Optimal Capacity and Allocation of Distributed Generation by Minimum Operation Cost in Distribution Systems

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Abstract - In the operation of distribution systems, DGs (Distributed Generations) are installed as an alternative to extension and the establishment of substations, transmission and distribution lines according to the increasing power demand. In the operation planning of DGs, determining optimal capacity and allocation achieves economical profitability and improves the reliability of power distribution systems. This paper proposes a determining method for the optimal number, size and allocation of DGs in order to minimize the operation costs of distribution systems. Capacity and allocation of DGs for economical operation planning duration are determined to minimize total cost composed with power buying cost, operation cost of DGs, loss cost and outage cost using the GA (Genetic Algorithm).

Keywords: Distributed Generation, Distribution System, Operation Cost and Reliability Index

1. Introduction

Recently, the conversion of the electric industry into a competitive structure and the reinforcement of environmental regulations have caused great interest in Distributed Generation (DG). Distributed Generation is typically defined as small generators, typically less than 10[kw], that are connected to utility distribution systems. DG technologies include photovoltaic, wind turbines, fuel cells, small & micro sized turbine packages, internal combustion engine generators and reciprocating engine generators. The applications for DG include combined heat and power, standby power, peak shaving, grid support and stand alone (grid isolated).

In the operation of distribution systems, the DGs can be installed as an alternative to extension and the establishment of substations, transmission and distribution lines according to the increasing power demand. The alternative plan to determine cost minimization will result in changes to the power loss, reliability and power quality of distribution systems.

Power system planning involves identification of the best equipment, along with its locations, manner of interconnecting to the system and schedule of deployment. Since cost is an important attribute in power planning, almost invariably one of the planner's chief goals is to minimize overall cost [1, 2].

Distribution system operators must analyze customer demands and costs of power to assist in making decisions on whether to obtain power from transmission systems or to generate power from the DG. Obtaining power from the operating DG not only reduces power cost, but also improves reliability of the system by supply to the interrupted area. The planners of distribution systems minimize overall costs in order to reduce operation costs and to improve reliability of the system.

Once total capacity of the DG is estimated by the load growth and existed line capacity, DG allocations are determined to minimize the total cost that is composed of power buying cost, operation cost of the DG, loss cost and outage cost using the GA (Genetic Algorithm). As well, reliability is estimated for each case in which DGs are installed and not installed and in which reliability cost is included and not included in the system planning process.

2. Operation strategy of DG

The operation strategy of the DG can be classified as follows:

First, DGs are operated during peak load. In the case in which the system load reaches its peak, the distribution system does not satisfy load capacity or electricity must be purchased at high cost, insufficient electricity is replenished by DG operation. Moreover, when the load capacity exceeds transmission line capacity, DGs are operated in order to supply electricity to the distribution system.

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Second, DGs are operated as electricity supplies. Load capacity in the distribution system has some differences according to load types, load characteristics, and individual loads. The cost that purchases electricity is determined by the change of load capacity according to time sequential. Therefore, if DGs that are connected to the grid are used as electricity supply sources, the planners of the distribution system attempt to reduce the operation cost by choosing more low-priced electricity comparing the operation cost of DG with the electricity buying cost according to time sequential.

Third, DGs are operated as a power supply (standby) when the system is interrupted. Each load point is isolated from the system by protective devices such as break and recloser when interruption is generated. Isolated load points are supplied by DGs. When interruptions take place, DGs can improve system reliability and reduce outage cost by supplying power at load point [3].

3. System Modeling

3.1 Load Modeling

The reliability index and the operation cost can be obtained exactly by modeling as a real system and can be more approachable in terms of minimization of total operation cost.

Generally, the load model is divided into 8760 discrete hours and the customers are classified into seven categories; large users, industrial, commercial, agriculture, residential, government and office [4].

Fig. 1 shows the percentages of hourly load in terms of daily peak for residential, commercial and government /institute customers during a summer day.

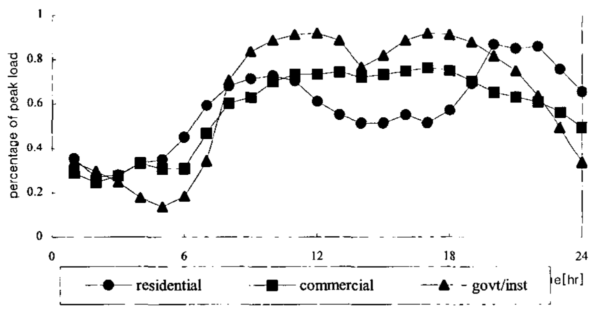

Fig. 1 Percentages of Hourly Load in Terms of Daily Peak

3.2 DG Modeling

The rated output of a DG is provided in this paper. The installation number of DGs is determined by load growth during operation planning duration and capacity of a DG by Eq. (1).

$$N_{DG} = \frac{\Delta P_L}{P_{DG}} \tag{1}$$

Where, N_{DG} : Installation number of DG

ΔP_L : Load growth, P_{DG} : Capacity of a DG

All DGs are installed in the early year of planning with one DG per load point. The line and bus capacity limits determine the capacity of DG and installation of the load point.

DGs allocations are determined by minimizing total cost with power buying cost, operation cost of DG, loss cost and outage cost using the Genetic Algorithm (GA).

3.3 Genetic Algorithm: GA

The Genetic Algorithm (GA) is a heuristic search algorithm based on the mechanism of natural selection and genetics and has several properties as follows:

- GA works with a set of coded variables referred to as the population of string.
- GA searches from a population of points as multiagents.
- GA uses only payoff (objective function) information, not derivatives or others.
- GA uses probabilistic transition rule.

A GA deals with a population with plural individuals (a set of coded variables). A coding process is the most important part in GA applications, in which variables are encoded to the string (chromosome).

Fig. 2 illustrates the coding process.

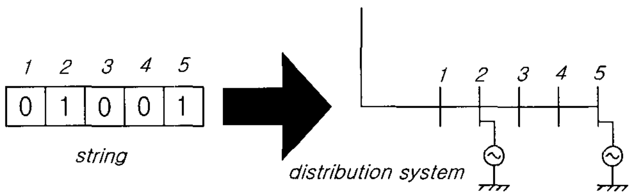

Fig. 2 Coding Process

The deployment pattern of DGs corresponds to a string according to the following rules, decision whether a DG is installed or not 1 (installed), 0 (not installed), a position of a node is a position of a chromosome and lengths of a chromosome is the number of total nodes at which a DG is able to be installed.

A measure indicating the performance of an individual is referred to as fitness. A certain function must be defined that evaluates each individual to determine its fitness value.

GA revaluates coding population through reproduction, crossover and mutation. Previously calculated series of calculation processes repeat by obtaining optimal solution

[5].

4. Reliability Index

4.1 System Average Interruption Frequency Index: SAIFI

This index refers to the system average interruption frequency of the subject region.

$$SAIFI = \frac{\sum_{i=R} \lambda_i N_i}{\sum_{i=R} N_i} \tag{2}$$

Where, λ_i : The failure rate of load point

N_i : The number of customers of load point

R : Total load point of system

4.2 System Average Interruption Duration Index: SAIDI

This index refers to the system average interruption duration of the subject region.

$$SAIDI = \frac{\sum_{i\in R} U_i N_i}{\sum_{i\in R} N_i} \tag{3}$$

Where, U_i : The annual outage time of load point

4.3 Average Service Availability Index: ASAI

This index refers to the average service availability of the subject region.

$$ASAI = \frac{\sum_{i\in R} 8760 N_i - \sum_{i\in R} U_i N_i}{\sum_{i\in R} 8760 N_i} \tag{4}$$

Where, 8760: The number of hours in a calendar year

4.4 Composite Frequency & Duration Index: CFDI

Protective device placement in a conventional (radial) feeder is designed to maximize network reliability, and therefore minimize the traditional reliability indices assuming energy source(s) located only at substation(s). In this paper, we will look at the standard reliability performance indices, such as a SAIDI and SAIFI, and the composite index as CFDI obtained as a combination of both.

One can optimize the recloser placement with respect to either of these two, or some other, indices. In order to include the effects of both sustained and momentary interruptions, a composite index may be used, as defined below

$$CFDI = W_{SAIFI} \frac{SAIFI - SAIFI_T}{SAIFI_T} + W_{SAIDI} \frac{SAIDI - SAIDI_T}{SAIDI_T} \tag{5}$$

Where, W_x : Appropriate reliability index weight

T : Target value

In the numerical example provided later, we will use the default weight and target value for SAIDI and SAIFI respectively. Note that these target values indicate satisfactory level of reliability for a conventional feeder, and may be exceeded in a DG-enhanced feeder yielding negative values for the composite index CFDI [6].

5. Minimization of Distribution System Operation Cost

5.1 Distribution System Operation Cost

The operation cost of distribution system is constituted by power buying cost, operation cost of DG, outage cost and loss cost. The optimal capacity and deployment of DG are formulated as follows in the objective function [7].

5.1.1 Objective function

Objective function is mathematically expressed as below by Eq. (6).

$$C_{Total} = C_{Buy} + C_{DGop} + C_{Out} + C_{Loss} \tag{6}$$

Where, C_{Total} : Sum of total operation cost

C_{Buy} : Power-buying cost in transmission system

C_{DGop} : Operation cost of DG , C_{Out} : Outage cost

C_{Loss} : Loss cost

The load capacity is determined by load type, load characteristics and consumption type of each load. The power buying cost to supply power at each load point is determined by load change for time-sequential.

The power buying cost is determined by comparing power buying cost per kWh with operation cost of DG per ㎾. The operation cost of DG in Eq. (8) is denoted by the number of operations for time-sequential. The outage cost can be determined by difference outage cost of state of no-

DG and with-DG by Eq. (9). The loss cost can be denoted by the power flow for power loss and annual generation cost per ㎾ by Eq. (10).

$$C_{Buy} = \sum_{j=1}^{m} K_j \cdot (P_{Buy} - \alpha \cdot P_{DG} \cdot n_{DGj}) \tag{7}$$

$$C_{DGop} = \alpha \cdot K_{DG} \cdot P_{DG} \cdot \sum_{j=1}^{m} n_{DGjk} \tag{8}$$

$$C_{Out} = \sum_{i=1}^{n} K_{outi} \cdot P_{outi} - \sum_{i=i_{DG}} K_{outi} \cdot P_{outi} \tag{9}$$

$$C_{Loss} = \sum_{i=1}^{m} K_{Loss} \cdot P_{Loss} \tag{10}$$

Where, i : Time duration (j=1, 2, ..., m),

j : Load point (i=1, 2, ..., n)

i_{DG} : Load point installed DG

K_j : Buying power cost per ㎾ at time

K_{DG} : Operation cost of DG per ㎾

K_{out} : Outage cost per ㎾

K_{Loss} : Generation cost per ㎾

P_{Buy} : Buying power, P_{DG} : Capacity of DG

P_{out} : Power not supplied at outage, at load i

P_{Loss} : Power loss of system

n_{DGj} : Total operation quantity of DG at time

$\alpha = \begin{cases} 0 : K_j \le K_{DG} \\ 1 : K_j > K_{DG} \end{cases}$: State of DG operation

5.1.2 Constraints

Difference of supplying electric power by buying power and operating DG according to load growth can't exceed capacity of line limit. Voltage constraint to restrict the voltage fluctuation in the distribution system is as follows:

$$0 < P_{Buy} - \alpha \cdot P_{DG} \cdot n_{DGj} < P_{LC} \tag{11}$$

$$V_{\min} \le V_i \le V_{\max} \tag{12}$$

Where, P_{LC} : Line limit capacity, V_i : Node voltage at node

$V_{\min}$: Lower limits of node voltage

$V_{\max}$: Upper limits of node voltage

5.2 Loss Cost

Transmission loss depends on resistance of the transmission line in the operation of the distribution system. The cost of transmission loss must be considered in order to operate the distribution system economically. DGs allocations are determined by minimizing total cost with the power flow of the distribution system.

$$P_{Loss} = \sum_{i=1}^{n} r_i \cdot \frac{P_i^2 + Q_i^2}{|V_i|} \tag{13}$$

Where, r_i : Resistance at line, P_i : Real power at line

Q_i : Reactive power at line, V_i : Voltage at line

5.3 Annual Interruption Capacity and Cost

The annual interruption capacity can be calculated with the peak load of each load point, outage rate (λ) and repair time (r) in the reliability index using the following equation.

$$P_{outi} = P_{peaki} \cdot \lambda_i \cdot r_i \tag{14}$$

Where, P_{peaki} : Peak load at load, λ_i : Outage rate at load

r_i : Repair time at load

Table 1 Sector Interruption Cost ($/KW)

User Sector	Interruption Duration (min. or hour) & Cost ($/kW)				
	1 min.	20min.	1 hour	4 hour	8 hour
Larger user	1.005	1.508	2.225	3.968	8.240
Industrial	1.625	3.868	9.085	25.16	55.808
Commercial	0.381	2.969	8.552	31.317	83.008
Agricultural	0.060	0.343	0.649	2.064	4.120
Residential	0.001	0.093	0.482	4.914	15.690
Govt. & Inst.	0.044	0.369	1.492	6.558	26.040
Office	4.778	9.878	21.065	68.830	119.16

The annual interruption cost is given by the sector customer damage functions (SCDF) shown in Table 1 that describe the cost of interruption for the given type of customer as a function of interruption duration and reliability index of each load point.

6. Case Study

6.1 System Model and Load Character

An urban distribution system connected to Bus 2 of the RBTS (Roy Billinton Test System) is used to conduct the case studies. The modified system is shown in Fig. 3, which is a typical distribution system with four feeders [8].

The total peak load is 20[MW], the rate of annual load growth is 5[%], the rated output of the DG unit is 2[MW] and the operation planning duration of DG is 12 years. The basic reliability parameters and load characteristics for this system are presented in reference [8].

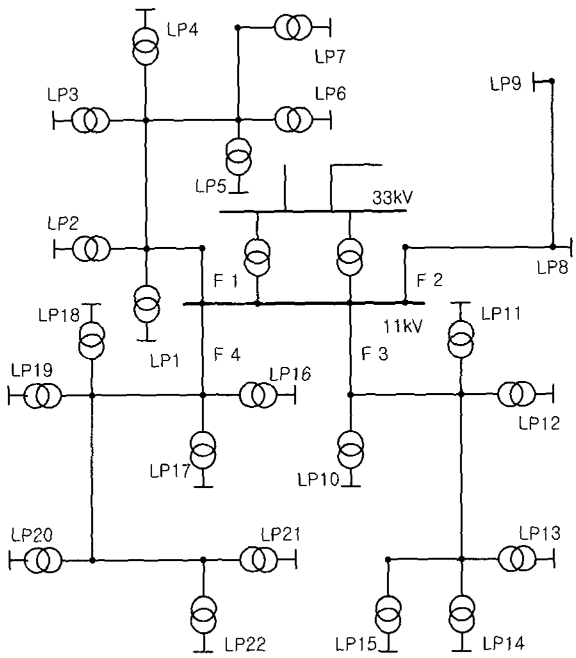

Fig. 3 Distribution System for RBTS Bus 2

6.2 Allocation of DG

The installation numbers of DG by load growth and line limits during the distribution system planning duration are indicated in Table 2. The installed load points of DGs are shown in Table 3. Table 4 illustrates loss cost, reliability cost and total cost for the case in which reliability cost is both considered and not considered.

Table 2 Installation Quantity of DG

Planning duration	Load increment [MW]	Installation quantity
1	1.000	-
2	1.050	-
3	1.103	-
4	1.158	2
5	1.216	-
6	1.276	-
7	1.340	2
8	1.407	-
9	1.477	-
10	1.551	2
11	1.629	-
12	1.710	-

Table 3 Installation Load Point of DG

DG installation	Only loss cost	All cost
Load point	6, 7, 15, 18,21, 22	2, 7, 14, 15,16, 22

Table 4 Cost Comparisons with Reliability Cost Application

Cost [$/yr]	Only loss cost	All cost
Loss cost	310,615	352,955
Reliability cost	1,242,460	530,710
Total cost	10,526,965	9,730,900

6.3 Installation Procedure of DG

The installation procedure of DG is determined by load, the characteristics of each load point, outage cost and line limits. The installation procedure of DG depends on commercial load due to the outage cost of commercial load being high. The installation procedure considering only loss cost and all cost can be expressed as follows.

Table 5 Installation Procedure of DG

	Installation procedure	1	2	3
Only loss cost	Planning year	4yr	7yr	10yr
	Load point	6, 22	7, 15	6, 18
All cost	Planning year	4yr	7yr	10yr
	Load point	16, 22	7, 15	2, 14

6.4 Reliability Assessment

We try to examine reliability assessment for installation of the DG. First, the reliability indices are calculated in the case in which DGs are installed and reliability cost is both considered and not. To obtain CFDI, target of SAIFI is 0.15, target of SAIDI is 2.85 and appropriate reliability index weight is 1.

Table 6 Reliability Indices Comparison with DG Installation

Reliability index	No-DG	With-DG
SAIFI	0.248827	0.216905
SAIDI	3.614251	3.155236
ASAI	0.999587	0.999640
CFDI	0.927002	0.553135

Table 7 Reliability Comparison with Reliability Cost

Reliability index	Only loss cost	All cost
SAIFI	0.217971	0.216905
SAIDI	3.161583	3.155236
ASAI	0.999639	0.999640
CFDI	0.562465	0.553135

Table 6 indicates that the reliability indices of with-DG became better than those of no-DG because power supply improves interruption frequency and time reduction. And, Table 8 shows that the reliability indices of all cost became better than those of only loss cost.

6.5 Convergence Characteristic Curve

Fig. 4 presents the convergence characteristics of GA.

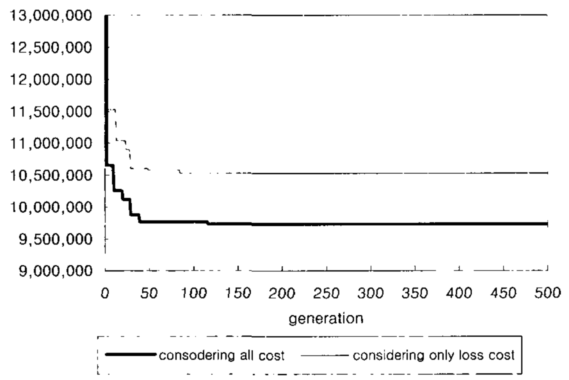

Fig. 4 Convergence Characteristic Curve of Total Cost

The total operation cost considering only loss cost is 10,526,965 [$/yr] and converges over 85 generations, and total operation cost considering total cost is 9,730,900 [$/yr] and converges over 116 generations. Fig. 4 shows that the case considering only loss cost converges more rapidly than the case considering total cost due to the small number of constraints.

7. Conclusion

This paper proposes a method that determines the optimal number, size and allocation of DGs, which is required to minimize the operation costs of the distribution system. The planners involved in the operation planning of distribution systems can reduce operation costs and improve reliability of the system by minimizing the total cost through the purchasing of electric power or operating the DG. Each of the indices and calculated total operation cost are compared with the case in which DGs are installed and reliability cost is considered and not considered. This calculation determines an optimal allocation and installation procedure by minimizing total operation costs. In calculation of reliability indices, installation of DGs and consideration of reliability cost can result in economic profitability and improvement in power reliability.

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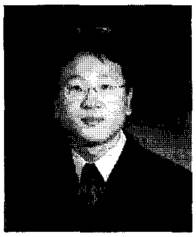

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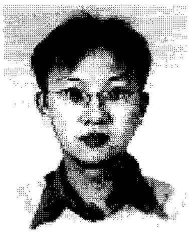

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