant power factor

Table 3. Information about the DGs in the modified test system

Bus	DG capacity		p.f.
	P [kW]	Q [kVar]	
12	200	40	0.98
22	250	80	0.95
25	150	40	0.96
29	600	300	0.89
33	400	60	0.98
Total	1600	520	-

mode. The energy generation cost of all DGs is assumed to be 500 won/kWh, and the operation cost of all CBs is 25,000 won per operation.

The failure rate of each line in the test system is shown in Table 4, and the outage time varies at each load point. We assume that the sustained fault repair time is 2 h, the switching time (T_{sw}) is 0.5 h, the load transfer time (T_{lt}) is 1.1 h and DG waiting time (T_{DGw}) is 5 minutes.

Table 4. Failure rate of each line in the test system

Line	λ [freq./y]	Line	λ [freq./y]	Line	λ [freq./y]
1	0.0067	14	0.0514	27	0.0918
2	0.036	15	0.0601	28	0.0693
3	0.0267	16	0.1398	29	0.0370
4	0.0278	17	0.0605	30	0.0890
5	0.0703	18	0.0147	31	0.0310
6	0.042	19	0.1316	32	0.0410
7	0.0487	20	0.0409	33	0.1838
8	0.0824	21	0.0764	34	0.1838
9	0.0832	22	0.0355	35	0.1838
10	0.0135	23	0.0744	36	0.046
11	0.0256	24	0.0740	37	0.046
12	0.1214	25	0.0148	-	-
13	0.0582	26	0.0207	-	-

The GA individual of the modified test system is shown in Fig. 3. The GA individual string has five columns because there are five loops in the test system. In initial population generation in GA, we made 100 individuals by changing randomly the five columns to other SW number. However, each column value is limited by solution range summarized in Table 5 for more fast convergence [2]. Then the proposed objective function of each individual is evaluated respectively. In crossover process, two individuals (parents) are selected among sorted the 100 individuals randomly, then two new individuals (children) are generated from the parent using single point crossover. In this case study, there are four crossover points between five columns. In this phase, total number of individuals is increased as 200. After the objective function evaluation and sorting, the 100 high cost individuals are eliminated. In mutation process, some child individual is selected randomly, and then a column value in the individual is modified as other value in the solution range. From the objective function evaluation to mutation process is repeated until final criteria are matched [2].

33	35	34	37	36

Fig. 3. GA individual of initial state of test system

Table 5. Solution range of GA individual

Chromosomes	Solution range
1	2,3,4,6,7,18,19,20,33
2	8,9,10,21,33,35
3	9,10,12,13,14,34
4	6,7,8,15,16,17,25,26,27,28,29,30,31,32,34,37
5	3,4,22,23,24,25,26,27,28,36

4.2 Case studies

To analyze the impact of the DG reliability cost on the network reconfiguration, we studied two cases. In the first case, most customer types are residential. The proportion of other customer types is relatively low. On the other hand, in the second case the proportion of industrial and commercial type customers is high. Therefore, the customer interruption cost of case 2 is higher than that of case 1. The customer type of each bus is summarized in Table 6.

Table 7 and Table 8 show the results of the network reconfigurations in the two cases. The normally opened switches must be opened to maintain the radial structure. Because of the difference in the normally opened switches between the initial case and each result, the reliability cost such as the ECOST, DGRC, and CCOST are different.

Table 6. Customer type of buses in case 1 and 2

Customer types	Case 1	Case 2
Residential	1, 2, 4, 6-13, 15-19, 21-23, 25-29, 31-33	1, 10, 17, 19, 21-22, 24, 33
Govt. and Inst.	5,14,24,30	2
Industrial	3	3, 5, 7, 9, 13, 15, 16, 18, 20, 25, 31
Commercial	20	4, 6, 8, 11, 12, 14, 23, 26-30, 32

Table 7. Results of the reconfiguration in the case of light load interruption cost (case 1)

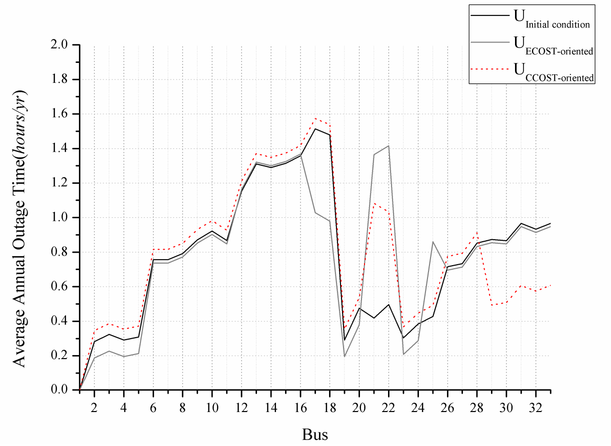
	Initial topology	ECOST-oriented topology	CCOST-oriented topology
Normally opened switches	33, 34, 35, 36, 37	16, 20, 24, 33, 34	20, 28, 34, 35, 37
ECOST $\times 10^3$ [won]	2,460	2,332	2,541
DGRC $\times 10^3$ [won]	924	1,110	813
CCOST $\times 10^3$ [won]	3,384	3,442	3,354

Table 8. Results of the reconfiguration in the case of high load interruption cost (case 2)

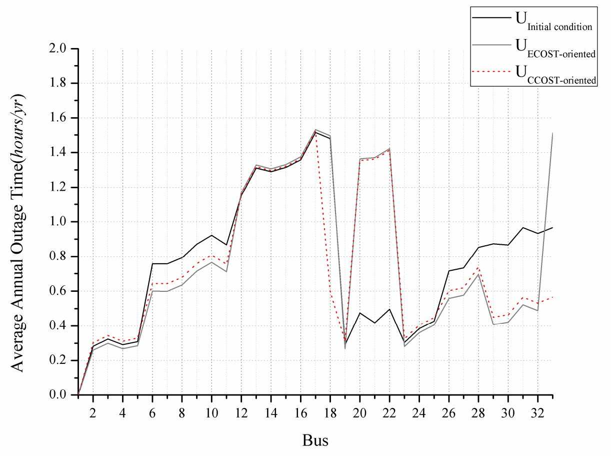
	Initial topology	ECOST-oriented topology	CCOST-oriented topology
Normally opened switches	33, 34, 35, 36, 37	19, 28, 32, 33, 34	17, 19,28, 33, 34
ECOST $\times 10^3$ [won]	19,198	16,152	16,240
DGRC $\times 10^3$ [won]	924	1,034	831
CCOST $\times 10^3$ [won]	20,122	17,186	17,071

Tables 7 and 8 provide a comparison between the results of two network reconfigurations, the objective functions of which are ECOST minimization and CCOST minimization, respectively. The ECOST oriented reconfiguration only tries to minimize ECOST, so DGRC increased slightly compared to the initial value. However, the CCOST-oriented reconfiguration considers ECOST as well as DGRC. Therefore, ECOST as well as DGRC decreased in case 2. In case 1, although the ECOST value is slightly higher than that in the ECOST-oriented topology, both CCOST and DGRC in the CCOST-oriented topology are the lowest. Because the interruption cost of customers in case 1 is lower than that in case 2, the DGRC proportion of the CCOST is higher than that in case 2. Therefore, the impact of DGRC in case 1 is higher than that in case 2.

Fig. 4 and Fig. 5 show the average annual outage time U and average failure rate λ at each bus, respectively. The low and high interruption cost systems are shown in each figure.



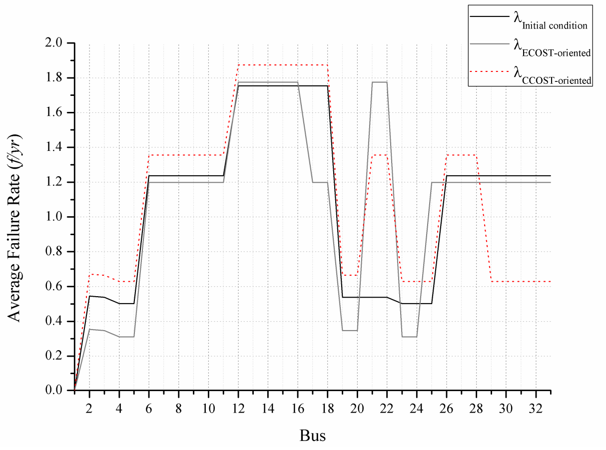
(a) Case 1 (low interruption cost)



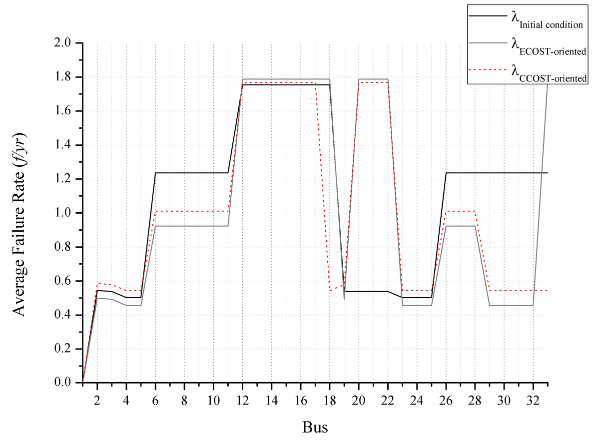
(b) Case 2 (high interruption cost)

Fig. 4. Average annual outage time at each bus

In the CCOST-oriented reconfiguration case shown in Fig. 4(a), U at buses 12, 22, and 25, where the DGs are installed, increased slightly, while U at buses 29 and 33 decreased. Because the capacity of the DGs installed at buses 29 and 33 is much higher than those at buses 12, 22, and 25, buses 29 and 33 have a higher weight than buses 12, 22, and 25 in the CCOST-oriented reconfiguration. For the same reason, λ only decreased at buses 29 and 33 in the CCOST-oriented reconfiguration in Fig. 5(a). In case 2, the difference in U and λ between the ECOST- and CCOST-oriented reconfigurations is small. Only bus 33 shows a highly different U and λ.



(a) Case 1 (low interruption cost)



(b) Case 2 (high interruption cost)

Fig. 5. Average failure rate at each bus

It should be noted that in the distribution system with a light load interruption cost (case 1), the DGRC has as much influence on CCOST as the ECOST does. However, owing to the lower DGRC compared to the ECOST, the DGRC has little influence on the CCOST in the test system with the heavy load interruption cost (case 2).

In general, DGs are usually installed in rural areas in order to maximize the installation effect, and the customer interruption cost in rural areas is normally low. In addition, because the penetration of the DGs will increase rapidly, a DGRC that reflects the interruption cost should be considered in the objective function appropriately.

In these case studies, we have confirmed that network reconfiguration with an objective function considering the customer reliability cost as well as the DGRC is more suitable in a distribution system in which the interruption cost of DGs is relatively higher than the customer interruption cost, such as in rural areas and high DG penetration areas.

5. Conclusion

Until now, the impact of DGs on distribution system reconfiguration has only been considered as one aspect of system loss reduction and reliability enhancement under intended islanding operation condition. In this paper, we presented a novel DG reliability cost that expresses the interruption damage of the DGs due to feeder faults when islanding operation is prohibited. The reliability cost, which is the CCOST, consists of the customer interruption cost (ECOST) and the DG reliability cost (DGRC). The CCOST is used as an objective function in network reconfiguration using a GA. The reconfiguration algorithm was implemented by MATLAB software, and network reconfiguration with the proposed objective function was applied to a test system. The results of the reconfiguration showed that in a distribution system with a light load interruption cost, the DGRC has as much influence on the CCOST as the ECOST does. However, owing to a lower DGRC than ECOST, the DGRC has little influence on the CCOST in the test system with a heavy load interruption cost.

Because the penetration of DGs will increase in future smart grids, the DGRC should be considered in the network reconfiguration. We expect that network reconfiguration for reliability enhancement with the proposed objective function will provide more suitable solutions in distribution systems with a high penetration of DGs.

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Sung-Min Cho He received his B.S. and M.S. degree from Soongsil University, Korea in 2003 and 2008, respectively. Currently, he is pursuing his Ph. D. at the School of Electrical Engineering, Soongsil University. His research interests are power system reliability, smart distribution systems, battery energy storage system, and distributed generation interconnection.

Jin-Hyun Park He received his B.S. and M.S. degree from Soongsil University, Korea in 2010 and 2012, respectively. Currently, he is an assistant research engineer at LS Industrial System Co., Ltd. His research interests are power distribution system reliability and circuit breaker.

Hee-Sang Shin He received his B.S. and M.S. degree from Soongsil University, Korea in 2007 and 2009, respectively. Currently, he is doctoral student at the Soongsil University Graduate School. His research interests are distribution system reliability, power quality, and electric railways.

Jae-Chul Kim He received his B.S. degree from Soongsil University, Korea in 1979 and his M.S. and Ph.D. degrees from Seoul National University, Korea in 1983 and 1987, respectively. Currently, he is a dean of College of Engineering and a professor of Electrical Engineering at the Soongsil University. He is a member of the Institute of Electrical and Electronics Engineers (IEEE). Also he is a fellow member of Korean Institute of Electrical Engineers (KIEE). His research interests are power quality, power system reliability, demand response, dispersed generation, distribution automation systems, asset management, power system diagnosis, electric railway systems, and superconducting fault current limiters.