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Dynamic Economic Dispatch Solution with Practical Constraints Using a Recurrent neural network

***Abstract**. This paper proposes a solution to the dynamic economic dispatch (DED) with practical constraints using a Hopfield neural network (HNN). The constrained DED which will be solved in this paper must satisfy (i) the system load demand (ii) the spinning reserve capacity (iii) ramp rate limits and (iv) prohibited operating zone. The feasibility of the proposed HNN method is demonstrated using two power systems, and it is compared with the other methods in terms of solution quality and computation efficiency.*

***Streszczenie.** Artykuł proponuje rozwiązanie dynamicznej gospodarki przesyłem energii z uwzględnieniem ograniczeń przy wykorzystaniu sieci neuronowych Hopfield (HNN). Zaproponowana metoda została sprawdzona w dwóch systemach elektroenergetycznych i porównana z innymi metodami pod względem jakości i efektywności rozwiązań obliczeniowych. (**Dynamiczne rozwiązanie gospodarki przesyłem energii przy wykorzystaniu sieci neuronowych**)*

Keywords: dynamic economic dispatch, Hopfield Neural Network, prohibited operating zone, ramping rate limits.
Słowa kluczowe: sieci neronowe Hoipfielda, gospodarka przesyłem energii.

Introduction

DED is used to determine the optimal schedule of generating outputs on-line so as to meet the load demand at the minimum operating cost under various system and operating constraints over the entire dispatch periods. DED is an extension of the conventional economic dispatch (ED) problem that takes into consideration the limits on the ramp rate of generating units to maintain the life of generation equipment [1, 2]. In general, the DED is solved by discretization of the entire dispatch period into a number of small time periods. Therefore, the static ED in each dispatch period is solved subject to the power balance constraints and generator operating limits. Previous efforts on solving static ED problems have employed various mathematical programming methods and optimization techniques (lambda-iteration method, the base point and participation factors method, the gradient method and dynamic programming (DP)) [3]. Unfortunately, for generating units with non-linear characteristics, such as prohibited operating zones, ramp rate limits, and non-convex cost functions, the conventional methods can hardly to obtain the optimal solution. Furthermore, for a large-scale mixed-generating system, the conventional methods often oscillate which result in a local minimum solution or a longer solution time [4].

In the past decade, the global optimization techniques known as genetic algorithms (GA), simulated annealing (SA), tabu search (TS), evolutionary programming (EP), and particle swarm optimization (PSO) have been successfully used to overcome the non-convexity problems of the constrained ED [5, 6, 7], but the greater CPU time/iteration was its drawback.

Artificial intelligent techniques, such as Hopfield neural networks (HNN), have also been employed to solve DED problems [8]. However, an unsuitable transfer function adopted in the Hopfield model may suffer from excessive numerical iterations, resulting in huge calculations [9].

To overcome these drawbacks, we have attempted to construct and implement of a HNN, which employs a linear transfer function.

Problem description

The ED planning must perform the optimal generation dispatch among the operating units to satisfy the system load demand, spinning reserve capacity, and practical operation constraints of generators that include the ramp rate limit and the prohibited operating zone [7].

A. Practical Operation Constraints of Generator

For convenience in solving the DED problem, the unit output is usually assumed to be adjusted smoothly and instantaneously. Practically, the operating range of all online units is restricted by their ramp rate limits [3, 4]. In addition, the prohibited operating zones in the input-output curve of generator are due to steam valve operation or vibration in a shaft bearing. The best economy is achieved by avoiding operation in areas that are in actual operation. Hence, these two constraints must be taken into account to achieve true economic operation.

1) Ramp Rate Limit: According to [5, 10, 11], the inequality constraints due to ramp rate limits for unit generation changes are given as follow:

(1) $$P_i^t - P_i^{t-1} \le R_i^{up}$$

(2) $$P_i^{t-1} - P_i^t \le R_i^{down}$$

$$i = 1,...,N \text{ and } t = 1,...,T$$

where P_i^t is the output power at interval t, and P_i^{t-1} is the previous output power. R_i^{up} is the upramp limit of i-th generator at period t, (MW/time-period); and R_i^{down} is the downramp limit of the i-th generator (MW/time period).

2) Prohibited Operating Zone: Fig. 1 shows the input–output performance curve for a typical thermal unit with Prohibited Zone.

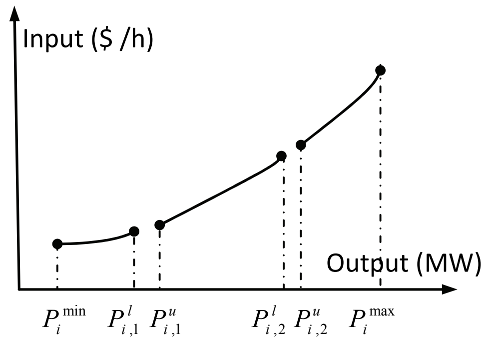

Fig. 1. shows the input– output performance curve for a typical thermal unit with Prohibited Zone.

The operating zones of unit can be described as follows:

$$
(3) \qquad P_i^t \in \begin{cases} P_i^{\min} \le P_i^t \le P_{i,1}^l \\ P_{i,j-1}^u \le P_i^t \le P_{i,j}^l \quad , j = 2,3,\dots,n_i \\ P_{i,n_i}^u \le P_i^t \le P_i^{\max} \end{cases}
$$

where n_i is the number of prohibited zones of generator *i*. $P_{i,j}^l$, $P_{i,j}^u$ are the lower and upper power output of the prohibited zones *j* of the generator *i*, respectively.

B. Objective function

The objective of DED is to simultaneously minimize the generation cost rate and to meet the load demand of a power system over some appropriate period while satisfying various constraints. To combine the above two constraints into a DED problem, the constrained optimization problem at specific operating interval can be modified as:

$$
(4) \min\ C_T = \sum_{t=1}^{T}\sum_{i=1}^{N} C_i^t(P_i^t) = \sum_{t=1}^{T}\sum_{i=1}^{N} a_i + b_i\, P_i^t + c_i\,(P_i^t)^2
$$

where C_T is the total generation cost; $C_i^t(P_i^t)$ is the generation cost function of ith generator at period t, which is usually expressed as a quadratic polynomial; a_i, b_i, and c_i are the cost coefficients of the *i*-th generator; P_i^t is the power output of the ith generator and *N* is the number of generators, *T* is the total periods of operation.

Subject to the following constraints

i) Power balance

$$
(5) \qquad \sum_{i=1}^{N} P_i^t = D^t + L^t
$$

where D^t is the load demand at period *t* and L^t is the total transmission losses, which is a function of the unit power outputs that can be represented using the B-coefficients:

$$
(6) \qquad L^t = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i^t B_{ij} P_j^t + \sum_{i=1}^{N} B_{0i} P_i^t + B_{00}
$$

where *B*, B_0 and B_{00} are the loss-coefficient matrix, the loss-coefficient vector and the loss constant, respectively.

(ii) System spinning reserve constraints

$$
(7) \qquad \sum_{i=1}^{N}\left[\min\left(P_i^{\max} - P_i^t, R_i^{up}\right)\right] \ge SR^t,\ t = 1,2,\dots,T
$$

ii) generator operation constraints

$$
(8) \quad \max(P_i^{\min}, P_i^{t-1} - R_i^{down}) \ \le\ P_i^t \ \le\ \min(P_i^{\max}, P_i^{t-1} + R_i^{up})
$$

where P_i^{min} and P_i^{max} are the minimum and maximum outputs of the *i*th generator respectively.

The generation output P_i^t must fall in the feasible operating zones of unit *i by* satisfying the constraint described by Eq.(3).

An enhanced HNN applied to ED

The continuous model of the HNN is based on continuous output variables, and the transfer function is a continuous and monotonically increasing function. The model is a mutual coupling and of non-hierarchical structure. The dynamic characteristic of each neuron can be described by:

$$
(9) \qquad \frac{dU_i}{dt'} = I_i + \sum_{j=1}^{N} T_{ij} V_j
$$

where U_i is the total input of neuron *i*; V_i is the output of neuron *i*; T_{ij} is the interconnection conductance from the output of neuron *j* to the input of neuron *i*; T_{ii} is the self-connection conductance of neuron *i* and I_i is the external input to neuron *i*.

It should be noted here that *t'* is not representing real time, it is a dimensionless variable.

The energy function of the continuous Hopfield model can be defined as:

$$
(10) \qquad E = -\frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N} T_{ij} V_i V_j - \sum_{i=1}^{N} I_i V_i
$$

In the computation process the model state always moves in such a way that energy function gradually reduces and converges to a minimum [12].

A. Mapping of ED into the Hopfield model

To solve the ED problem using the HNN, energy function is defined as follows:

$$
(11)\ E = \frac{W_{PM}}{2}\left((D+L) - \sum_{i=1}^{N} P_i\right)^2 + \frac{W_F}{2}\sum_{i=1}^{N}\left(a_i + b_i P_i + c_i P_i^2\right)
$$

where positive weighting factors W_{PM} and W_F introduce the relative importance of P_m and total fuel cost *F, respectively*. To avoid saturation, a linear model is used to describe the transfer function, where U_{min} and U_{max} are the minimum and maximum input of neurons.

:

$$
(12)\ P_i = \begin{cases} \dfrac{U_i - U_{\min}}{U_{\max} - U_{\min}}.(P_i^{\max} - P_i^{\min}) + P_i^{\min} & U_{\min} \le U_i \le U_{\max} \\ P_i^{\max} & U_i \ge U_{\max} \\ P_i^{\min} & U_i \le U_{\min} \end{cases}
$$

.

Comparing the energy function Eq.11 with the Hopfield energy function Eq.10, we get:

$$
(13) \qquad T_{ii} = -\ W_{PM} - W_F.c_i
$$

$$
(14) \qquad T = -W
$$

$$
(15) \qquad I_i = W_{PM}\left(D + L\right) - W_F\left(b_i / 2\right)
$$

Substituting Eq.13, Eq.14 and Eq.15 into Eq.8, the dynamic equation becomes,

$$
(16) \qquad dU_i / dt' = AP_m - (W_F/2)(dC_i/dP_i)
$$

with $\qquad P_m = D - \sum_{i=1}^{N} P_i$

Substituting Eq.12 in Eq.16 the dynamic equation becomes:

$$
(17) \qquad dU_i / dt' = AP_m - \left(W_F/2\right)\left(b_i + 2c_i\left(Z_{1i}U_i + Z_{2i}\right)\right)
$$

with

$Z_{1i} = \left(P_i^{\max} - P_i^{\min}\right) / \left(U_{\max} - U_{\min}\right)$ and

$Z_{2i} = P_i^{\min} - Z_{1i}U_{\min}$

Solving Eq.17 for the neuron's input function

(18) $U_i(t') = \left(U_i(0) + \left(Z_{4i}/Z_{3i}\right)\right)e^{K_{3i}t'} - \left(Z_{4i}/Z_{3i}\right)$

with $Z_{3i} = -W_{PM}\, c_i Z_{1i}$

and $Z_{4i} = -W_{PM} c_i Z_{2i} - \left(W_{PM}/2\right) b_i + W_F P_m$

From Eq.12, the neuron's output $P_i(t')$ is obtained as:

(19)
$$P_i(t') = \left(2W.P_m - b_i\right)/2c_i + \\ .+\left(Z_{2i} + Z_{1i}U_i(0) - \left(2W.P_m - b_i\right)/2c_i\right) e^{Z_{3i}t'}$$

with $W = W_F / W_{PM}$

The second term in Eq.19 decays exponentially and finally becomes vanishingly small. Eventually setting $t' = \infty$ gives,

(20) $$P_i(\text{inf}) = \left(2.W.P_m - b_i\right)/2c_i$$

Here $P_i(\text{inf})$ is the final output of neuron *i* and represents the optimal generation level of unit *i*, which is the required solution.
Back substituting of Eq.20 in Eq.19, give a more simple formula for the generation function:

(21) $$P_i(t') = P_i(\text{inf}) + \left(P_i(0) - P_i(\text{inf})\right) e^{Z_{3i}t'}$$

where $P_i(0)$ is obtained from Eq.19 by letting $t' = 0$, to give:

(22) $$P_i(0) = Z_{1i}U_i(0) + Z_{2i}$$

Using the power mismatch definition and Eq.20 we obtain:

(23) $$P_m = \left(\left((1/2)\sum_{i=1}^{N}\left(b_i/c_i\right)\right) + D\right) \Big/ \left(1 + W.\sum_{i=1}^{N}\left(1/c_i\right)\right)$$

Eq.20 through Eq.23 constitute the Hopfield model for the ED.

Inclusion of transmission losses in a hybrid algorithm

For each time period *t*, a dichotomy solution method for solving the ED including transmission losses combined to the HNN is proposed in the following steps:
Step 1: initialization of the interval search [D_3 D_1], where D_3 is the power demand at period *t* and D_1 is a maximum forecast of power demand plus losses at the same period *t*.
ε : a pre-specified tolerance.
Initialize the iteration counter *k =1*.
$D_3^k = D$; $D_2^k = D_1^k$.
Step 2: Determine the optimal generators' power outputs P_i, $i = 1,...,N$ using the HNN algorithm, by neglecting losses and setting the power demand as $D^k = D_2^k$;
Step 3: Calculate the transmission losses L^k for the current iteration *k* using Eq.6;
Step 4: if D_1^k-D_3^k < ε , stop otherwise go to step 5;
Step 5: if D_2^k-L^k < *D*, update D_3 and D_2 for the next iteration as follows:
$D_3^{k+1} = D_2^k$ and $D_2^{k+1} = D_2^k + (D_1^k - D_2^k)/2$;
Replace *k* by *k+1* and go to step 2;
Step 6: if D_2^k-L^k > *D*, update D_1 and D_2 for the next iteration as follows:
$D_1^{k+1} = D_2^k$
$D_2^{k+1} = D_2^k - (D_2^k - D_3^k)/2$;
Replace *k* by *k+1* and go to step 2.

A novel strategy for Prohibited Zone Problem

To prevent the units with prohibited operating zones from falling in those zones during the dispatching process, we propose a novel strategy to take care of it. In the strategy, we introduce an medium production point, $P_{i,j}^M$, for the *j*th prohibited zone of unit *i*. The corresponding incremental cost, $\lambda_{i,j}^M$, is defined by:

(24) $$\lambda_{i,j}^M = \left[F_i(P_{i,j}^u) - F_i(P_{i,j}^l)\right] \Big/ \left(P_{i,j}^u - P_{i,j}^l\right)$$

For each period *t*, a minimum and maximum outputs $P_i^{min,t}$ and $P_i^{max,t}$ of the *i*th generator is allowed due to the ramp rate limit, as follow:

(25) $$P_i^{\min,t} = \max(P_i^{\min}, P_i^{t-1} - R_i^{down})$$

(26) $$P_i^{\max,t} = \min(P_i^{\max}, P_i^{t-1} + R_i^{up})$$

The three possible cases of the prohibited cases with respect to the minimum and maximum allowed outputs are given in Fig. 2.

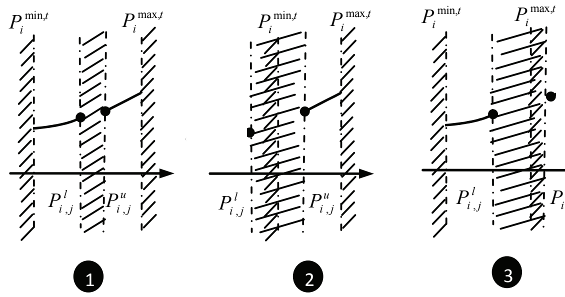

Fig. 2. The three possible cases of prohibited zones with respect to the minimum and maximum generator's outputs

For the quadratic fuel cost functions, the incremental cost $\lambda_{i,j}^M$ is actually equal to the average cost of the prohibited zone. The medium point divides the prohibited zone into a left and a right prohibited subzones.
Case 1: The prohibited zone is within the minimum and maximum generator's outputs of the period *t*.
Dispatch unit *i* with generation level at or above $P_{i,j}^u$ if the system incremental cost exceeds $\lambda_{i,j}^M$, by setting $P_i^{\min,t} = P_{i,j}^u$.
Conversely, dispatch unit *i* with generation level at or below $P_{i,j}^l$, if the system incremental cost is less than $\lambda_{i,j}^M$, by setting $P_i^{\max,t} = P_{i,j}^l$.
Case 2: The minimum generator's outputs allowed of the period *t* exceeds the lower bound of the prohibited zone. Dispatch unit *i* by setting $P_i^{\min,t} = P_{i,j}^u$.
Case 3: The maximum generator's outputs allowed of the period *t* is less than the upper bound of the prohibited zone. Dispatch unit *i* by setting $P_i^{\max,t} = P_{i,j}^l$.

When a unit operates in one of its prohibited zones, the idea of this strategy is to force the unit either to escape from the left subzone and go toward the lower bound of that zone or to escape from the right subzone and go toward the upper bound of that zone.

Computational procedures

Based on the employment of the strategy mentioned above, the computational steps for the proposed approach for solving the constrained DED with 24-hour dispatch intervals (one day) are summarized as follows:

Step 0: Specify the generation for all units, at interval t-1.

Step 1: At t dispatch interval, specify the lower and upper bound generation power of each unit using Eq.25 and Eq.26, a manner to satisfy the ramp rate limit. Pick the hourly power demand D^t. Apply the algorithm of section 3, based on HNN model to determine the optimal generation for all units without considering transmission losses and the prohibited zones.

Step 2: Apply the hybrid algorithm of section 3, based on dichotomy method to adjust the optimal generation of step 1for all units, to include transmission losses.

Step 3: If no unit falls in the prohibited zone, the optimal generation obtained in Step 2 is the solution, go to Step 5; otherwise, go to Step 4.

Step 4: Apply the strategy of section 5 to escape from the prohibited zones, and redispatch the units having generation falling in the prohibited zone.

Step 5: Let $t=t+1$ and if $t \leqq 24$, then go to Step 1. Otherwise, Terminate the computation.

Numerical examples and results

To verify the feasibility of the proposed hybrid HNN method, a 6-unit and a 15-unit power systems was tested. The ramp rate limits and prohibited zones of units were taken into account, so the proposed Hybrid HNN method can be compared with other methods. The results of the proposed HNN are compared with those obtained by the FEP and IFEP, and PSO algorithms from [7, 13] in terms generation cost and average computational time as shown in Table 5 (6-units and 15-units). The software was written in Matlab language and executed on a Pentium IV 1.8 personal computer with 256MB RAM.

The 15-unit example: The system contains 15-units whose characteristics are given in Table 1 and Table 2 . Total power capacities were committed to meet the 24-hour load demands from 2215 MW to 2953 MW that was shown in Table 3 . In normal operation of the system, the loss coefficients B matrices with the 100 MVA base capacity are given in [11]. The spinning reserve was requested to be greater than 5% of the load demand.

Table 1. Generating unit data of example 1.

Unit	P_i^{max}	P_i^{min}	a_i ($/h)	b_i ($/MWh)	c_i ($/MW^{2}h)	P_i^0	R_i^{up} (MW/h)	R_i^{down} (MW/h)
1	455	150	671	10.1	0.000299	394.44	80	120
2	455	150	574	10.2	0.000183	450.27	80	120
3	130	20	374	8.8	0.001126	50.111	130	130
4	130	20	374	8.8	0.001126	113.36	130	130
5	470	150	461	10.4	0.000205	426.35	80	120
6	460	135	630	10.1	0.000301	207.10	80	120
7	465	135	548	9.8	0.000364	286.51	80	120
8	300	60	227	11.2	0.000338	262.88	65	100
9	162	25	173	11.2	0.000807	94.579	60	100
10	160	25	175	10.7	0.001203	133.78	60	100
11	80	20	186	10.2	0.003586	66.78	80	80
12	80	20	230	9.9	0.005513	29.90	80	80
13	85	25	225	13.1	0.000371	46.25	80	80
14	55	15	309	12.1	0.001929	15.01	55	55
15	55	15	323	12.4	0.004447	51.49	55	55

Table 2. Prohibited zones of generating units of example 1

Unit	*Prohibited zone* (MW)
2	[185 225] [305 335] [420 450]
5	[180 200] [305 335] [390 420]
6	[230 255] [365 395] [430 455]
12	[30 40] [55 65]

Table 3. The daily load demand (mw) of example 1

Hour	1	2	3	4	5	6	7	8	9	10
Load	*2236*	*2215*	*2226*	*2236*	*2298*	*2316*	*2331*	*2443*	*2651*	*2728*
Hour	11	12	13	14	15	16	17	18	19	20
Load	*2783*	*2785*	*2780*	*2830*	*2953*	*2950*	*2902*	*2803*	*2651*	*2584*
			Hour	21	22	23	24			
			Load	*2432*	*2312*	*2261*	*2254*			

Table 4. The solution of Case 1 by the Hybrid HNN method of case 1

Unit	P_{i0}	1	2	3	4	5	6	7	8	9	10	11	12
1	394,44	344,98	377,86	389,16	393,03	411,47	416,34	420,40	451,43	455	455	455	455
2	450,27	335	344,15	362,61	368,94	399,07	407,02	413,65	455	455	455	455	455
3	50,11	130	130	130	130	130	130	130	130	130	130	130	130
4	113,36	130	130	130	130	130	130	130	130	130	130	130	130
5	426,35	335	215	150	150	150	150	150	150	230	305	385	445,79
6	207,10	287,10	365	395	395	408,74	413,57	417,60	455	460	460	460	460
7	286,51	366,51	446,51	465	465	465	465	465	465	465	465	465	465
8	262,88	162,88	62,88	60	60	60	60	60	60	60	60	60	60
9	94,58	25	25	25	25	25	25	25	25	25	25	25	25
10	133,78	33,78	25	25	25	25	25	25	25	53,16	59,47	38,66	25
11	66,78	20	20	20	20	20,37	20,77	21,11	23,70	80	80	80	53,37
12	29,90	40	40	40	40	40,46	40,72	40,94	42,62	80	80	80	65

13	46,25	25	25	25	25	25	25	25	25	25	25	25	25
14	15,01	15	15	15	15	15	15	15	15	15	15	15	15
15	51,49	15	15	15	15	15	15	15	15	15	15	15	15
Gen. Cost		29,247	21,394	20,770	20,970	22,106	22,429	22,702	24,749	28,163	31,468	35,663	39,337

Unit	13	14	15	16	17	18	19	20	21	22	23	24
1	455	455	455	455	455	455	455	455	444	415,26	401,32	399,35
2	455	455	455	455	455	455	455	455	452,22	405,26	382,48	379,27
3	130	130	130	130	130	130	130	130	130	130	130	130
4	130	130	130	130	130	130	130	130	130	130	130	130
5	440,88	470	470	470	470	464,34	344,34	224,34	150	150	150	150
6	460	460	460	460	460	460	460	460	455	412,50	398,65	396,70
7	465	465	465	465	465	465	465	465	465	465	465	465
8	60	60	93,39	60	60	60	60	60	60	60	60	60
9	25	25	39,12	25	25	25	25	25	25	25	25	25
10	25	25	85	129,12	79,41	25	25	25	25	25	25	25
11	53,09	69,22	80	80	80	54,43	31,46	60,40	23,08	20,68	20	20
12	65	72,23	80	80	80	65	47,67	66,49	42,22	40,66	40	40
13	25	25	25	25	25	25	25	25	25	25	25	25
14	15	15	15	15	15	15	15	15	15	15	15	15
15	15	15	15	15	15	15	15	15	15	15	15	15
Gen. Cost	38,968	41,451	44,508	44,124	42,414	40,771	32,467	27,228	24,521	22,357	21,446	21,321

Table 5. The summary of the daily generation cost and cpu time

Method	Total Generation Cost ($)		CPU time/interval	
	6-Units	15-Units	6-Units	15-Units
FEP [7]	315,634	796,642	357.58	362.63
IFEP [7]	315,993	794,832	546.06	574.85
PSO [13]	314,782	774,131	2.27	3.31
Hybrid HNN	313,579	759,796	1,52	2.22

The daily generation power was shown in Table 4. The generation cost is given in the last row of Table 4.Table 5 summarized both the daily generation cost and computation efficiency of the proposed methods for two test system (6-units and 15-units).

As can be seen, the simulation results given in Table 4 and Table 5 showed that the proposed methods could obtain good solutions satisfying both the ramp rate limit, spinning reserve and the prohibited operating zones limit of generators. In a small-scale system as in the 6-units power system, though the advantage of HNN method was not very obvious, it could still have the fastest computation efficiency and the minimum daily total generation cost, as shown in Table 5. The method was tested in a medium system of 15-units taken from [11], the advantage of the proposed HNN method was very obvious, and it could obtain both the fastest computation efficiency and the minimum daily total generation cost, as shown in Table 5.

Conclusion

The DED is a complex optimization problem, whose importance may increase as competition in power generation intensifies. The DED planning must perform the optimal generation dispatch at the minimum operating cost among the operating units to satisfy the system load demand, spinning reserve capacity, and practical operation constraints of generators that include the ramp rate limit and the prohibited operating zone. In this paper, we have successfully employed a HNN method to solve the constrained DED problem. The HNN algorithm has been demonstrated to have superior features, including high-quality solution and good computation efficiency. The results showed that the proposed HNN method was indeed capable of obtaining higher quality solution efficiently in constrained DED problems.

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