DYNAMIC CONSTRAINED ECONOMIC/EMISSION DISPATCH SCHEDULING USING NEURAL NETWORK

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Abstract. *In this paper, a Dynamic Economic/Emission Dispatch (DEED) problem is obtained by considering both the economy and emission objectives with required constraints dynamically. This paper presents an optimization algorithm for solving constrained combined economic emission dispatch (EED) problem and DEED, through the application of neural network, which is a flexible Hopfield neural network (FHNN). The constrained DEED must not only satisfy the system load demand and the spinning reserve capacity, but some practical operation constraints of generators, such as ramp rate limits and prohibited operating zone, are also considered in practical generator operation. The feasibility of the proposed FHNN using to solve DEED is demonstrated using three power systems, and it is compared with the other methods in terms of solution quality and computation efficiency. The simulation results showed that the proposed FHNN method was indeed capable of obtaining higher quality solutions efficiently in constrained DEED and EED problems with a much shorter computation time compared to other methods.*

Keywords

Dichotomy method, dynamic economic dispatch, environmental dispatch, gas emission, Hopfield neural network, prohibited operating zone.

1. Introduction

Dynamic economic dispatch (DED) is used to determine the optimal schedule of generating outputs online 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. This is one of the important optimization problems in a power system. Many approaches [1], [2], [3], [4], [5], [6] have been listed to formulate and solve the ED problem; other methods [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], are dedicated to solve DED.

Currently, a large part of energy production is done with thermal sources. Thermal electrical power generating is one of the most important sources of carbon dioxide (CO_2), sulfur dioxide (SO_2) and nitrogen oxides (NO_2) which create atmospheric pollution [7]. Emission control has received increasing attention owing to increased concern over environmental pollution caused by fossil based generating units and the enforcement of environmental regulations in recent years [18]. Numerous studies have emphasized the importance of controlling pollution in electrical power systems [18], [19] and [20].

To get the choice in term of the best solution between ED, EED, a good power management strategy is required. Several optimization techniques such as lambda iteration, linear programming (LP), nonlinear programming (NLP), quadratic programming (QP) and interior point method (IPM) are employed for solving the security constrained economic dispatch and unit commitment problem [9]. Among these methods, the lambda iteration method has been applied in many software packages due to its ease of implementation and used by power utilities for ELD [10]. Most of the time, alone λ-method does not find the optimal solution because of power system constraints. Therefore, the lambda method is used in conjunction with other optimization techniques. The solution of ED and DED problem using genetic algorithm required a large number of iterations/generations when the power system has a large number of units [5]. EED has been proposed in the field of power generation dispatch, which simultaneously minimizes both fuel cost and pollutant emissions. When the emission is minimized the fuel cost may be unacceptably high or when the fuel cost is minimized the emission may be high.

In literature, EED is commonly known as environmental ED or economic emission dispatch, many algorithms are used to solve EED problem. Literature [20] proposed a cooling mutation technique in EP algorithm to solve EED problem for 9-unit system. Proposed methods in [12] convert a multi-objective problem into a single objective problem by assigning different weights to each objective. This allows a simpler minimization process but does require the knowledge of the relative importance of each objective and the explicit relationship between the objectives usually does not exist.

2. DED Problem Formulation

The DED planning must perform the optimal generation dispatch for each period t 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 [16].

2.1. Practical Operation Constraints

1) Ramp Rate Limit

According to [2], [5] and [14], the inequality constraints due to ramp rate limits is given as follows:

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

$$P_i^{t-1} - P_i^t \le R_i^{down}, i = 1, \dots N \text{and } t = 1, \dots T, \qquad (2)$$

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 the 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

References [1], [11], and [17] have shown the input-output curve for a typical thermal unit with valve points. These valve points generate many prohibited zones. In practical operation, adjusting the generation output P_i of a unit must avoid unit operation in the prohibited zones. Figure 1 shows the input output performance curve for a typical thermal unit with Prohibited Zone. The feasible operating zones of the unit can be described as follows.

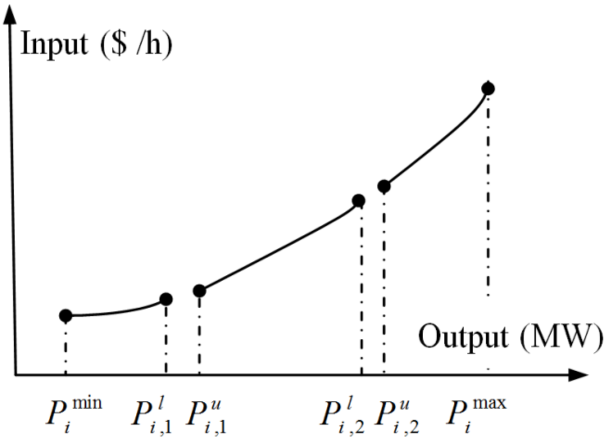

Fig. 1: The input–output performance curve for a typical thermal unit with Prohibited zone.

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

where n_i is the number of prohibited zones of the i-th generator. $P_{i,1}^l$, $P_{i,j}^u$ are the lower and upper power output of the prohibited zones j of the i-th generator, respectively.

2.2. Practical Operation Constraints

The objective of ED 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 ED problem, the constrained optimization problem at specific operating interval can be modified:

$$\begin{aligned} F_T &= \sum_{t=1}^{T} \sum_{i=1}^{N} F_i^t \left(P_i^t\right) = \\ &= \sum_{t=1}^{T} \sum_{i=1}^{N} a_i + b_i P_i^t + c_i \left(P_i^t\right)^2, \end{aligned} \qquad (4)$$

where F_{Tj} is the total generation cost; $F_i^t \left(P_i^t\right)$ is the generation cost function of i-th generator at period t, which is usually expressed as a quadratic polynomial or can be expressed in more complex form [3]; 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 i-th generator and N is the number of generators committed to the operating system, T is the total periods of operation. Subject to the following constraints.

1) Power balance

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

where D^t is the load demand at period t and L^t is the total transmission losses of the same period.

Transmission losses can be modeled either by running a complete load flow analysis to the system [3] or by using the loss coefficients method (also known as the B-coefficients) developed by Kron and Kirchmayer [13]. In the B-coefficients method, the transmission losses are expressed as a quadratic function of the generation level of each generator as follows:

$$\sum_{i=1}^{N} P_i^t = D^t + L^t, \tag{6}$$

where D^t is the load demand at period t and L^t is the total transmission losses of the same period.

Transmission losses can be modeled either by running a complete load flow analysis to the system [3] or by using the loss coefficients method (also known as the B-coefficients) developed by Kron and Kirchmayer [13]. In the B-coefficients method, the transmission losses are expressed as a quadratic function of the generation level of each generator as follows:

$$L^t = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i^t B_{ij} P_j^t + \sum_{i=1}^{N} B_{0i} P_i^t + B_{00}, \tag{7}$$

where B, B_0 and B_{00} are the loss-coefficient matrix, the loss-coefficient vector and the loss constant, respectively, or approximately [3], [18]:

$$L^t = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i^t B_{ij} P_j^t. \tag{8}$$

2) System spinning reserve constraints

$$\sum_{i=1}^{N} \left(min \left(P_i^{max} - P_i^t, R_i^{up} \right) \right) \geq SR^t, \quad t = 1, 2, \ldots, T. \tag{9}$$

3) Generator operation constraints

$$max \left(P_i^{min}, P_i^{t-1} - R_i^{down} \right) \leq min \left(P_i^{max}, P_i^{t-1} - R_i^{up} \right), \tag{10}$$

where P_i^{min} and P_i^{max} are the minimum and maximum outputs of the i-th generator respectively. The output P_i^t must fall in the feasible operating zones of unit i by satisfying the constraint described by Eq. (3).

2.3. Dynamic Economic and Emission Dispatch

In an ED problem, the gas emission is not considered. The gas emission from a conventional thermal generator unit depends on the power generation. Like the fuel cost, total gas emission can be approximated by a quadratic function of Eg. (11), [19]. The emission dispatch problem can be described as the optimization of total gas emission defined by:

$$E_T = \sum_{i=1}^{N} \left(\alpha_i P_i^2 + \beta_i P_i + \gamma_i \right), \tag{11}$$

where E_T is the total amount of emission (ton/h) which can be SO_2 or NO_x or any other gas; α_i, β_i and γ_i, are the coefficient of generator emission characteristics.

The gas emission dispatch can be done in parallel with a ED problem by including emission cost. Different types of emissions are modeled in literature as a cost in addition to the fuel cost. In fact, DEED is a multi-objective problem. But DEED can be transformed into single objective optimization problem by using a price penalty factor [7]:

$$\begin{aligned} min\ \phi_T &= F_T(P) + hE_T(P) = \\ &= \sum_{t=1}^{T}\sum_{i=1}^{N} F_i^T \left(P_i^T \right) + h_i E_i^T \left(P_i^T \right) = \\ &= \sum_{t=1}^{T}\sum_{i=1}^{N} a_i + b_i P_i^T + c_i \left(P_i^T \right)^2 + \\ &+ h_i \left(\alpha_i + \beta_i P_i^T + \gamma_i \left(P_i^T \right)^2 \right) = \\ &= \sum_{t=1}^{T}\sum_{i=1}^{N} \acute{a}_i + \acute{b}_i P_i^T + \acute{c}_i \left(P_i^T \right)^2, \end{aligned} \tag{12}$$

where ϕ_T is the total cost of the system; $\acute{a}_i$, $\acute{b}_i$ and $\acute{c}_i$ are the combined cost and emission function coefficients and h_i is the price penalty factor in (\$/kg) for unit i with:

$$\acute{a}_i = a_i + h_i \alpha_i, \tag{13}$$

$$\acute{b}_i = b_i + h_i \beta_i, \tag{14}$$

$$\acute{c}_i = c_i + h_i \gamma_i, \tag{15}$$

$$h_i = \frac{F_T \left(P_i^{max} \right)}{E_T \left(P_i^{max} \right)}. \tag{16}$$

Equation (12) is subjected to the previous constraints of Eq. (5) to Eq. (9). A tuning for problem formulation is introduced through two weight factors k_1 and k_2 as follow:

$$min\ \phi_T = k_1 F_T(P) + k_2 h E_T(P). \tag{17}$$

For $k_1 = 1$ and $k_2 = 0$ the solution will give results of ED. For k $k_1 = 0$ and $k_2 = 1$ results will give emission dispatch and for $k_1 = k_2 = 1$, DEED results can be obtained.

3. A Flexible FHNN Applied to Combined Economic and Emission Dispatch

The HNN model with continuous output variables and a continuous and monotonically increasing transfer function $f_i(U_i)$ have a dynamic characteristic of each neuron which can be described by:

$$\frac{\mathrm{d}U_i}{\mathrm{d}\acute{t}} = I_i + \sum_{j=1}^{N} T_{ij} V_j. \tag{18}$$

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 and $\acute{t}$ is a dimensionless variable. The model is a mutual coupling neural network and with of non-hierarchical structure.

It has been proved [13] that the continuous Hopfield model state through the computation process always moves in such a way that energy converges to a minimum, which can be defined as [18]:

$$E = -\frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N} T_{ij} V_i V_j - \sum_{i=1}^{N} I_i V_i. \tag{19}$$

3.1. Mapping of EED into the Hopfield model

To map the EED problem using the Hopfield method, the energy function E including both power mismatch, P_m and total fuel cost F (fuel and emission) can be stated as follows [13], [15], [17], [19]:

$$\begin{aligned} E = {} & \tfrac{A}{2}\textstyle\sum_{i=1}^{N} \acute{a}_i + \acute{b}_i P_i^t + \acute{c}_i \left(P_i^t\right)^2 + \\ & + \tfrac{B}{2}\left(\left(D^t + L^t\right) - \textstyle\sum_{i}^{N} P_i^t\right), \end{aligned} \tag{20}$$

where $t = 1, \ldots, T$; P_i^t is the power output of the i-th generator for t time period; A and B are positive weighting factors.

The inputoutput model of HNN is the sigmoid function:

$$\begin{aligned} V_i = {} & V_i^{min} + \\ & + \tfrac{1}{2}\left(V_i^{max} - V_i^{min}\right)\left(1 + \tanh\left(\tfrac{U_i}{u_0}\right)\right), \end{aligned} \tag{21}$$

with a shape constant u_0 of the sigmoidal function. Comparing the energy function Eq. (20) with the Hopfield energy function Eq. (19), we get the interconnection conductances, the self-connection and the external inputs, respectively:

$$T_{ij} = -A - B\acute{c}_i, \tag{22}$$

$$T_{ii} = -A, \tag{23}$$

$$I_i = A(D + L) - B\left(\frac{\acute{b}_i}{2}\right). \tag{24}$$

The HNN solves the static part of the EED problem without considering transmission losses. To enforce this constraint into the solution, a dichotomy solution method as described in [13] is done to obtain a EED solution including losses. The proposed algorithm is introduced as follows. For each time period t, do the following:

- 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 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 using the HNN algorithm of [13], 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 $D_1^k - D_3^k < \epsilon$, 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. $D_1^{k+1} = D_2^k$; $D_2^k - \left(D_2^k - D_3^k\right)$. Replace k by $k+1$ and go to step 2.

4. A Strategy for the Prohibited Zone Problem

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

$$\lambda_{i,j}^M = \frac{\left[F_i\left(P_{i,j}^u\right) - F_i\left(P_{i,j}^l\right)\right]}{\left(P_{i,j}^u - P_{i,j}^l\right)}. \tag{25}$$

For each period t, a minimum and maximum outputs of the i-th generator is modified as follow:

$$P_i^{min,t} = max\left(P_i^{min}, P_i^{t-1} - R_i^{down}\right), \tag{26}$$

$$P_i^{max,t} = min\left(P_i^{max}, P_i^{t-1} - R_i^{up}\right). \tag{27}$$

For the fuel cost functions, the incremental cost $\lambda_{i,j}^M$ is equal to the average cost of the prohibited zone. The medium point divides it into 2 subzones:

Tab. 1: The 3-Unit system data.

Unit	P_i^{max} (MW)	P_i^{min} (MW)	a (\$/h)	b (\$/MWh)	c (\$/MW^{2}h)	R_i^{up} (\$/MWh)	R_i^{down} (\$/MWh)
1	600	150	561	7,29	0,00156	100	100
2	400	100	310	7,85	0,00194	80	80
3	200	50	78	7,97	0,00482	50	50

- 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's 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 output 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 output 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.

5. Computational Procedures of FHNN for DEED

Based on the employment of the strategy mentioned above, the computational steps for the proposed approach for solving the DEED with a given number of dispatch intervals T (e.g. one day) are summarized as follows:

- step 0: Let $k_1 = k_2 = 1$ in Eq. (17). Specify the generation for all units, at $t-1$ dispatch interval. Calculate the combined cost and emission function coefficients $\acute{a}_i$, $\acute{b}_i$ and $\acute{c}_i$ using Eq. (13) to Eq. (16),
- step 1: At t dispatch interval, specify the lower and upper bound generation power of each unit using Eq. (26) and Eq. (27), a manner to satisfy the ramp rate limit. Pick the hourly power demand D^t. Apply the algorithm based on HNN model of [13] 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 1 for 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 4 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 $t \leq T$, then go to Step 1. Otherwise, terminate the computation.

The FHNN can be modified to handle EED as follow:

- set the number of dispatch interval to 1 ($t = 1$),
- let $R_i^{up} = R_i^{down} = \infty$, since the ramp rate limits were not taken into account in EED and classical ED,
- escape step 4 in the procedure if prohibited zones of units is not taken into account.

The proposed FHNN can be modified to handle simply DED by setting $k_1 = 1$, $k_2 = 0$ in Eq. (17) or can be modified to handle emission ED by setting $k_1 = 0$, $k_2 = 1$ in Eq. (17).

6. Numerical Examples and Results

In order to validate the proposed procedure and to verify the feasibility of the FHNN method to solve the DEED, a 3-unit system is tested. The proposed method is implemented with the graphical language LabVIEW on a Pentium 4, 3 GHz. The data is given in Tab. 1 and the prohibited zones are given in Tab. 2, [19]. The load demand varies from 550 to 900 MW as shown in Tab. 3. The emission functions coefficients are given in Tab. 4 and Tab. 5 for (SO$_2$) and (NO$_x$) emission respectively. Transmission losses are calculated using Eq. (8). The transmission B-coefficients are given by:

$$B_{ii} = [0,00003 \quad 0,00009 \quad 0,00012]\,, B_{ij} = 0. \quad (28)$$

Here, for comparison, we have applied the proposed method to the DED (see Tab. 6), the (SO_2) emission dynamic dispatch (see Tab. 7), the (NO_x) emission dynamic dispatch (see Tab. 8), the combined (SO_2) emission and economic dispatch (see Tab. 9) and the combined (NO_x) emission and economic dispatch (see Tab. 10).

Tab. 2: Prohibited zones of generating units of 3-Unit system.

Unit	**Prohibited zone (MW)**
1	[293 309] [410 420]
2	[164 170] [310 340]

Tab. 3: The daily load demand (MW) of 3-Unit system.

Hour	**1**	**2**	**3**	**4**	**5**
Load	550	600	700	800	850

Tab. 4: SO_2 emission data of 3-Unit system.

α_{SO2} **(ton/h)**	β_{SO2} **(ton/MWh)**	γ_{SO2} **(ton/MW^{2}h)**
0,5783298	0,00816466	1.6103 e^{-6}
0,3515338	0,00891174	5,4658 e^{-6}
0,0884504	0,00903782	5,4658 e^{-6}

Tab. 5: NO_2 emission data of 3-Unit system.

α_{NOx} **(ton/h)**	β_{NOx} **(ton/MWh)**	γ_{NOx} **(ton/MW^{2}h)**
0,04373254	-9,4868099 e^{-6}	1,4721848 e^{-7}
0,055821713	-9,7252878 e^{-5}	3,0207577 e^{-7}
0,027731524	-3,5373734 e^{-4}	1,9338531 e^{-6}

The results from [18] and reported in Tab. 11 showed that the proposed HNN method was indeed capable of obtaining higher quality solution efficiently in constrained DED problems, compared with those obtained by the FEP , IFEP, and PSO algorithms from [10], [15] in terms generation cost and average computational time. The same method is used to solve classical DED. The Tab. 6 summarizes the results of classical DED solution using FHNN method for the six time interval, including power generation for the three units, production costs, line losses, the NO_x and SO_2 emissions in (ton/h). It can be seen from the results that the prohibited zone and the ramp rate limit constraints are respected. The results of the FHNN for NO_x and SO_2 minimum emission dispatch of the same test system are shown in Tab. 7 and Tab. 8 respectively. From the tables, for each time interval, the production cost is greater than the production cost in the case of classical DED (see Tab.6), because the objectives are different, in Tab. 7 and Tab. 8, the objective is to obtain the minimum gas emission NO_x and SO_2, respectively. Contrarily in Tab. 7 and Tab. 8, gas emission NO_x and SO2 are lower than those resulted from classical DED solution (minimum cost), respectively.

The results of the FHNN method for the combined dynamic emission/economic dispatch are shown in Tab. 9 and Tab. 10 for SO_2 and NO_x emission, respectively. The production cost is lower than the emission dispatches and the latter are higher than the emission dispatches. The execution time of the FHNN for the 3-unit system is about 0,01 seconds for all cases.

Through the comparison of simulations results of Tab. 11, it can be seen that the proposed method has the best solution quality and calculation time compared to the other methods.

7. Conclusion

The DEED planning must perform the optimal generation dispatch at the minimum operating cost and emission among the operating units to satisfy the system and practical operation constraints, of generators. In this paper, we have successfully employed a flexible HNN method to solve both the DEED and EED problems with generator constraints. In relation to the procedure involved in solving the DEED and DED, the simulation results achieved by FHNN to the case studies of 3-units, 6 and 15-unit, respectively, demonstrated that the proposed method has superior features, including high-quality solution and good computation efficiency. The results of these simulations with FHNN approaches are very encouraging and represent an important contribution to neural network setups. Methods combining HNN with evolutionary methods can be very effective in solving DEED and EED problems. In the future, we will focus mainly on the conception of such hybrid approaches.

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Tab. 6: Classical DED (minimum cost) using FHNN method.

Interval/Unit	**1**	**2**	**3**	**4**	**5**	**6**
P_1	255,65	279,77	328,18	401,23	425,70	475,06
P_2	223,88	243,30	282,27	341,09	360,79	400,00
P_3	77,66	85,47	101,16	124,83	132,76	148,760
L (MW)	7,19	8,55	11,62	17,17	19,26	23,82
D (MW)	550	600	700	850	900	1000
F_T **($)**	5578,59	6028,28	6942,55	8351,54	8831,54	9806,72
SO$_2$ (ton/h)	6,21486	6,73286	7,79265	9,44265	10,009	11,1651
NO$_X$ (ton/h)	0,09021	0,090380	0,09263	0,10087	0,10493	0,11504

Tab. 7: Emission NO$_X$ dispatch (minimum NO$_X$) using FHNN method.

Interval/Unit	**1**	**2**	**3**	**4**	**5**	**6**
P_1	310,30	343,03	408,70	507,76	540,93	600,00
P_2	155,17	171,12	203,13	251,40	267,57	306,61
P_3	90,550	93,044	98,040	105,580	108,110	114,200
L (MW)	6,03	7,20	9,87	14,76	16,62	20,82
D (MW)	550	600	700	850	900	1000
F_T **($)**	5583,13	6033,06	6949,20	8364,66	8847,62	9825,76
SO$_2$ (ton/h)	6,08467	6,58188	7,59864	9,18039	9,72295	10,8467
NO$_X$ (ton/h)	0,08803	0,08809	0,08972	0,09592	0,09901	0,10676

Tab. 8: Emission SO$_2$ dispatch (minimum SO$_2$) using FHNN method.

Interval/Unit	**1**	**2**	**3**	**4**	**5**	**6**
P_1	406,14	453,64	532,98	600,00	600,00	600,00
P_2	100,00	100,00	100,00	137,98	163,76	219,95
P_3	50	53,77	77,15	126,44	152,23	200
L (MW)	6,140	7,410	10,130	14,431	15,993	19,950
D (MW)	550	600	700	850	900	1000
F_T **($)**	5638,31	6110,24	7061,94	8468,28	8925,86	9870,61
SO$_2$ (ton/h)	6,01140	6,50121	7,50304	9,06076	9,60530	10,74760
NO$_X$ (ton/h)	0,09348	0,09441	0,09605	0,10188	0,10650	0,12319

Tab. 9: The combined SO$_2$ emission/ economic dispatch using FHNN method.

Interval/Unit	**1**	**2**	**3**	**4**	**5**	**6**
P_1	264,18	292,23	348,51	433,36	461,77	518,76
P_2	212,31	226,38	254,60	297,14	311,39	339,96
P_3	80,420	89,517	107,750	135,250	144,460	162,920
L (MW)	6,920	8,130	10,860	9,312	17,620	21,660
D (MW)	550	600	700	850	900	1000
F_T **($)**	5576,65	6025,50	6938,08	8344,69	8823,80	9797,42
SO$_2$ (ton/h)	6,18840	6,69225	7,71996	9,31216	9,85663	10,9662
NO$_X$ (ton/h)	0,08952	0,08943	0,09126	0,09912	0,10313	0,11324

Tab. 10: The combined NO$_X$ emission /economic dispatch using FHNN method.

Interval/Unit	**1**	**2**	**3**	**4**	**5**	**6**
P_1	309,53	330,76	373,42	437,81	459,51	502,96
P_2	157,407	182,963	234,300	311,810	337,930	390,230
P_3	89,11	93,61	102,65	116,31	120,91	130,12
L (MW)	6,05	7,34	10,38	15,93	18,36	23,32
D (MW)	550	600	700	850	900	1000
F_T **($)**	5582,40	6029,12	6939,11	8344,43	8826,69	9805,11
SO$_2$ (ton/h)	6,08685	6,60256	7,66529	9,33693	9,91864	11,1108
NO$_X$ (ton/h)	0,088036	0,088164	0,090251	0,980330	0,101910	0,111570

Tab. 11: The summary of the daily generation cost and CPU time.

Method	**Total Cost** ($)		**CPU time**	
	6-Units	**15-Units**	**6-Units**	**5-Units**
FEP [10]	315,634	796,642	357,580	362,630
IFEP [10]	315,993	794,832	546,06	574,85
PSO [18]	314,782	774,131	2,27	3,31
FHNN, proposed	313,579	759,796	1,52	2,22

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