Feeder Reconfiguration for Loss Reduction in Distribution System with Distributed Generators by Tabu Search

N. Rugthaicharoencheep and S. Sirisumrannukul

Abstract— *Feeder reconfiguration is a procedure to alter topological structures of the network by changing the statuses of tie and disconnecting switches. It provides an effective way to control the tie and sectionalizing switches in the system to give an appropriate connection for several reasons such as loss reduction, load balancing, and fast restoration. The main objective of this paper is to minimize the system power loss in the presence of distributed generators that cause reverse power flows and voltage variations. The optimization problem is subject to system constraints consisting of load-point voltage limits, radial configuration format, no load-point interruption and current feeder capability limits. The feeder reconfiguration problem for active power loss minimization is solved by a Tabu search algorithm that effectively utilizes a memory to provide an efficient search for optimality. The developed methodology is tested with a 69-bus distribution system having 48 load points. The study results indicate that for a given set of distributed generators and their locations, the proposed method can identify optimal on/off patterns of the switches that yield the minimum loss while satisfying the constraints.*

Keywords— **Feeder reconfiguration, Tabu search, Tie and sectionalizing switches, Loss reduction, Distributed generators.**

1. INTRODUCTION

Electricity is generated at central stations, powered up through transformers and transmitted over high voltage transmission lines, and passed down through low voltage distribution lines to final circuits for delivery to the customers. This 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.

Over the last decade, distribution systems have seen a significant increase in small-scaled generators as they can compensate the disadvantages encountered in the centralized generation dispatch. These generators, also known as distributed generation (DG), are installed in the network to serve as a source of power at on or near the site where they are to be used. They can be driven by different types of resource and technology such as wind, solar, fuel cells, hydrogen, and biomass.

The introduction of DG units brings a number of technical issues to the system. Many technical effects of distributed generators on the distribution system have been reported in literature such as thermal rating of equipment, system fault levels, stability, reverse power flow capabilities of tap-changers, line drop compensation, voltage rise, power losses, power quality (such as flickers and harmonics) and protection [1]. Distributed generators may introduce positive or negative impacts to the system depending on the system's operating conditions and their characteristics and locations. The emphasis of this paper is paid toward economic benefits presented in terms of active power loss reduction. The active power loss in the distribution network, which varies with the square of the branch current, is appreciable and constitutes a large portion of the overall power system loss. It was reported in [2] that distribution systems cause a power loss about 5–13% of the total power generated. Therefore, reducing the loss will financially and technically benefit the utility.

DG units can normally, but not necessarily, help reducing current flow in the feeders and hence contribute to power loss reduction, mainly because they are usually placed near the load being supplied. Minimizing the power loss, of course, requires an optimization process that can determine the optimal size and location of DG units to be installed. However, in practice, such an optimal solution could not be implemented as distributed generation plants are generally not planned by the utility but are developed by entrepreneurs (e.g., small power producer). For this reason, the location and rating of generators are limited by a number of constraints such as land and resource availability, and environment. For example, the location of a combined heat and power plant is determined by the position of the heat load, and their operation is generally controlled in response to the energy demand of the host site or of a district heating scheme [3]. Therefore, these constraints complicate the issue of loss since the distribution network with DG units is no longer passive.

Many methods have been employed for reducing the active power loss, for example, increasing conductor size, shortening circuit lengths, adjusting transformer tap, and installing capacitors. Another efficient operation that can improve the performance of distribution systems is feeder reconfiguration. It is a process that changes the

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topology of a distribution system by altering the open/closed status of switches.

This paper emphasizes the advantage of feeder reconfiguration to the distribution system in the presence of DG units for loss reduction and bus voltage improvement. The major effect of DG units on the feeder reconfiguration problem lies on the fact that power flows in the distribution system, which is normally radially operated, are no longer unidirectional (i.e., power can be fed back to the grid). Such reversible power flow, therefore, complicates the feeder reconfiguration problem for loss minimization. The application of a Tabu search algorithm is developed to determine the optimal on/off patterns of the switches to minimize the system loss subject to system constraints. The effectiveness of the methodology is demonstrated by a practical sized distribution system consisting of 69 bus and 48 load points.

2. FEEDER RECONFIGURATION

Feeder reconfiguration in a distribution system is an operation in configuration management that determines the switching operations for many purposes such as decreasing network loss, balancing system load, and improving bus voltages or system reliability. The configuration may be varied via switching operations to transfer loads among the feeders. Two types of switches are used: normally closed switches (sectionalizing switches) and normally open switches (tie switches) [4].

There are a number of closed and normally opened switches in a distribution system. The number of possible switching actions makes feeder reconfiguration become a complex decision-making for system operators. Figure 1 shows a schematic diagram of a simplified primary circuit of a distribution system [4]. In the figure, CB1-CB6 are normally closed switches that connect the line sections, and CB7 is a normally open switch that connects two primary feeders. The two substations can be linked by CB8, while CB9, when closed, will create a loop. A flowchart for feeder reconfiguration algorithm is shown in Figure 2.

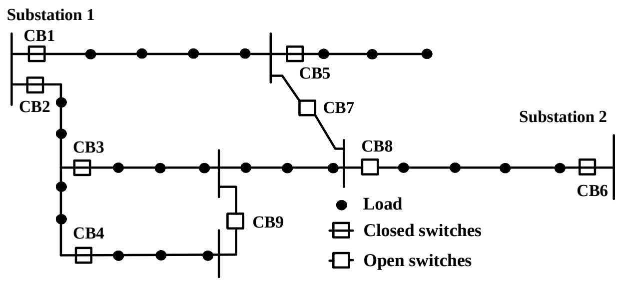

Fig.1. Schematic Diagram of a Distribution System.

3. PROBLEM FORMULATION

The objective function of the network configuration problem in this paper is to minimize the total power loss as:

$$\text{Minimize } Z = \sum_{n=1}^{N_L}\sum_{k=1}^{l}\left|I_{k,n}\right|^2 R_k \tag{1}$$

The objective function is subjected to the following constraints.

- Power flow equations:

$$P_{i,n} = \sum_{j=1}^{N_B}\left|Y_{ij}V_{i,n}V_{j,n}\right|\cos(\theta_{ij}+\delta_{j,n}-\delta_{i,n}) \tag{2}$$

$$Q_{i,n} = -\sum_{j=1}^{N_B}\left|Y_{ij}V_{i,n}V_{j,n}\right|\sin(\theta_{ij}+\delta_{j,n}-\delta_{i,n}) \tag{3}$$

- Bus voltage limits:

$$V^{\min} \le V_{i,n} \le V^{\max} \tag{4}$$

- Current transfer capability of feeders:

$$I_{k,n} \le I_k^{\max}\ ;\ k \in \{1,2,...,l\} \tag{5}$$

- Radial configuration format.
- No load-point interruption.

4. TABU SEARCH

Background

Tabu search (TS) is a meta-heuristic that guides a local heuristic search strategy to explore the solution space beyond local optimality. Tabu search was developed by Glover and has been used to solve a wide range of hard optimization problems, such as resource planning, telecommunications, financial analysis, scheduling, space planning, and energy distribution [5].

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 [6]. The quality of a move in solution space is assessed by aspiration criteria that provide a mechanism (see Figure 3) for overriding the Tabu list. Aspiration criteria are analogous to a fitness function of the genetic algorithm and the Bolzman function in the simulated annealing.

Neighborhood

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 4 shows the main concept of a search direction in Tabu search [7].

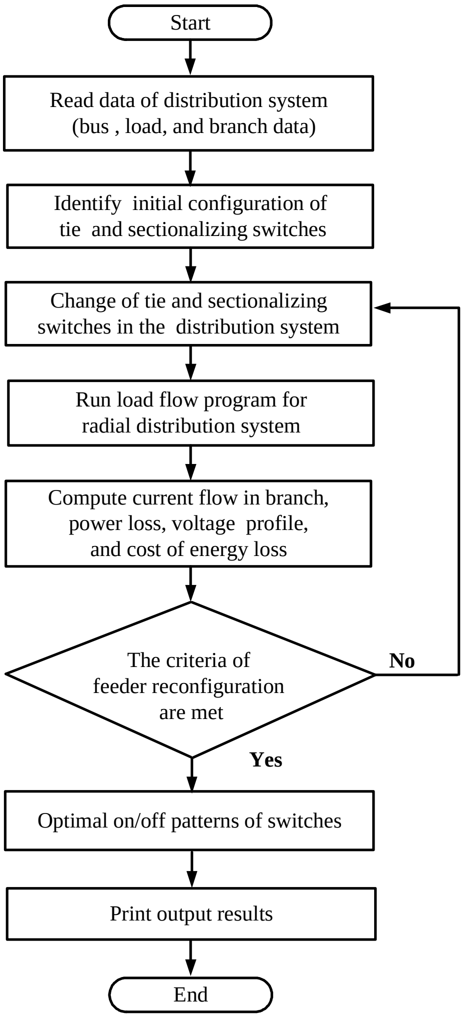

Fig.2. Flowchart of Feeder Reconfiguration.

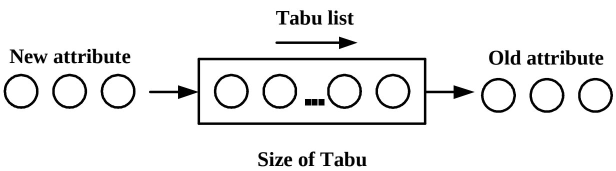

Fig.3. Mechanism of Tabu list.

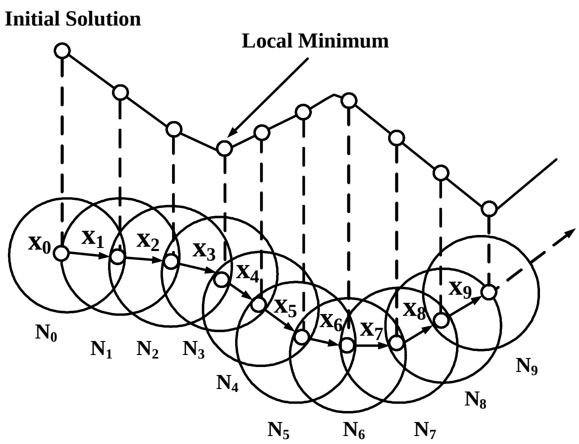

Fig.4. Search direction of Tabu Search.

5. SOLUTION ALGORITHM BY TABU SEARCH

The Tabu search algorithm is applied to solve the optimal or near optimal solution of the feeder configuration problem by taking the following steps:

Step 1: Read the bus, load and branch data of a distribution system including all the operational constraints.

Step 2: Randomly select a feasible solution from the search space: $S_0 \in \Omega$. The solution is represented by the switch number that should be opened during network reconfiguration.

Step 3: Set the size of a Tabu list, maximum iteration and iteration index $m = 1$.

Step 4: Let the initial solution obtained in step 2 be the current solution and the best solution: $S_{\text{best}} = S_0$, and $S_{\text{current}} = S_0$.

Step 5: Perform a power flow analysis to determine power loss, bus voltages, and branch currents.

Step 6: Calculate Z using (1) and check whether the current solution satisfies the constraints. A penalty factor is applied for constraint violation.

Step 7: Calculate the aspiration level of S_{best}: $f_{\text{best}} = f(S_{\text{best}})$. The aspiration level is the sum of Z and a penalty function

Step 8: Generate a set of solutions in the neighborhood of S_{current} by changing the switch numbers that should be opened. This set of solutions is designated as S_{neighbor}.

Step 9: Calculate the aspiration level for each member of S_{neighbor}, and choose the one that has the highest aspiration level, $S_{neighbor\_best}$.

Step 10: Check whether the attribute of the solution obtained in step 9 is in the Tabu list. If yes, go to step 11, or else $S_{current} = S_{neighbor\_best}$ and go to step 12.

Step 11: Accept $S_{neighbor\_best}$ if it 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 12: Update the Tabu list and set $m = m + 1$.

Step 13: Repeat steps 8 to 12 until a specified maximum iteration has been reached.

Step 14: Report the optimal solution.

An application of the Tabu search algorithm is shown by a three-feeder distribution system in Figure 5 [8]. The system consists of 16 buses, 13 load points, 13 normally closed switches, and 3 normally open switches. The initial configuration states that switches located on branch No. 14, No. 15 and No. 16 are open. With this configuration, the initial power loss is 511.44 kW. Figure 6 shows moves from the current solution to two feasible solutions generated by the Tabu search: neighborhood solutions 1 and 2. The moves to solutions 1 and 2 give a power loss of 676.63 kW and 483.87 kW, respectively. The same process continues until 100 iterations. The optimal solution indicates that switch No. 16 remains open and the statuses of switches No. 7 and 8 are changed from 'closed' to 'open', giving a real power loss of 466.12 kW.

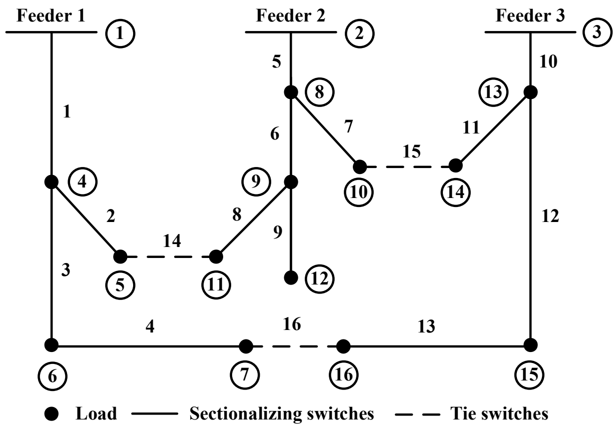

Fig.5. Single-line diagram of 16-bus distribution system.

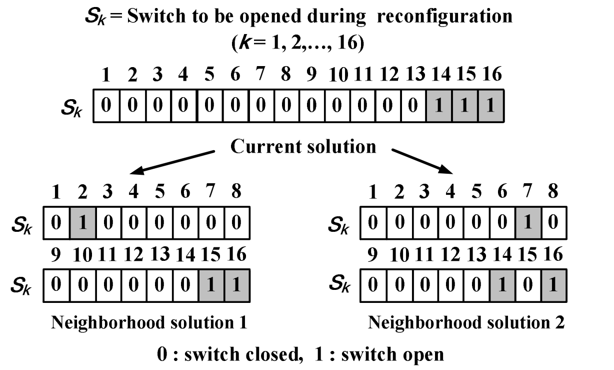

Fig.6. Neighborhood search for tie and sectionalizing Switches.

6. CASE STUDY

The test system for the case study is a 12.66 kV radial distribution system with 69 buses, 7 laterals and 5 tie-lines (looping branches), as shown in Figure 7. The current carrying capacity of branch No.1-9 is 400 A, No. 46-49 and No. 52-64 are 300 A and the other remaining branches including the tie lines are 200 A. Each branch in the system has a sectionalizing switch for reconfiguration purpose. The load data and branch data are provides in Table A1 and A2 [9]. The data associated with the loads in peak and off-peak periods are given in Table A3 [10]. Four cases are examined as follows:

Case 1: The system is without distributed generators and feeder reconfiguration

Case 2: The same as case 1 except that the feeders can be reconfigured by the available sectionalizing switches and the tie switches.

Case 3: The same as case 1 except that there are 4 small power producers who can provide only firm active power to the system by their DG units. The producers are located at buses 14, 35, 36, and 53 with capacities of 300, 200, 100, and 400 kW, respectively.

Case 4: The same as case 3 but with feeder reconfiguration.

The initial statuses of all the sectionalizing switches (switches No. 1-68) are closed while all the tie-switches (switch No. 69-73) open. The total loads for this test system are 3,801.89 kW and 2,694.10 kVAr. The feeder configuration algorithm, based on Tabu search as detailed in Section 5, is used to search the most appropriation topology of the system under a peak and off-peak load pattern. The minimum and maximum voltages are set at 0.95 and 1.05 p.u. The maximum iteration for the Tabu search algorithm is 100.

The test results for the four cases are summarized in Table 1. It is confirmed from case 3 that the distributed generators help reduce the system loss from 224.63 kW to 195.68 kW during the peak period and from 104.51 kW to 87.49 kW during the off-peak period, giving an annual saving of 478,406.50 Baht. However, if compared with Case 2, Case 3 sees a higher power loss. The minimum loss is seen in case 4, where there are changes in branch currents after the reconfiguration.

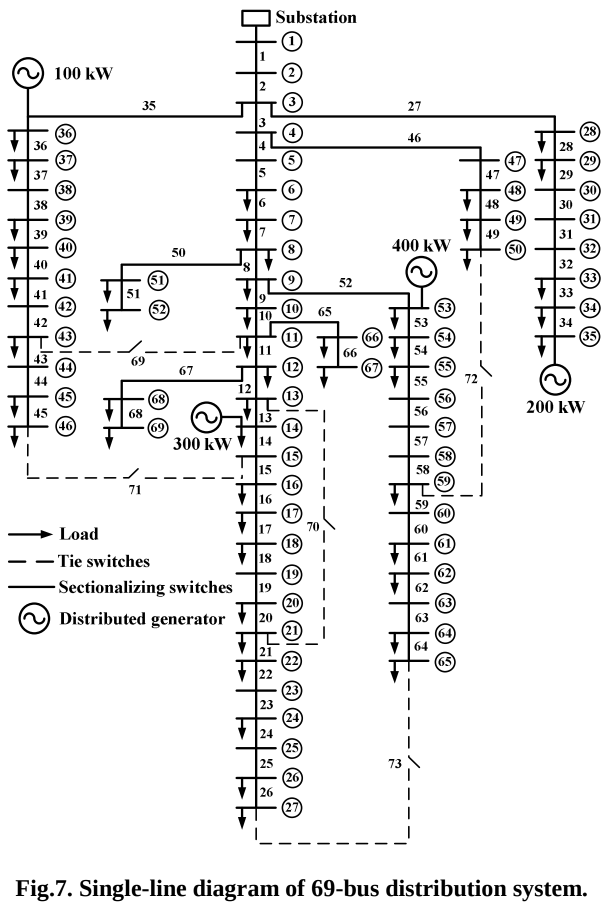

Fig.7. Single-line diagram of 69-bus distribution system.

Table 1. Results of Case Study

	Case 1	Case 2		Case 3	Case 4	
		TS	SA		TS	SA
Sectionalizing switches to be open	-	14, 56, 61	14, 57, 61	-	12, 52, 61	12, 18, 52, 61
Tie switches to be closed	-	71, 72, 73	71, 72, 73	-	71, 72, 73	70, 71, 72, 73
Power loss in peak period (kW)	224.63	98.56	99.58	195.68	82.58	82.92
Power loss in off-peak period (kW)	104.51	47.05	47.06	87.49	38.34	38.05
Total energy loss cost (Baht/year)	3,588,682.66	1,579,941.50	1,594,156.54	3,110,276.16	1,318,934.51	1,322,359.21

For example, the current flows in branch No. 3 to 11 are lower than those before reconfiguration. Because of the opening of switch No.12, these branches do not need to carry the currents to supply downstream load points at buses 13, 14, 16-18, 20-22, 24, and 25-26. However, the loads on these buses are not disconnected since tie-switch No.71 is closed so that the power is supplied through branch No.35-46 and 71, and therefore the current flows in these branches are increased.

In fact, feeder reconfiguration increases branch currents in some feeders while decreasing current flow in others but the latter effect outweighs the former. With this logical idea, feeder reconfiguration can, therefore, result in loss reduction. For this system, approximately 54-58% as much as loss reduction is achieved from the feeder reconfiguration for case 2 when compared with case 1 and for case 4 when compared with case 3. The solution convergence of this test system is shown in Figure 8, which reveals that the solution converges after iteration 51 for both peak and off-peak periods. The computation time for cases 2 and 4 is 924.61and 965.06 seconds.

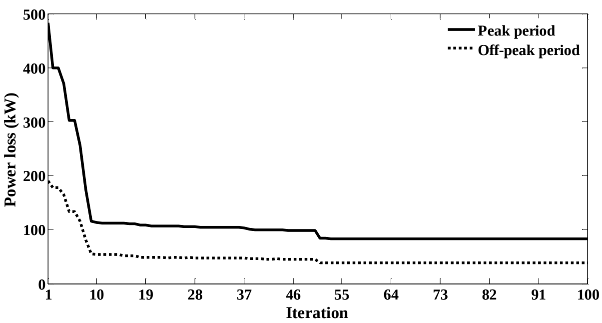

Fig.8. Convergence report of optimal solution.

The bus voltage profile for all the cases during peak period depicted in Figures 9 and 10 and off-peak period in Figures 11 and 12. It is observed that in cases 1 and 3, the voltages at buses 57-65 during peak period and at buses 61-65 in off-peak period are below 0.95 p.u. because a large load of 1,244 kW are drawn at bus 61. But for cases 2 and 4, all bus voltages satisfy the 0.95 p.u.-voltage constraint.

For the purpose of comparison, we have developed a simulated annealing (SA) algorithm applied to the feeder reconfiguration problem. The results from the two methods (i.e., Tabu search and simulated annealing) for case 2 and case 4 are provided in the Table 1. It can be observed that the power loss obtained from the two methods is comparable for on- and off-peak periods. However, the TS yields better savings in the energy loss cost mainly because the power loss in peak period, where the cost of energy is high, is lower. Note that for the TS in case 4, only 3 switching operations, instead of 4 as in the SA, are associated and is therefore preferred by the system operator.

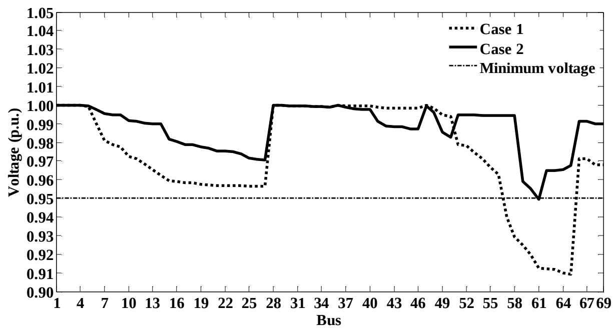

Fig.9. Bus voltage profile in peak period Case 1 and Case 2.

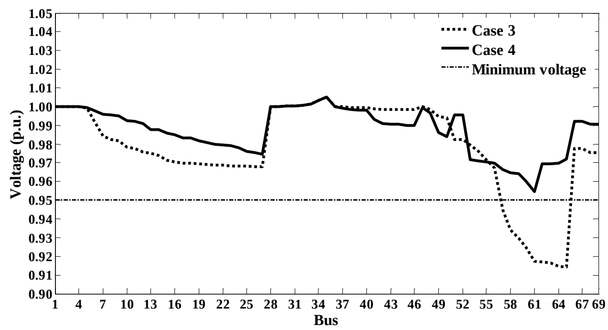

Fig.10. Bus voltage profile in peak period Case 3 and Case 4.

7. CONCLUSION

A Tabu search-based optimization technique has presented in this paper to find the most appropriate topology of the distribution system in the presence of distributed generators. The objective function of feeder reconfiguration is to minimize the total system loss. The objective function is subject to power flow equations, bus voltage limits, current transfer capability of feeders, radial configuration format, and no load-point interruption. A 69-bus distribution system with four distributed generators is used to demonstrate the effectiveness of the proposed technique. Although the distributed generators contribute to loss reduction, some bus voltages violate the minimum voltage constraint. Such a problem can be remedied by feeder reconfiguration. Not only are these bus voltages improved above the limit, but also the system power loss can be further reduced. The decrease in loss produces significant savings on the annual energy loss cost, thus emphasizing the benefit of feeder reconfiguration.

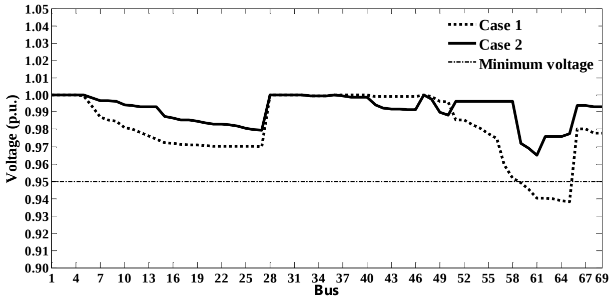

Fig.11. Bus voltage profile in off-peak period Case 1 and Case 2.

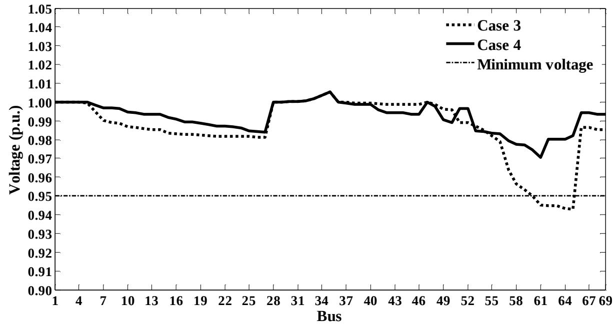

Fig.12. Bus voltage profile in off-peak period Case 3 and Case 4.

ACKNOWLEDGMENT

The first author would like to express his sincere thanks to the Rajamangala University of Technology Phra Nakhon (RMUTP), Thailand for financial support.

NOMENCLATURE

Z	total cost of energy loss
N_L	number of load levels
l	number of feeders
$I_{k,n}$	current flow in branch k at load level n
R_k	resistance of branch k
$P_{i,n}$	active power at bus i at load level n
N_B	number of buses
Y_{ij}	element (i, j) in bus admittance matrix
$V_{i,n}$	voltage of bus i at load level n
$V_{j,n}$	voltage of bus j at load level n
θ_{ij}	angle of Y_{ij}
$\delta_{i,n}$	voltage angle at bus i at load level n
$\delta_{j,n}$	voltage angle at bus j at load level n
$Q_{i,n}$	reactive power at bus i at load level n
$V^{\min}$	minimum voltage
$V^{\max}$	maximum voltage
$I_k^{\max}$	maximum current capability of branch k
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}

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APPENDIX

Table A1. Load Data of 69-bus Distribution System

Bus No.	P_L (kW)	Q_L (kVAr)	Bus No.	P_L (kW)	Q_L (kVAr)
6	2.60	2.20	37	26.00	18.55
7	40.40	30.00	39	24.00	17.00
8	75.00	54.00	40	24.00	17.00
9	30.00	22.00	41	1.20	1.00
10	28.00	19.00	43	6.00	4.30
11	145.00	104.00	45	39.22	26.30
12	145.00	104.00	46	39.22	26.30
13	8.00	5.00	48	79.00	56.40
14	8.00	5.50	49	384.70	274.50
16	45.50	30.00	50	384.70	274.50
17	60.00	35.00	51	40.50	28.30
18	60.00	35.00	52	3.60	2.70
20	1.00	0.60	53	4.35	3.50
21	114.00	81.00	54	26.40	19.00
22	5.00	3.50	55	24.00	17.20
24	28.00	20.00	59	100.00	72.00
26	14.00	10.00	61	1,244.00	888.00
27	14.00	10.00	62	32.00	23.00
28	26.00	18.60	64	227.00	162.00
29	26.00	18.60	65	59.00	42.00
33	14.00	10.00	66	18.00	13.00
34	19.50	14.00	67	18.00	13.00
35	6.00	4.00	68	28.00	20.00
36	26.00	18.55	69	28.00	20.00

Base 100 MVA, 12.66 kV

Table A2. Branch Data of 69-bus Distribution System

Branch Number	Sending end bus	Receiving end bus	R (Ω)	X (Ω)
1	1	2	0.0005	0.0012
2	2	3	0.0005	0.0012
3	3	4	0.0015	0.0036
4	4	5	0.0251	0.0294
5	5	6	0.3660	0.1864
6	6	7	0.3811	0.1941
7	7	8	0.0922	0.0470
8	8	9	0.0493	0.0251
9	9	10	0.8190	0.2707
10	10	11	0.1872	0.0619
11	11	12	0.7114	0.2351
12	12	13	1.0300	0.3400
13	13	14	1.0440	0.3450
14	14	15	1.0580	0.3496
15	15	16	0.1966	0.0650
16	16	17	0.3744	0.1238
17	17	18	0.0047	0.0016
18	18	19	0.3276	0.1083
19	19	20	0.2106	0.0690
20	20	21	0.3416	0.1129
21	21	22	0.0140	0.0046

Table A2. (Continued)

Branch Number	Sending end bus	Receiving end bus	R (Ω)	X (Ω)
22	22	23	0.1591	0.0526
23	23	24	0.3463	0.1145
24	24	25	0.7488	0.2475
25	25	26	0.3089	0.1021
26	26	27	0.1732	0.0572
27	3	28	0.0044	0.0108
28	28	29	0.0640	0.1565
29	29	30	0.3978	0.1315
30	30	31	0.0702	0.0232
31	31	32	0.3510	0.1160
32	32	33	0.8390	0.2816
33	33	34	1.7080	0.5646
34	34	35	1.4740	0.4873
35	3	36	0.0044	0.0108
36	36	37	0.0640	0.1565
37	37	38	0.1053	0.1230
38	38	39	0.0304	0.0355
39	39	40	0.0018	0.0021
40	40	41	0.7283	0.8509
41	41	42	0.3100	0.3623
42	42	43	0.0410	0.0478
43	43	44	0.0092	0.0116
44	44	45	0.1089	0.1373
45	45	46	0.0009	0.0012
46	4	47	0.0034	0.0084
47	47	48	0.0851	0.2083
48	48	49	0.2898	0.7091
49	49	50	0.0822	0.2011
50	8	51	0.0928	0.0473
51	51	52	0.3319	0.1114
52	9	53	0.1740	0.0886
53	53	54	0.2030	0.1034
54	54	55	0.2842	0.1447
55	55	56	0.2813	0.1433
56	56	57	1.5900	0.5337
57	57	58	0.7837	0.2630
58	58	59	0.3042	0.1006
59	59	60	0.3861	0.1172
60	60	61	0.5075	0.2585
61	61	62	0.0974	0.0496
62	62	63	0.1450	0.0738
63	63	64	0.7105	0.3619
64	64	65	1.0410	0.5302
65	11	66	0.2012	0.0611
66	66	67	0.0047	0.0014
67	12	68	0.7394	0.2444
68	68	69	0.0047	0.0016
Tie line				
69	11	43	0.5000	0.5000
70	13	21	0.5000	0.5000
71	15	46	1.0000	0.5000
72	50	59	2.0000	1.0000
73	27	65	1.0000	0.5000

Table A3. Load Levels and Cost Data

Load level	Load (p.u.)	Duration (hr)	Cost of energy (Baht/kW)
Off-peak	0.7	4, 015	1.1154
Peak	1.0	4, 745	2.9278