Feeder Reconfiguration with Dispatchable Distributed Generators in Distribution System by Tabu Search

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Abstract-**This paper presents a feeder reconfiguration problem to the distribution system with dispatchable distributed generators. The feeder configuration of the system and the dispatch of the distributed generators are two problems that need to be considered. A Tabu search algorithm is applied to search for the on/off patterns of the sectionalizing switches and tie switches to obtain the minimum total power loss, whereas the dispatch schedule of the distributed generators which gives the minimum total cost of generation is solved by an optimal power flow. The developed methodology is demonstrated by a 69-bus radial distribution system with distributed generators. The study results show that the optimal on/off patterns of the switches and the optimal dispatch schedule of the distributed generators can give the minimum total cost of generation while satisfying the system operational constraints and benefiting from savings in reduction of power loss and generation cost.**

Index Terms--**Feeder reconfiguration, Distributed Generator, Distribution system, Generation dispatch, Tabu search**

I. INTRODUCTION

Distribution systems are normally configured radially for effective coordination of their protective devices [1]. Two types of switches are generally found in the system for both protection and configuration management. These are sectionalizing switches (normally closed switches) and tie switches (normally opened switches) [2]. By changing the statuses of the sectionalizing and tie switches, the configuration of distribution system is varied, and loads are transferred among the feeders while the radial configuration format of electrical supply is still maintained. This implementation is known as feeder reconfiguration. The advantages obtained from feeder reconfiguration are, for example, real power loss reduction, balancing system load, bus voltage profile improvement, increasing system security and reliability, and power quality improvement [3-4].

Over the last decade, distribution systems have seen a significant increase in small-scaled generators, which is known as distributed generation (DG). Distributed generators are grid-connected or stand-alone electric generation units located within the distribution system at or near the end user. Recent development in DG technologies such as wind, solar, fuel cells, hydrogen, and biomass has drawn an attention for utilities to accommodate DG units in their systems [5]. As the penetration of distributed generation is expected to increase significantly in the near future, a paradigm shift in control, operation and planning of distribution networks may be necessary if this generation is to be integrated in a cost-effective manner. Such a transition enables the system operator to maximize the use of the existing circuits by taking full advantage of generator dispatch, control of transformer taps, voltage regulators, reactive power management and system reconfiguration in an integrated manner [6].

This paper emphasizes the implementation of feeder reconfiguration to the distribution system with dispatchable distributed generators by a Tabu search technique. The objective of the feeder reconfiguration is to minimize the total system power loss while keeping the generation cost of distributed generators at minimum. The purposed methodology is demonstrated by a 69-bus radial distribution system.

II. TABU SEARCH

Tabu search 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 [7] and has a great variety of real-world problems, such as resource planning, telecommunications, financial analysis, scheduling, space planning, and energy distribution [8].

Tabu search is a local search technique that uses an iterative search procedure to progressively improve the solution by a series of local moves to neighborhood solutions. Tabu search has the ability to escape from local minima 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 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 [9-10]. The quality of a move in solution space is assessed by aspiration criteria that provide a mechanism (see Fig. 1) for overriding the Tabu list.

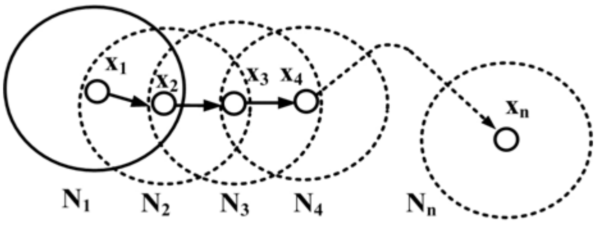

Fig. 1. Concept of Tabu search

III. 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) [3].

An application of the Tabu search algorithm is shown by a three-feeder distribution system in Fig. 2 [11]. 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. Fig. 3 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.

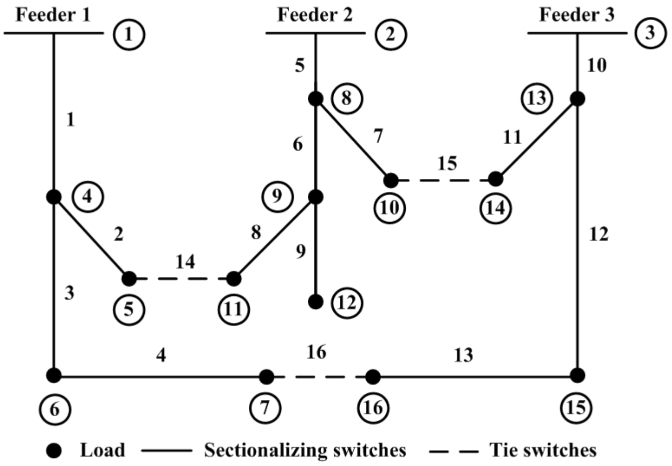

Fig.2. Single-line diagram of 16-bus distribution system

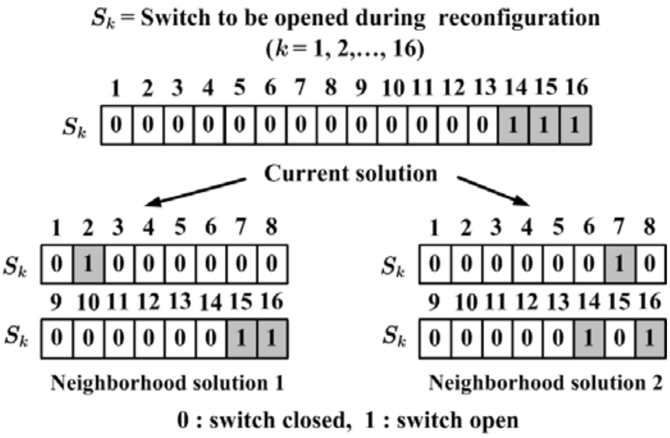

Fig.3. Neighborhood search for tie and sectionalizing switches

IV. PROBLEM FORMULATION

The optimization problem consists of two subproblems; namely, optimal feeder reconfiguration and optimal power flow. The objective of the optimal feeder reconfiguration problem is to minimize the total power loss as:

$$\text{Minimize } L = \sum_{t=1}^{Nl}\sum_{k=1}^{l} \left|I_k\right|^2 R_k \tag{1}$$

where L = total power loss
Nl = number of load levels
l = number of feeders
I_k = current flow in branch k
R_k = resistance of branch k

The objective function in (1) is subject to the following constraints.

- Power flow equations:

$$P_i = \sum_{j=1}^{Nb} \left|Y_{ij}V_iV_j\right| \cos(\theta_{ij} + \delta_j - \delta_i) \tag{2}$$

$$Q_i = -\sum_{j=1}^{Nb} \left|Y_{ij}V_iV_j\right| \sin(\theta_{ij} + \delta_j - \delta_i) \tag{3}$$

where P_i, Q_i = active and reactive power at bus i
Nb = number of buses
Y_{ij} = element(i, j) in bus admittance matrix
V_i, V_j = voltage of bus i and bus j
θ_{ij} = angle of Y_{ij}
δ_i, δ_j = voltage angle of bus i and bus j

- Bus voltage limits:

$$V^{\min} \le V_i \le V^{\max} \tag{4}$$

- Feeder capability limits:

$$\left|I_k\right| \le I_k^{\max} \quad k \in \{1,\ 2,\ 3,\ldots,\ l\} \tag{5}$$

- Maximum number of switching operations:

$$N_{sw} \le N_{sw}^{\max} \tag{6}$$

- Radial configuration format:
  The system has to remain radially operated after reconfiguration.
- No load-point interruption:
  All load points have to be served after reconfiguration.

where $V^{\min}$, $V^{\max}$ = minimum and maximum voltage
$I_k^{\max}$ = maximum current capability of branch k
N_{sw} = number of switching operations
$N_{sw}^{\max}$ = maximum number of switching operations

After the optimal on/off patterns of the switches are identified, an optimal power flow is performed to minimize the total generation cost of the active power generated by the distributed generators and the grid supply point as:

$$\text{Minimize } Z = \sum_{n=1}^{Ng} f_n(P_n) \tag{7}$$

The fuel cost functions of generation units can be presented as quadratic functions:

$$f_n(P_n) = a_n P_n^2 + b_n P_n + c_n \tag{8}$$

where Z = total fuel cost of generating units
f_n = cost function of unit n
P_n = active power generation of unit n
Ng = number of generating units
a_n, b_n, c_n = cost coefficients of unit n

The objective function in (7) is subject to the following constraints.

- Bus voltage limits:

$$V^{\min} \le V_i \le V^{\max} \tag{9}$$

- Active power generation limits:

$$P_n^{\min} \le P_n \le P_n^{\max} \tag{10}$$

- Reactive power generation limits:

$$Q_n^{\min} \le Q_n \le Q_n^{\max} \tag{11}$$

where $P_n^{\min}, P_n^{\max}$ = minimum and maximum active power of unit n
$Q_n^{\min}, Q_n^{\max}$ = minimum and maximum reactive power of unit n

V. SOLUTION METHODOLOGY

The Tabu search algorithm is applied to solve the feeder configuration problem using 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 an optimal power flow by a MATPOWER software package [12] to determine power loss, bus voltages, branch currents and generation schedules of the distributed generators.

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

Step 7: Calculate the aspiration level of $S_{\text{best}} : f_{\text{best}} = f(S_{\text{best}})$. The aspiration level is the sum of L 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, $S_{\text{neighbor\_best}}$.

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 $S_{\text{current}} = S_{\text{neighbor\_best}}$ and go to step 12.

Step 11: Accept $S_{\text{neighbor\_best}}$ if it has a better aspiration level than f_{best} and set $S_{\text{current}} = S_{\text{neighbor\_best}}$, 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: Repeat step 5 and report the optimal solution.

VI. CASE STUDY

The developed methodology is demonstrated by a radial distribution system with 69 buses, 7 laterals and 5 tie-lines (looping branches), as shown in Fig. 4. 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. Four DG units are located at buses 21, 33, 46, and 62 with capacities of 300, 100, 200, and 400 kW, respectively. The total installed capacity of the four DGs is 1,000 kW, accounting for 26.3% of the total system demand. The base values for voltage and power are 12.66 kV and 100 MVA. Each branch in the system has a sectionalizing switch for reconfiguration. The load data are given in Table AI and cost functions of the generators in Table AII. Table AIII provides branch data [13].

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 minimum and maximum voltages are set at 0.95 and 1.05 p.u. The maximum iteration for the Tabu search algorithm is 100. Five cases are examined as follows:

Case 1: The DGs provide only active power and the system is without feeder reconfiguration.
Case 2: The same as case 1 except that the system is reconfigured.
Case 3: The same as case 2 except that the DGs can also generate reactive power.
Case 4: The same as case 3 with a constraint that the number of switching operations of sectionalizing and ties switches must not exceed 4.
Case 5: The same as case 3 but the daily load pattern is divided into a 13-hour peak duration with a peak demand of 1.00 p.u. and a 11-hour off-peak duration with a peak demand of 0.70 p.u.

The numerical results for the 5 cases are summarized in Table I. It is seen that bus voltages for all cases are controlled to stay within the allowable range. When the feeders are reconfigured, the magnitudes of bus voltages in cases 2, 3 and 4 are improved compared with those of case 1. In addition, in these cases, the power loss and the total generation cost are decreased by changing switch statuses. Comparing case 2 with case 3, a power loss of 17 kW can be saved from the reactive power supplied from the DGs. As shown in case 4, a power loss is increased by 19 kW when the total number of switching operations is limited at 4. Like cases 2 and 3, case 5 in which the two load levels are taken into consideration requires 6 switching operations but with different sectionalizing switches to be open. Reconfiguration for case 5 is shown in Fig 5.

With reference to the dispatch results in Table I, the cheapest unit, DG_3 in case 1 supplies only 136.30 kW. The reason is that it is sufficient to cover the demands located between buses 36 and 46. After reconfiguration by closing switch No.71 for cases 2, 3, and 5 or switch No. 69 for case 4, the loading of DG_3 is at maximum because it can provide its power to the path connected to these switches. Also in case 1, DG_4, the most expensive unit, is loaded at its upper limit because it is located near the largest load of the system (1,244 kW) at bus 61.

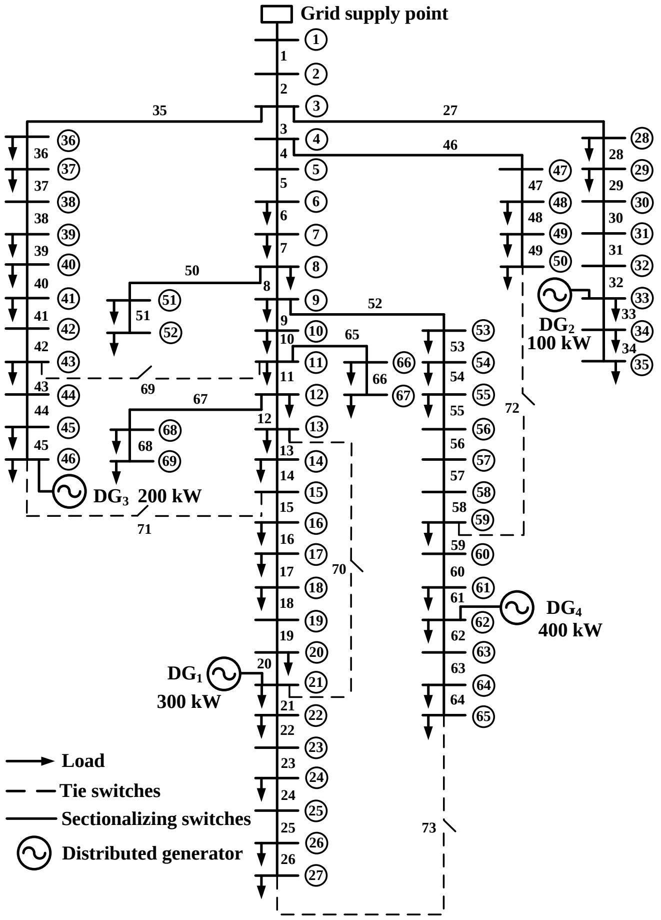

Fig. 4. Single-line diagram of 69-bus distribution system

After reconfiguration by opening switch No. 56 for cases 2, 4 and 5 or switch No. 58 for case 3, DG_4 is dispatched at its lower limit since the grid supply point and DG_3 are able to make up the 350 kW difference through the alternate path to bus 61.

TABLE I
RESULTS OF CASES STUDY

	Case 1	Case 2	Case 3	Case 4	Case 5	
					Peak	Off-peak
Active power from grid supply point (kW)	3,042.06	3,477.05	3,474.56	3,380.97	3,522.15	2,347.59
Active power of DG_1 (kW)	300.00	96.90	87.81	200.62	57.05	50.00
Active power of DG_2 (kW)	59.79	60.07	54.74	54.75	50.00	50.00
Active power of DG_3 (kW)	136.30	200.00	200.00	200.00	200.00	200.00
Active power of DG_4 (kW)	400.00	50.00	50.00	50.00	50.00	50.00
Reactive power from grid supply point (kVAr)	2,757.61	2,771.46	1,971.55	1,999.04	2,221.05	1,544.10
Reactive power of DG_1 (kVAr)	-	-	250.00	250.00	220.24	157.02
Reactive power of DG_2 (kVAr)	-	-	10.00	10.00	22.37	10.00
Reactive power of DG_3 (kVAr)	-	-	175.00	175.00	114.04	77.37
Reactive power of DG_4 (kVAr)	-	-	350.00	350.00	190.00	132.34
Minimum voltage (p.u.)	0.981 (Bus 61)	1.002 (Bus 61)	1.008 (Bus 61)	0.995 (Bus 65)	1.002 (Bus 61)	1.017 (Bus 61)
Maximum voltage (p.u.)	1.050 (Bus 1)	1.050 (Bus 1)	1.050 (Bus 1)	1.050 (Bus 1)	1.050 (Bus 1)	1.050 (Bus 33)
Number of switching operations	-	6	6	4	6	
Sectionalizing switches to be open	-	12, 56, 63	12, 58, 62	42, 56	14, 56, 61	
Tie switches to be closed	-	71, 72, 73	71, 72, 73	69, 72	71, 72, 73	
Power loss (kW)	136.00	82.00	65.00	84.00	77.00	36.00
Total cost of distributed generators ($/day)	8,453.43	7,886.66	7,870.87	7,995.43	7,828.22	

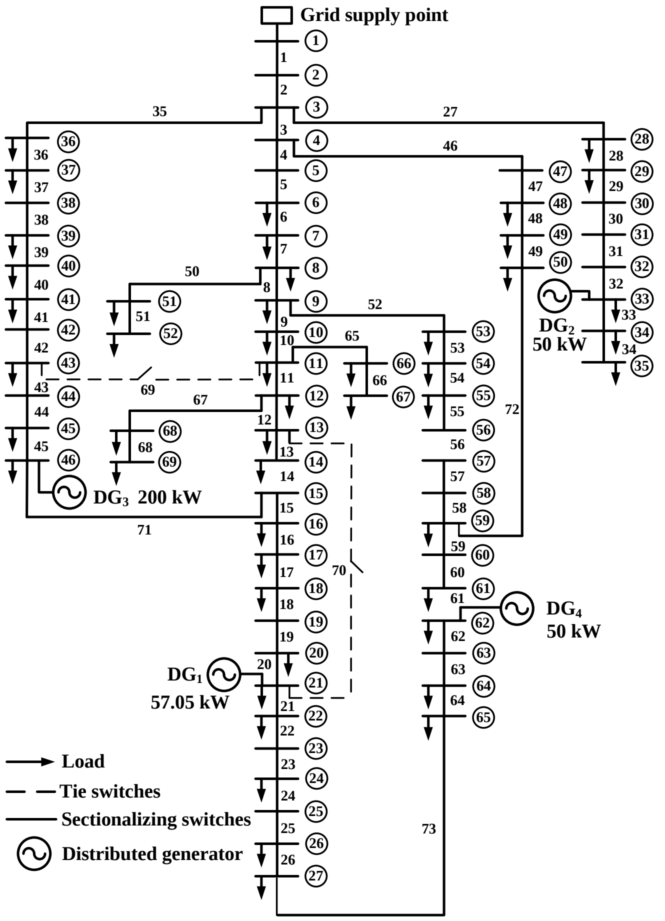

Fig. 5. Reconfiguration of 69-bus distribution system for case 5

VII. CONCLUSION

As the penetration of distributed generation is expected to increase significantly in the near future, the economic merit of feeder reconfiguration in the distribution system with distributed generators is evaluated in terms of reduction in power loss and generation cost. The topology of the feeders is reconfigured by opening sectionalizing switches and closing tie switches such that the power from the grid supply point and from distributed generators can be re-routed. The main tools employed in the investigation are Tabu search and optimal power flow. The results from the case study reveals that the statuses of tie and sectionalizing switches can be appropriately adjusted in conjunction with the dispatch schedule of the distributed generators so that savings from power loss and generation cost can be achieved while satisfying all the constraints imposed by the system and by the individual distributed generating units.

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REFERENCES

[1] M. A. Kashem, V. Ganapathy and G. B. Jasmon, "Network reconfiguration for load balancing in distribution networks," *IEE Proc.-Gener. Transm. Distrib.*, vol. 146, no. 6, pp. 563-567, November 1999.

[2] C. T. Su, and C. S. Lee, "Network reconfiguration of distribution systems using improved mixed-integer hybrid differential evolution," *IEEE Trans. Power Delivery*, vol. 18, no. 3, pp. 1022-1027, July. 2003.

[3] M. E. Baran, and F. F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing," *IEEE Trans. on Power Delivery*, vol. 4, no 2, pp. 1401-1407, April 1989.

[4] A. Autonino Augugliaro, L. Dusonchet, M. Giuseppe, and E. Riva, "Minimum losses reconfiguration of MV distribution networks through local control of tie-switches," *IEEE Trans. on Power Delivery*, vol. 18, no 3, pp. 762-771, July 2003.

[5] N. G. A. Hemdan, and M. Kurrat, "Distributed generation location and capacity effect on voltage stability of distribution networks," *Student paper annual IEEE Conf.*, pp.1-5, February 2008.

[6] T. Ackerman, "*Wind Power in Power System*," John Wiley and Sons, 2005.

[7] F. Glover, "Tabu search-part I," *ORSA J. Computing*, vol. 1, no.3, 1989.

[8] B. Dengiz, and C. Alabas, "Simulation optimization using tabu search," in *Proc. Winter Simulation Conf.*, pp. 805-810, 2000.

[9] H. Mori, and Y. Ogita, "Parallel tabu search for capacitor placement in radial distribution system," in *Proc. Power Engineering Society Winter Meeting Conf.*, pp 2334-2339. 2002.

[10] H. Mori, and Y. Iimura, "An improved tabu search approach to distribution network expansion planning under new environment," in *Proc. Power Technology. Conf.*, pp. 981-986, 2004.

[11] C. T. Su, , and C. S. Lee, , "Network reconfiguration of distribution systems using improved mixed-integer hybrid differential evolution," *IEEE Trans. on Power Delivery*, vol. 18 no. 3, pp 1022-1027, 2003.

[12] R. D. Zimmerman, C. E. Murillo-Sánchez, and D. Gan, "A MATPOWER™ power system simulation package version 3.1b2", *Power Systems Engineering Research (PSERC)*, September, 2006.

[13] J. S. Savier, and D. Das, "Impact of network reconfiguration on loss allocation of radial distribution systems," *IEEE Trans. on Power Delivery*, vol. 22, no. 4, pp. 2473-2480, October 2007.

APPENDIX

TABLE AI
LOAD DATA OF 69-BUS DISTRIBUTION SYSTEM

Bus Number	P_L (kW)	Q_L (kVAr)	Bus Number	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

TABLE AII
COST FUNCTIONS OF DISTRIBUTED GENERATORS

	cost function coefficients			P_i^{min}	P_i^{max}	Q_i^{min}	Q_i^{max}
	a_i	b_i	c_i	(kW)	(kW)	(kVAr)	(kVAr)
DG_1	0.015	46	77	50	300	10	250
DG_2	0.008	45	78	50	100	10	75
DG_3	0.004	45	78	50	200	10	175
DG_4	0.005	49	77	50	400	10	350

TABLE AIII
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
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

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