

Optimal Placement of Distributed Generation for Reliability Benefit in Distribution Systems

N. Rugthaicharoencheep, A. Chalangsut

Department of Electrical Engineering, Faculty of Engineering, Rajamangala University of Technology Phra Nakhon, Bangkok, Thailand
Email: nattachote.r@rmutp.ac.th

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ABSTRACT

A distributed generator is a small-scaled active generating unit located on or near the site where it is to be used. Several benefits have been realized by installing distributed generators in a distribution network. Among them is reliability improvement if their locations and sizes are appropriately determined. For this reason, reliability benefit is investigated in this paper with the main objective for the optimal placement and sizing of distributed generators in a distribution system to minimize the customer interruption cost subject to the maximum number of distributed generators, total capacity of distributed generators, bus voltage limits, current transfer capability of the feeders and only one distributed generator for one installation position. The technique employed to solve the minimization problem is based on a developed Tabu search algorithm and reliability worth analysis. The Tabu search algorithm is a local search that uses memory to avoid being trapped around a local neighborhood and help to move away from a local optimum solution. The reliability worth analysis provides an indirect measure for cost implication associated with power failure. The developed methodology is tested with a distribution system of Provincial Electricity Authority (PEA). Numerical results from the tests demonstrate that distributed generators can be used to promote the reliability of the distribution system.

Keywords: Distributed Generation; Reliability; Tabu Search; Distribution System

1. Introduction

Electricity has always been the major part of human development and it has gone through various changes with time. Traditionally, much of the electricity generated has been produced by large-scaled, centralized power plants using fossil fuels (*e.g.*, coal, oil and gas), hydropower or nuclear power. The electrical energy is transmitted over long distances by extra high voltage (EHV) or ultra high voltage (UHV) transmission lines and from there the high voltage levels are converted to low voltage levels through distribution lines in the distribution system to end-use customers [1].

Such a centralized generation pattern, however, suffers a number of drawbacks, such as a high level of dependence on imported fuels that are very vulnerable, transmission losses, the necessity for continuous upgrading and replacement of the transmission and distribution facilities and therefore high operating cost, and environmental impact. In addition, as electric demand is substantially increasing as a result of economic and social growths, the construction of a large sized power plant is running into financial and technical difficulties, because it is capital intensive and needs considerable amount of time.

An ideal alternative on electric distributions to electric users is the installation of a small sized generator or commonly known as distributed generator (DG). DG is a small-scale active generating unit located on or near the site where it is to be used (*i.e.*, in distribution systems). The primary energy resources of DG could be wind, solar, biomass, fuel cells and hydrogen, etc [2].

Although DGs have gained many positive effects, they still have some economic and technical issues to be addressed before their applications in the distribution system can be realized. The main objective of this paper is to investigate the impact of distributed generation on distribution system reliability. It is expected that reliability on the installation of DGs can be improved because they can be served as backup generation when a utility supply interruption occurs. In other words, some of the load points can still be electrically supplied by the DGs and therefore economic loss as a result of the power outage can be reduced. However, amount of reliability improvement depends on location and size of the DGs to be installed. It is therefore proposed in this paper a method to determine the optimal placement and sizing of DGs in a distribution system to minimize the customer interruption cost subject to system operational constraints [3].

The technique employed to solve the minimization problem is based on a developed Tabu search algorithm and reliability worth analysis. The Tabu algorithm systematically searches solutions expressed in forms of the location and size of DGs. The solution obtained will then be passed to reliability worth analysis to evaluate the quality of the solution. The process is repeated until the best solution has been found. The developed methodology is tested with a distribution system of Provincial Electricity Authority (PEA) with 26 load points.

2. Tabu Search

Tabu search is a meta-heuristic that guides a local heuristic search strategy to explore the solution space beyond local optimality [4]. The basic idea behind the search is a move from a current solution to its neighborhood by effectively utilizing a memory to provide an efficient search for optimality. The memory is called “Tabu list”, which stores attributes of solutions. In the search process, the solutions are in the Tabu list cannot be a candidate of the next iteration. As a result, it helps inhibit choosing the same solution many times and avoid being trapped into cycling of the solutions [5]. The quality of a move in solution space is assessed by aspiration criteria that provide a mechanism for overriding the Tabu list. Aspiration criteria are analogous to a fitness function of the genetic algorithm and the Boltzman function in the simulated annealing.

In the search process, a move to the best solution in the neighborhood, although its quality is worse than the current solution, is allowed. This strategy helps escape from local optimal and explore wider in the search space. A Tabu list includes recently selected solutions that are forbidden to prevent cycling. If the move is present in the Tabu list, it is accepted only if it has a better aspiration level than the minimal level so far. **Figure 1** shows the main concept of a search direction in Tabu search [6].

3. Reliability Indices

The basic distributed system reliability indices at a load point are average failure rate λ , average outage duration r , and annual outage duration U . With these three basic load point indices, the following system reliability indices can be calculated [7].

System average interruption frequency index (SAIFI)

$$SAIFI = \sum \frac{\lambda_i N_i}{N_i} \tag{1}$$

System average interruption duration index (SAIDI)

$$SAIDI = \sum \frac{U_i N_i}{N_i} \tag{2}$$

Customer average interruption duration index (CAIDI)

$$CAIDI = \sum \frac{U_i N_i}{\lambda_i N_i} \tag{3}$$

Average service availability index (ASAI)

$$ASAI = \frac{\sum N_i \times 8760 - \sum U_i N_i}{\sum N_i \times 8760} \tag{4}$$

Average service unavailability index (ASUI)

$$ASUI = 1 - ASAI = \frac{\sum U_i N_i}{\sum N_i \times 8760} \tag{5}$$

Energy not supplied index (ENS)

$$ENS = \sum L_{a(i)} U_i \tag{6}$$

Average energy not supplied index (AENS)

$$AENS = \frac{\sum L_{a(i)} U_i}{\sum N_i} \tag{7}$$

where

λ_i = failure rate of load point i

N_i = number of customers of load point i

U_i = annual outage time of load point i

$L_{a(i)}$ = average load connected to load point i

λ_h = failure rate of contingency h

r_h = average outage time of contingency h

A basic approach to quantifying the worth of electric service reliability is to estimate customer interruption costs due to electric power supply interruptions. One convenient way is an interpretation of customer interruption costs in terms of customer damage functions. The customer damage functions can be determined for given customer types and aggregated to make sector customer damage functions (SCDF), which reflect economic consequences of supply interruption as a function of cost in different groups of customers [8].

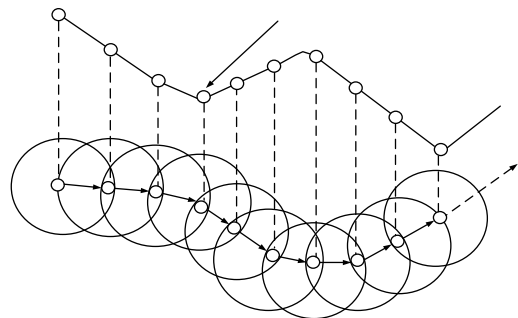


Figure 1. Search direction of Tabu search.

4. Problem Formulation

Objective function:

$$\text{Minimize } ECOST = \sum_{h=1}^{n_h} \sum_{i=1}^{n_i} L_i C_{hi} (r_h) \lambda_{r_h} \quad (8)$$

Constraints:

Power flow equations:

$$P_k = \sum_{i=1}^{N_B} |Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i) \quad (9)$$

$$Q_k = -\sum_{i=1}^{N_B} |Y_{ik} V_i V_k| \sin(\theta_{ik} + \delta_k - \delta_i) \quad (10)$$

Voltage of each bus must be within specified limits:

$$V_k^{\min} \leq V_k \leq V_k^{\max} \quad (11)$$

Current transfer capability of feeders:

$$I_l \leq I_l^{\max}, \quad l \in \{1, 2, \dots, N_l\} \quad (12)$$

Maximum number of DGs to be installed:

$$\sum_{k=1}^{N_B} e_{jk} \leq n_{DG} \quad j \in \{1, 2, \dots, N_C\} \quad (13)$$

Maximum installed capacity of DGs:

$$\sum_{k=1}^{N_B} \sum_{j=1}^{N_C} C_j \cdot e_{jk} \leq G \quad (14)$$

Decision variables for the installation of a DG:

$$e_{jk} = \begin{cases} 0 & \text{if the DG is not installed at bus } k \\ 1 & \text{if the DG is installed at bus } k \\ & \text{with the capacity at step } j \end{cases} \quad (15)$$

Only one DG can be installed at one position:

$$\sum_{j=1}^{N_C} e_{jk} \leq 1 \quad k \in \{1, 2, \dots, N_B\} \quad (16)$$

where

C_{hi} = Outage cost (\$/kW) of customer due to contingency h with an outage duration of r_h

L_h = load at load point i

n_i = total number of load points

n_h = number of contingencies

P_k = power active power at bus k

Q_k = power reactive power at bus k

Y_{ik} = element (i, k) in bus admittance matrix

θ_{ik} = angle of Y_{ik}

δ_k = voltage angle at bus k

V_k^{\min} = minimum voltage at bus k

V_k^{\max} = maximum voltage at bus k

N_l = number of feeders

I_l = current flow in feeder l

I_l^{\max} = maximum current capability of feeder l

N_B = number of buses

e_{jk} = decision variable for installation of a DG at bus k with the capacity at step j

n_{DG} = total maximum of distributed generation

N_C = number of capacity steps of a DG

C_j = capacity at step j of distributed generation

G = maximum total installed capacity

5. Solution Algorithm

The solution algorithm for the problem is described step by step as follows:

- Step 1: Randomly select a feasible solution from the search space: $S_0 \in \Omega$. Set the size of a Tabu list, maximum iteration and iteration index $m=1$.
- Step 2: Let the initial solution obtained in step 1 be the current solution and the best solution: $S_{\text{best}} = S_0$, and $S_{\text{current}} = S_0$.
- Step 3: Perform a power flow analysis to determine whether the current solution satisfies the constraints defined in (9) and (10). A penalty factor is applied for constraint violation.
- Step 4: Calculate $ECOST$ using (8) with consideration of load point restoration.
- Step 5: Calculate the aspiration level of S_{best} : $f_{\text{best}} = f(S_{\text{best}})$. The aspiration level is the sum of $ECOST$ and a penalty function.
- Step 6: Generate a set of solutions in the neighborhood of S_{current} . This set of solutions is designated as S_{neighbor} .
- Step 7: Calculate the aspiration level for each member of S_{neighbor} , and choose the one that has the highest aspiration level, $S_{\text{neighbor_best}}$.
- Step 8: Check whether the attribute of the solution obtained in step 7 is in the Tabu list. If yes, go to step 9, or else $S_{\text{current}} = S_{\text{neighbor_best}}$ and go to step 10.

- Step 9: Accept $S_{neighbor_best}$ if has a better aspiration level than f_{best} and set $S_{current} = S_{neighbor_best}$, or else select a next-best solution that is not in the Tabu list to become the current solution.
- Step 10: Update the Tabu list and set $m = m+1$.
- Step 11: Repeat steps 6 to 10 until the specified maximum iteration has been reached and report the best solution.

where

- S_0 = initial solution
- Ω = search space
- S_{best} = best solution in search space
- $S_{current}$ = current solution in search space
- f_{best} = objective function of S_{best}
- $S_{neighbor}$ = neighborhood solutions of $S_{current}$
- $S_{neighbor_best}$ = best solution of $S_{neighbor}$

6. Case Study

The developed Tabu search algorithm was tested with a distribution system of PEA consisting of two feeders KWA01 and KWA06. The system is modified [9] to include disconnecting switches and fuses so that the benefit of DGs can be realized. There are 6 load points in feeder KWA01 and 20 load points in feeder KWA06. The configuration of the system is shown in **Figure 2**. The maximum iteration for Tabu search is 1,000. The minimum and maximum voltages for each bus are 0.95 p.u. and 1.05 p.u. The sizes of DGs are 100 kW, 200 kW, 300 kW, 400 kW and 500 kW. The failure of a transformer is recovered by repair. All the protective devices and DGs are assumed to be fully reliable. Seven cases are investigated in this case study.

- Case 1: No DG is installed in the system.
- Case 2: No more than one DG can be installed in the system.
- Case 3: No more than two DGs can be installed in the system.
- Case 4: No more than three DGs can be installed in the system.
- Case 5: Total installed capacity of DGs cannot be greater than 600 kW and no more than four DGs can be installed in the system
- Case 6: The same as case 5 except that total installed capacity of DGs cannot be greater than 800 kW.
- Case 7: The same as case 5 except that total installed capacity of DGs cannot be greater than 1,000 kW

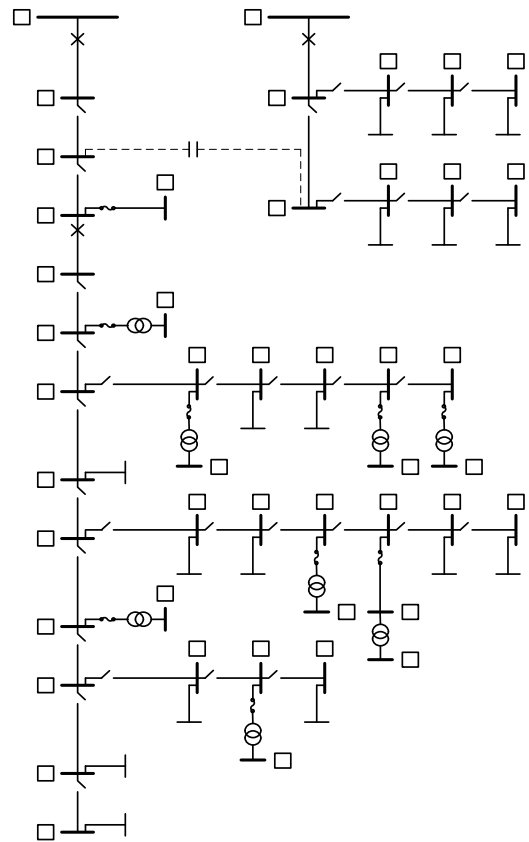


Figure 2. Single line diagram of two feeders of PEA.

The results from the case study are shown in **Tables 1, 2 and 3**. All the cases have the same SAIFI because this index depends only on the reliability of components (e.g., lines, transformers) and is not affected distributed generators to be installed.

We can see that the overall reliability indices of cases 2 to 7 are improved compared with that of case 1 (base case). In cases 2, 3, and 4, where the number of DGs is limited at 1, 2, and 3 respectively, see reductions in the system ECOST. It is very interesting to note that the constraint given in (13) is binding for these three cases.

Table 1. Location and capacity of distributed generators.

Case	Location of DG (bus)		Capacity of DG (kW)	
	KWA01	KWA06	KWA01	KWA06
1	-	-	-	-
2	-	24	-	500
3	6	24	300	500
4	6, 9	24	300, 300	500
5	7	24	100	500
6	9	24	300	500
7	9	18, 24	300	200, 500

Table 2. Reliability indices of case study 1-4.

Reliability indices	Case			
	1	2	3	4
SAIFI	7.33998	7.33998	7.33998	7.33998
SAIDI	17.8899	14.7669	14.7593	14.7484
CAIDI	2.43733	2.01184	2.01080	2.00932
ASAI	0.997958	0.998314	0.998316	0.998317
ASUI	0.002042	0.001686	0.001684	0.001683
ENS	45,746.8	42,008.7	41,347.6	40,833.1
AENS	116.404	106.892	105.210	103.007
ECOST	1,787,061	1,622,746	1,592,748	1,569,397

Table 3. Reliability indices of case study 5-7.

Reliability indices	Case		
	5	6	7
SAIFI	7.33998	7.33998	7.33998
SAIDI	14.7633	14.7521	14.3976
CAIDI	2.011356	2.009821	1.961523
ASAI	0.998315	0.998315	0.998356
ASUI	0.001685	0.001684	0.001643
ENS	41,958.9	41,494.1	41,313.7
AENS	106.766	105.583	105.124
ECOST	1,620,491	1,599,395	1,592,721

The reason is that to minimize the system ECOST, as many DGs as possible should be installed. However, for example, in case 3, a 300 kW unit, instead of a 400 kW or a 500 kW unit, is placed at bus 6. An explanation for this is that the 300 kW unit is sufficient for the demand at bus 6. Had the 400 or 500 kW unit been placed at bus 6 the system ECOST would have been the same. Likewise, a 300 kW in case 4 installed at bus 9 can sufficiently cover the demands of LP4, LP5, and LP6.

With regard to cases 5, 6, and 7, the constraint on total capacity of DGs is binding but the constraint on maximum number of DGs is not. The same reason given in cases 2, 3, and 4 are also used to explain the binding of these three cases. It is observed that a DG, if its size is large enough, tends to be installed at the end of a feeder. Such a placement is reasonable because the load point at the end of feeder has the highest failure rate and therefore most frequently needs a backup generation. In addition, the DG is able to supply power to upstream load points.

7. Conclusions

This paper has presented a Tabu search-based method for optimal placement of distributed generation in distribution systems with the main objective to maximize reliability benefits described in forms of the customer interruption cost. From reliability point of view, distributed generators are served as back up generation for load points that would otherwise have been left disconnected until the repair of a faulted component had been completed. The effectiveness of the proposed method was demonstrated by a case study of a distribution network of PEA with 26 load points. It can be seen from the case study that distributed generators can reduce the customer interruption cost and therefore improve the reliability of the system.

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Appendix

Table A1. Customer data of feeder KWA01.

Load Point	Number of Customer	Type	Demand	
			P (kW) Average	Q (kVAR)
LP1	1	Large Business	700	433.83
LP2	1	Large Business	700	433.83
LP3	1	Medium Business	220.5	136.65
LP4	1	Medium Business	35	21.69
LP5	1	Medium Business	105	65.07
LP6	1	Medium Business	105	65.07

Table A2. Customer data of feeder KWA06.

Load Point	Number of Customer	Type	Demand	
			P (kW) Average	Q (kVAR)
LP1	1	Large Business	3,130.75	1,940
LP2	105	Residence	32.50	20.14
LP3	31	Residence	9.75	6.04
LP4	1	Medium Business	110.25	68.33
LP5	31	Residence	9.75	6.04
LP6	31	Residence	9.75	6.04
LP7	21	Residence	6.50	4.03
LP8	1	Government	45.50	28.20
LP9	21	Residence	6.50	4.03
LP10	1	Small Business	10.50	6.51
LP11	1	Medium Business	175	108.46
LP12	31	Residence	9.75	6.04
LP13	84	Residence	26	16.11
LP14	1	Medium Business	56	34.71
LP15	1	Medium Business	175	108.46
LP16	1	Government	22.75	14.10
LP17	1	Government	17.50	10.85
LP18	1	Government	35	21.69
LP19	21	Residence	6.50	4.03
LP20	1	Government	9.75	6.04

Table A3. Customer damage function.

Type	Duration in Hours and Interruption Cost (Baht/kW)			
	1 hr	2 hr	4 hr	8 hr
Residence	8.694	19.050	39.762	80.716
Small Business	166.172	288.467	591.748	1,054.216
Medium Business	55.006	92.647	193.661	363.221
Large Business	50.877	79.913	145.614	251.938
Government	20.025	28.827	40.175	50.941

Table A4. Reliability parameters of feeders KWA01 and KWA06.

Component	λ (f/yr)	r (hr)	sw (hr)
Transformers	0.0150	200	-
Line	0.3700	5	1.06

where λ = failure rate of component; r = repair time; sw = switching time

Table A5. Type and length of feeder KWA01.

Line No.	Type	Length (km)
1	SAC 185	1.0760
2	PIC 185	0.9740
3	PIC 185	0.0066
4	PIC 185	0.1960
5	SAC 185	2.1750
6	SAC 185	0.4150
7	SAC 185	0.0610
8	SAC 185	0.0130
9	SAC 185	0.9800

Table A6. Type and length of feeder KWA06.

Line No.	Type	Length (km)
1	SAC 185	8.7400
2	SAC 185	0.3830
3	SAC 185	0.4290
4	SAC 185	0.2890
5	SAC 185	3.0060
6	ACSR 50	0.1900
7	ACSR 50	1.0690
8	ACSR 50	0.8540
9	ACSR 50	0.0170
10	ACSR 50	0.2220
11	ACSR 50	0.1580
12	ACSR 50	0.0810
13	ACSR 50	0.5080
14	ACSR 50	0.0640
15	ACSR 50	0.3120
16	ACSR 50	0.0510
17	ACSR 50	0.4660
18	ACSR 50	0.0910
19	ACSR 50	0.4100
20	ACSR 50	0.1660
21	ACSR 50	0.3190
22	ACSR 50	0.5050
23	ACSR 50	0.1300
24	ACSR 50	0.3940
25	ACSR 50	0.6930
26	ACSR 50	0.4300
27	ACSR 50	0.2910
28	ACSR 50	0.0910