Modified Adaptive Tabu Search Algorithms for Economic Load Dispatch

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Abstract

This paper presents an application of the modified adaptive tabu search algorithms (mATS) to economic load dispatch (ELD). The proposed mATS algorithms with adaptive neighborhood easily handles different constraints like transmission losses, ramp rate limits and also prohibited operating zones. Simulations were divided into two parts, the first part has been set for static economic load dispatch over the six-unit test system and another part for dynamic economic load dispatch (DED) has treated over the five-unit test system with nonsmooth fuel cost function concerning valve point loading effects. Simulation results were a comparison between of the proposed mATS and of the other algorithms including the original ATS, genetic algorithms (GA) and particle swarm optimization (PSO). The findings affirmed the robustness and proficiency of the proposed algorithms over other existing techniques.

Keywords: Adaptive tabu search algorithms, Modified adaptive tabu search algorithms, Economic load dispatch, Ramp rate limit, Prohibited operating zones

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1. Introduction

The ELD problem, one of the different non-linear programming sub-problems of unit commitment in power system, is about minimizing the fuel cost of generating units for a specific period of operation so as to accomplish optimal generation dispatch among operating units and, in turn, to satisfy the system load demand and generator operation constraints with ramp rate limits and prohibited operating zones [1]. The resulting ELD is a non-convex optimization problem, which is a challenging one and cannot be solved by the traditional methods. Various search algorithms, eg. genetic algorithm (GA) [2], particle swarm optimization (PSO) [2], simulated annealing (SA) and tabu search (TS), [3-5], have previously been implemented on the ELD problem at hand.

This paper proposes a new optimization approach, to solve the ELD problem using an modified adaptive tabu search (mATS). In this paper, an attempt has been made to solve both the static and dynamic economic load dispatch problems in order to establish the capability of mATS to optimize a smooth quadratic cost function with generator constraints, power loss and ramp rate limits and prohibited operating zones through the six-generator test system for static ELD and dynamic ELD on five-generator test system. This paper is organized as follows. In Section 2, the problem description is presented. In Section 3, the modified adaptive tabu search algorithms is reviewed. In Section 4, simulation results and discussions are demonstrated. Finally, Section 5 is conclusion of this paper.

2. Problem Formulation

2.1 Static ELD

The static economic load dispatch problem (ELD) is to determine the optimal combination of power outputs of all generating units to minimize the total fuel cost while satisfying the load demand and operational constraints. The smooth cost function can be formulated as the following equation

$$\text{minimize } F = \sum_{i=1}^{N_G} f_i\left(P_i\right) \qquad (1)$$

where $f_i\left(P_i\right) = \alpha_i P_i^2 + \beta_i P_i + \gamma_i$, i=1,2,3, N_G, is the expression for cost function corresponding to i^{th} generating unit and α_i, β_i and γ_i are its cost coefficients. P_i is the real power output (in MW) of i^{th} generator corresponding to time period t. N_G is the number of online generating units to be dispatched.

Power balance constraint:

This constraint is based on the principle of equilibrium between total system generation and total system demand loads (P_D) and losses (P_L) as shown in equation (2),

$$\sum_{i=1}^{N_G} P_i = P_D + P_L \qquad (2)$$

where P_L can be obtained by equation (3)

$$P_L = \sum_{i=1}^{N_G}\sum_{j=1}^{N_G} P_i B_{ij} P_j + \sum_{i=1}^{N_G} B_{oi} P_i + B_{oo} \qquad (3)$$

where B- coefficients of the six unit test system are

$$B_{ij} = 10^{-3} \times \begin{bmatrix} 1.7 & 1.2 & 0.7 & -0.1 & -0.5 & -0.2 \\ 1.2 & 1.4 & 0.9 & 0.1 & -0.6 & -0.1 \\ 0.7 & 0.9 & 3.1 & 0 & -1.0 & -0.6 \\ -0.1 & 0.1 & 0 & 0.24 & -0.6 & -0.8 \\ -0.5 & -0.6 & -0.1 & -0.6 & 12.9 & -0.2 \\ 0.2 & -0.1 & -0.6 & -0.8 & -0.2 & 15.0 \end{bmatrix},$$

$$B_{oi} = 10^{-3} \times \begin{bmatrix} -0.3908 \\ -0.1297 \\ 0.7047 \\ 0.0591 \\ 0.2161 \\ -0.6635 \end{bmatrix}^T \; and \; B_{oo} = 0.056.$$

Generator capacity constraints:

The output power of each generating unit has a lower and upper bound so that it lies in between these bounds. This constraint is represented by a pair of inequality constraints as shown in equation (4),

$$P_i^{\min} \le P_i \le P_i^{\max} \quad (4)$$

where, $P_i^{\min}$ and $P_i^{\max}$ are lower and upper bounds for power outputs of the i^{th} generating unit.

Ramp rate limits:

The inclusion of ramp rate limits modifies the generator operation constraints as shown in equation (5),

$$\max\left(P_i^{\min}, P_i^0 - DR_i\right) \le P_i \le \min\left(P_i^{\max}, P_i^0 + UR_i\right) \quad (5)$$

where $P_i - P_i^0 \le UR_i$ as the power generation increases, or $P_i^0 - P_i \le DR_i$ as the power generation decreases. P_i^0 is the output power of previous hour of generating unit i. UR_i and DR_i are the upper and lower ramp rate limits, respectively.

Prohibited operating zones:

The generating units may have certain zones where operation is restricted on the grounds of physical limitations of machine components or instability e.g. due to steam valve or vibration in shaft bearings. Consequently, discontinuities are produced in cost curves corresponding to the prohibited operating zones.

The characteristics of the six thermal generating units are listed in Table 1.

Table 1 Generating unit capacity, Coefficients, Rate ramp limits and Prohibited zones

Unit	Capacity		Coefficients			Ramp rates limits			Prohibited Zones
	$P_i^{\min}$ (MW)	$P_i^{\max}$ (MW)	α_i ($)	β_i ($/MW)	γ_i ($/MW^2)	P_i^0 (MW)	UR_i (MW/h)	DR_i (MW/h)	(MW)
P_1	100	500	240	7.0	0.0070	440	80	120	[210 240] , [350 380]
P_2	50	200	200	10.0	0.0095	170	50	90	[90 110] , [140 160]
P_3	80	300	220	8.5	0.0090	200	65	100	[150 170] , [210 240]
P_4	50	150	200	11.0	0.0090	150	50	90	[80 90] , [110 120]
P_5	50	200	220	10.5	0.0080	190	50	90	[90 110] , [140 150]
P_6	50	120	190	12.0	0.0075	110	50	90	[75 85] , [100 105]

2.2 Dynamic ELD with valve point loading effect

Normally, the dynamic ELD (DED) can be formulated as a total cost function expressed in equation (6),

$$F = \sum_{t=1}^{T} \sum_{i=1}^{N_G} F_{it}\left(P_{it}\right) \quad (6)$$

where F is the total operating cost over the whole dispatch periods, T is number of hours in the horizon, N_G is number of generating unit, P_{it} is the total generating power output during t^{th} interval and $F_{it}\left(P_{it}\right)$ is the individual generation production cost in terms of real power output P_i at time t. $F_{it}\left(P_{it}\right)$ can be expressed as shown in equation (7),

$$F_{it}\left(P_{it}\right) = \alpha_i P_{it}^2 + \beta_i P_{it} + \gamma_i + \left|\delta_i \sin\left(\varepsilon_i \left(P_{it}^{\min} - P_{it}\right)\right)\right| \quad (7)$$

where α_i, β_i, and γ_i are constants of fuel cost function used in both ELD and DED but δ_i and ε_i are constants from valve point effect which are employed only to DED problem. The objective function will be minimized under these constraints 1) real power balance constraint $\sum_{i=1}^{N_G} P_{it} - P_{Dt} - P_{Lt} = 0$ where P_{Dt} and P_{Lt} are the total assumed load demand and the total transmission loss during the t^{th} interval respectively, see equation (1) with *B*-coefficient

$$B_{ij} = 10^{-5} \times \begin{bmatrix} 4.9 & 1.4 & 1.5 & 1.5 & 2.0 \\ 1.4 & 4.5 & 1.6 & 2.0 & 1.8 \\ 1.5 & 1.6 & 3.9 & 1.0 & 1.2 \\ 1.5 & 2.0 & 1.0 & 4.0 & 1.4 \\ 2.0 & 1.8 & 1.2 & 1.4 & 3.5 \end{bmatrix},\ B_{oi} = [0]_{1\times 5}\ and\ B_{oo} = 0$$

2) real power operating limit constraint $P_i^{\min} \le P_i \le P_i^{\max}$ and 3) generating ramp rate limit constraint $P_{it} - P_{i(t-1)} \le UR_i$ and $P_{i(t-1)} - P_{it} \le DR_i$. The P_{Lt} is obtained using B- coefficients given by [4].

Generating unit capacity, coefficients and rate ramp limits of the five-unit test system are summarized in Table 2 and Table 3 shows the demand power over twenty four hours.

Table 2 Generating unit capacity, Coefficients and Rate ramp limits. [4]

Unit	Capacity		Coefficients					Ramp rates limits	
	$P_i^{\min}$ (MW)	$P_i^{\max}$ (MW)	α_i ($/MW²h)	β_i ($/MWh)	γ_i ($/h)	δ_i ($/h)	ε_i (1/MW)	UR_i (MW/h)	DR_i (MW/h)
P_1	10	75	0.0080	2.0	25	100	0.042	30	30
P_2	20	125	0.0030	1.8	60	140	0.040	30	30
P_3	30	175	0.0012	2.1	100	160	0.038	40	40
P_4	40	250	0.0010	2.0	120	180	0.037	50	50
P_5	50	300	0.0015	1.8	40	200	0.035	50	50

Table 3 Demand power on the five-unit system in 24 hour.

Hour	P_{demand} (MW)	Hour	P_{demand} (MW)	Hour	P_{demand} (MW)	Hour	P_{demand} (MW)
1	410	7	626	13	704	19	654
2	435	8	654	14	690	20	704
3	475	9	690	15	654	21	680
4	530	10	704	16	580	22	605
5	558	11	720	17	558	23	527
6	608	12	740	18	608	24	463

3. Modified Adaptive Tabu Search

3.1 Concept of mATS

Tabu search (TS) is based on two main strategies: intensification strategy and diversification strategy. It has played an important role in optimization kernel for more than two decades [6,7]. In 2004, adaptive tabu search (ATS) was launched with two key mechanisms, back-tracking mechanism (BT) to unlock the deadlock by moving backward to a visited solution and adaptive search radius mechanism (AR) to accelerate search speed by reducing search radius when the current cost is in a threshold. Sujitjorn et al [8] has suggested that initial search radius should be in the ranges 20% - 60% of search space and other setting parameters of ATS are also consulted. There have been several approaches to enhance efficiency and performance of TS [9]. Until early 2011, modified adaptive tabu search (mATS) [10] was proposed to improve the performance of ATS by adding an adaptive neighborhood mechanism, namely AN. AN is normally invoked at the same time of AR. The mATS algorithms can be summarized in four steps as follows:

STEP 0: Initialization

Generate an initial solution, neighborhood, set the best solution, aspiration criteria (AC), termination criteria (TC), tabu list (TL), counter, search radius (R), and k^{th} backward.

STEP 1: Iteration

Generate search space and possible solutions in a neighborhood. Evaluate cost values for all solutions. If the current best solution has a lower cost than the best solution, replace the best solution by the current best and update the TL by tabuing the previous solution, otherwise the best solution remains unchanged and the current best solution becomes tabu instead. If the search does not improve the best solution for a time, go to STEP 3. Update counter.

STEP 2: Termination

Exit if the TC is met, otherwise go to STEP 1.

STEP 3: AR BT and AN mechanisms

If deadlock occurs, invoke the BT mechanism. If the cost value of the current best solution is lower than the preset cost, invoke the AR and AN mechanisms. Update counter and go to STEP 1.

There are two types of mATS used in this paper. First type is mATS-a which varies AN by reducing the number of neighbors and the second type, mATS-b will increase the number of neighbors when AN is invoked.

The objective function, J, for ELD problem is formulated in equation (8)

$$\text{minimize } J = F + \sum_{i=1}^{N_C} w_i C_i \qquad (8)$$

where F is cost function and $\sum_{i=1}^{N_C} w_i C_i$ is a sum of all constraint functions. w_i are the weighting functions and C_i are constraint functions. For ELD, there are four constraints, power balance, capacity, rate ramp limit and prohibited zones, respectively. That is $N_C = 4$, $w_1 = w_2 = 10^3$, $w_3 = w_4 = 10^5$. Another case, there are only three constraints for the dynamic ELD, $N_C = 3$, $w_1 = w_2 = 10^3$, $w_3 = 10^5$, power balance, capacity and rate ramp limit, respectively. Interested readers can see more details in [10].

3.2 Setting parameters for mATS

3.2.1 Static ELD

Initial parameters of mATS are R=20, TL=5, k^{th} backward=5, number of neighbors (N)=20. TC are max_count=10,000 or J<1.5452 x 10^4. mATS-a was obtained by adding AN with increasing number of neighbors into an ATS. Alternatively, by adding AN with decreasing number of neighbors into an ATS will obtain mATS-b. In mATS-a, there are six steps of AR-AR#1(if J<5 x 10^5 then R=5), AR#2(if J<2 x 10^4 then R=0.1), AR#3(if J<1.555 x 10^4 then R=0.001), AR#4(if J<1.55 x 10^4 then R=1 x 10^{-5}), AR#5(if J<1.547 x 10^4 then R=1 x 10^{-6}) and AR#6(if J<1.546 x 10^4 then R=1 x 10^{-8}) of mATS-a AN in mATS-a consists of three steps reducing number of neighbors from the beginning, 15 10 and 5, respectively, as follows AN#1(if J<5 x 10^5 then N=15), AN#2(if J<1.555 x 10^4 then N=10) and AN#3(if J<1.546 x 10^4 then N=5). AN in mATS-b also consists of three steps increasing number of neighbors from the beginning, 25 30 and 35 respectively, as follows AN#1(if J<5 x 10^5 then N=25), AN#2(if J<1.555 x 10^4 then N=30) and AN#3(if J<1.546 x 10^4 then N=35).

3.2.2 Dynamic ELD

Initial parameters of mATS are R=35, TL=5, k^{th} backward=5, number of neighbors =20. TC=(max_count = 10,000 or J<5.0 x 10^4). mATS-a was obtained by adding AN with decreasing number of neighbors into an ATS. Alternatively, by adding AN with increasing number of neighbors into an ATS will obtain mATS-b. In mATS-a, there are eight steps of AR-AR#1(if J<3.5 x 10^8 then R=0.07), AR#2(if J<8.4 x 10^6 then R=0.05), AR#3(if J<1 x 10^6 then R=0.01), AR#4(if J<9 x 10^4 then R=1 x 10^{-3}), AR#5(if J<5.7x10^4 then R=5 x10^{-4}) AR#6(if J<5.5 x10^4 then R=1x 10^{-5}) AR#7(if J<5.35 x 10^4 then R=1 x 10^{-6}) and AR#8(if J<5.265 x 10^4 then R=1 x 10^{-7}) of mATS-a AN in mATS-a consists of three steps reducing number of neighbors from the beginning, 15 10 and 5 respectively, as follows AN#1(if J<3.5 x 10^8 then N=15), AN#2(if J<1x 10^6 then N=10) and AN#3(if J<5.5 x 10^4 then N=5). AN in mATS-b also consists of three steps increasing number of neighbors from the beginning, 25 30 and 35 respectively, as follows AN#1(if J<3.5 x 10^8 then N=25), AN#2(if J<1 x 10^6 then N=30) and AN#3(if J<5.5 x 10^4 then N=35). Interested reader see more details in [7-8].

The same objective function equated (8) as used in static ELD case can be readily used for the dynamic ELD case by charging N_C from 4 to 3 as be seen in [5] where $w_1 = w_2 = 10^3$, $w_3 = 10^5$. C_i are the three constraint functions, power balance, capacity, and rate ramp limit, respectively.

4. Results and Discussion

The program was developed using MATLAB and run on a 2.6 GHz Intel dual-core CPU with 2 GB RAM and 160 GB HDD.

4.1 Static ELD

From 20 trials, the simultion results of mATS on the six-unit system were obtained and shown in Table 3 and the convergence curves of the best cases were selected for illustrating in Fig. 1.

Minimum cost results of the three search methods shown in Table 3 are investigated. PSO can obtain the lower cost (15450 \$/h) than of the GA's (15459 \$/h). Currently, both the proposed mATSs can do better than those. mATS-a found the lowest cost (15445 \$/h) that differs from the mATS-b's (15446 \$/h) about one dollar. The average CPU time of mATS-b, 5.1259 seconds, is shorter than a half of the mATS-a's, 11.5117 seconds.

Fig. 1 shows the comparative convergence characteristics between the mATS-a and mATS-b. Although the initial solution of mATS-b (J=2.1857x10^6) is higher than of mATS-a's (J=1.4035 x 10^6), however it could meet the termination criteria (TC, J<1.5452 x 10^4) very fast. mATS-b spent only 1.2979 seconds within 194 iterations, but mATS-a spent 4.8141 seconds within 2046 iterations.

Table 4 Results of six unit system (1,263 MW demand)

Generator power output (MW)	mATS-a	mATS-b	PSO [2]	GA [2]
P_1	447.6362	437.1214	447.4970	474.8066
P_2	167.1717	173.0921	173.3221	178.6363
P_3	261.5180	254.1248	263.4745	262.2089
P_4	138.4030	147.6131	139.0594	134.2826
P_5	170.8444	171.7864	165.4761	151.9039
P_6	90.0663	91.6474	87.1280	74.1812
Total power gen. (MW)	1275.69	1275.38	1276.01	1276.03
Minimum cost (\$/h)	15445.57	15446.65	15450	15459
P_{loss} (MW)	12.6333	12.3905	12.9584	13.0217
Maximum cost (\$/h)	15451.91	15451.86	-	-
Average cost (\$/h)	15449.52	15449.40	-	-
Average CPU time(sec)	11.5117	5.1259	-	-

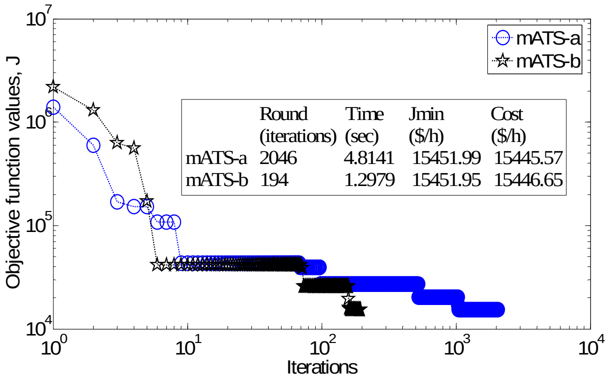

Fig. 1 Convergence curves of both types of mATS on the six-unit system

4.2 Dynamic ELD

The simulation results of mATS and ATS on the five-unit system were obtained from independent 20 trials and listed in Table 5 and Table 6.

Table 5 Comparison between the original ATS and mATSs

	Generation Cost ($), J				CPU time $_{av}$
	Min.	Max	Average	SD.	(sec)
ATS	52,591	1,661,744	1,035,284	599,793	517.136
mATS-a	1,155,464	2,654,207	1,849,993	425,979	421.193
mATS-b	52,398	55,162	53,074	638	1,541.105

Table 5 shows the results of ATS, mATS-a and mATS-b. We can see that mATS-b can obtain the better solution than the other two methods, ATS and mATS-a, because its minimum maximum and also average costs are closed together according to the obtained standard deviation values. mATS-b gave the average objective function, J=53,074 $, mATS-a's is 1,849,993 $ and of the ATS-a is 1,035,284 $.

Table 6 shows the best solution of mATS-b with total cost (J) 52,398 $ as the highest quality of the obtained solution under the same termination criteria (10,000 iterations) for all trials.

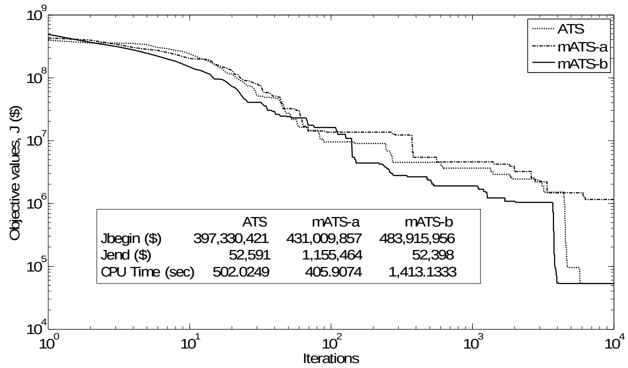

Fig. 2 Convergence curves of both types of mATS on the five-unit system

The convergence curves of the best cases were selected for illustrating in Fig. 2. It shows that mATS-b's curve can reach to the lower objective function value, (J=52,398 $). The closer one of ATS's is with a little bit higher values, J=52,591 $ and the last one of mATS-a's ends at a very high J, 1,155,464 $. The inferior outcome from mATS-a may be an effect of inadequate number of neighbors to keep the right direction to the global solution. However, mATS-b is still applicable for solving the dynamic ELD problem. Although right now it may not be able to find the better quality of solution than of the previous methods reported in [5], but a better technique to tune parameters of the mATS may help them get better performance in such dynamic ELD problem soon.

Both results of static and dynamic ELD problems show that increasing number of neighbors in mATS-b can obtain higher quality of solutions and can also gain better performance in search process with respect to mATS-a. It encourages the user of mATS to confidently select mATS-b type for solving the ELD problems.

Table 6 The best solution of mATS-b on the five-unit system on 24-hour demand**.**

Hour	P_{demand} **(MW)**	$P_{generate}$ **(MW)**	P_{G1} **(MW)**	P_{G2} **(MW)**	P_{G3} **(MW)**	P_{G4} **(MW)**	P_{G5} **(MW)**
1	410	413.62	66.2055	38.6384	46.4159	136.9680	125.3981
2	435	438.75	41.5080	42.7011	71.4806	114.1334	168.9274
3	475	479.79	16.9491	71.9084	94.8769	103.9938	192.0672
4	530	535.97	20.5211	61.8005	97.1071	147.5260	209.0216
5	558	564.49	38.7419	79.2453	125.4632	121.4353	199.6079
6	608	615.84	41.8369	86.4193	125.0531	119.9511	242.5790
7	626	634.16	59.9768	110.0256	111.2564	141.7067	211.1986
8	654	663.25	71.7054	123.8370	102.7655	115.9614	248.9779
9	690	700.44	53.7815	101.0718	91.1947	160.8955	293.4943
10	704	714.78	45.5126	107.0155	97.3736	193.3707	271.5058
11	720	731.00	62.6820	119.8645	124.9821	194.4878	228.9851
12	740	751.65	73.8895	92.2959	122.4612	198.9689	264.0353
13	704	714.53	60.1191	71.5405	121.2674	222.0677	239.5378
14	690	700.00	41.5135	98.7742	142.0185	185.4285	232.2792
15	654	663.19	66.9373	102.3399	115.7803	166.6477	211.4934
16	580	587.06	45.3906	85.3830	110.2498	145.2624	200.7756
17	558	564.92	43.6824	110.8779	113.2114	138.0341	158.7317
18	608	616.16	59.5939	97.6113	139.8856	142.5079	176.0559
19	654	663.39	41.7664	107.7159	144.1478	162.4198	207.1436
20	704	714.87	55.5788	95.8465	145.4042	179.5553	238.0015
21	680	690.22	60.7439	114.5169	129.4365	134.9216	250.3086
22	605	613.18	48.8404	86.7701	108.7512	164.3799	203.9678
23	527	532.98	19.1110	64.9793	118.1193	116.7060	213.9469
24	463	467.72	15.4945	62.4078	100.6812	116.5722	172.3374

5. Conclusion

In this paper, we have successfully employed the mATS method to solve both constrained ELD problems, static and dynamic ELDs. In static ELD case, the mATS algorithm has been demonstrated to have a superior feature on high-quality solutions. Although mATS-b can obtain a slightly better solution than mATS-a's, but the average CPU time of 20 trials shows that mATS-b can do faster than the mATS-a does about two times. Convergence property of mATS on ELD problem is also experimentally proved. Many nonlinear characteristics of the generator such as ramp rate limits and prohibited zones are considered for practical generator operation in the proposed methods. The results show that the proposed methods were indeed capable of obtaining higher quality solutions efficiently in six-unit ELD problems. Another case in the name of dynamic ELD or DED, the mATS with its efficient AN mechanism could effectively solve a five-unit DED problem with nonsmooth cost function included generating rate rate limit constraint. The presented scheme attempts to show the advantage of mATS-b against mATS-a and ATS over a DED problem. The test results over the five-unit test system reveal that the optimal dispatch solutions obtained through the mATS-b lead to less operating cost than those found by other methods, which show the capability of the proposed algorithm to determine the global or near global solution for DED problem. The proposed mATS-b outperforms original ATS and another mATS-a for the five-unit DED problem in terms of quality of solution under certain number of iterations.

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