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Harmony Search Algorithm to solve Dynamic Economic Environmental Dispatch (DEED)

Abstract. *This paper presents an application of Harmony Search algorithm (HSA) to solve the Dynamic Economic-Environmental Dispatch (DEED) problem under some equality and inequality constraints. The equality constraints reflect a real power balance, and the inequality constraint reflects the limits of real generation. The voltage levels and security are assumed to be constant. Dynamic Economic-Environmental Dispatch problem is obtained by considering both the economy and emission objectives. This bi-objective problem is converted into a single objective function using a price penalty factor. Harmony Search algorithm is tested on six generators system and its results are compared with the solutions obtained in paper of Keerati. The results are quite encouraging and useful in the economic emission environment.*

Streszczenie. *Zbadano zastosowanie algorytmu HSA do rozwiązania problemów dynamicznego rozsyłu energii. Uwzględniono realny balans mocy jak i realne ograniczenia. Algorytm przetestowano na sześciu systemach. (**Algorytm HSA w zastosowaniu do dynamicznego i ekonomicznego rozsyłu mocy**)*

Keywords: Dynamic Economic-Environmental Dispatch, Pollution Emission, Fuel cost, bi-objective to mono-objective optimization, Harmony Search algorithm.
Słowa kluczowe: rozsył energy, algorytm HSA, koszty paliwa.

Introduction

Economic dispatch is one of the most important optimization problems in power system operation and forms the basis of many application programs. The main objective of economic load dispatch of electric power generation is to schedule the committed generating unit outputs so as to meet the load demand at minimum operating cost while satisfying all unit and system constraints. One of those constraints which always taken into account is the environmental constraint. That is minimization of pollution emission (NO_x, CO_2, SO_2, small quantities of toxic metals, etc) in case of power plants. However, the rise of interests in environment problem in the recent years, it become necessary for power utilities to count this constraint as one of the main objectives, which should be solved together with the cost problem [2, 3]. Thus, we are facing with a bi-objective optimization problem to deal with. This problem is converted into mono-objective optimisation problem by introducing price penalty factor.

In this paper, A Harmony Search Algorithm [4] is applied to solve Dynamic Economic-Environmental Dispatch problem. A six generators system is considered to investigate the effectiveness of the proposed algorithm.

Problem formulation

Economic dispatch

Economic dispatch is the important component of power system optimization. It is defined as the minimization of the combination of the power generation, which minimizes the total cost while satisfying the power balance relation. The problem of economic dispatch can be formulated as minimization of the cost function subjected to the equality and inequality constraints [5].

In power stations, every generator has its input/output curve. It has the fuel input as a function of the power output. But if the ordinates are multiplied by the cost of $/Btu, the result gives the fuel cost per hour as a function of power output [6].

In the practical cases, the fuel cost of generator i may be represented as a polynomial function of real power generation:

$$F(P_{Gi}^t) = a_i\, {P_{Gi}^t}^3 + b_i\, {P_{Gi}^t}^2 + c_i\, P_{Gi}^t + d_i \tag{1}$$

Where F is the total fuel cost of the system at time t, P_{Gi}^t is real power output at time t, ng is the number of generators including the slack bus, a_i , b_i , c_i and d_i are the cost coefficients of the i-th unit.

The total cost of active power generation may be expressed by:

$$G(P_{Gi}^t) = \sum_{t=1}^{24} \sum_{i=1}^{ng} F_i(P_{Gi}^t) \tag{2}$$

The Economic Dispatch Problem can be mathematically represented as:

$$\text{Minimise}\; G(P_{Gi}^t) \tag{3}$$

Emission dispatch

The emission function can be expressed as the sum of all types of emission considered, such as NO_x, SO_2, CO_2, particles and thermal emissions, ect, with suitable pricing of weighting on each pollutant emitted [7].

In the present study, emission of SO_2, CO_2 and NO_x are taken into account. The emission function of the unit i can be expressed as polynomial function of real power generation of the unit [1]. Therefore, the objective function is:

Minimize

$$E_{gas}(P_{Gi}^t) = \sum_{i=1}^{ng} a_{gasi} {P_{Gi}^t}^3 + b_{gasi} {P_{Gi}^t}^2 + c_{gasi} P_{Gi}^t + d_{gasi} \tag{4}$$

where E_{gas} is the emission of a specific gas at time t and a_{gasi} , b_{gasi} , c_{gasi} and d_{gasi} are the emission coefficients of the i-th unit

Constraints

Equality constraints

The total power generation must cover the total demand P_d^t and the transmission loss of the system P_L^t . Hence,

$$\sum_{i=1}^{ng} P_{Gi}^t - P_d^t - P_L^t = 0 \tag{5}$$

Inequality Constraints

Generation power should be within the minimum output $P_{Gi\min}$ and the maximum output $P_{Gi\max}$.

$$(6) \qquad P_{Gi\min} \le P_{Gi}^t \le P_{Gi\max} \quad i = 1,...,ng$$

Combined economic and emission dispatch

Aggregating equations (1) to (6), the power dispatch problem is expressed as a bi-objective optimization problem as follows:

$$(7) \qquad Min[G(P_{Gi}^t), \sum_{gas} E_{gasi}(P_{Gi}^t)]$$

The bi-objective combined economic emission dispatch problem is converted into single optimization problem by introducing price penalty factor P_{fgas}^t as follows:

$$(8) \qquad Min[G(P_{Gi}^t) + \sum_{gas} P_{fgas}^t . E_{gasi}(P_{Gi}^t)]$$

Subject to the power constraints given by (5) and (6).

The price penalty factor P_{fgas} is the ratio between the maximum fuel cost and maximum emission of corresponding generator [8, 9]

$$(9) \qquad P_{fgasi} = \frac{F(P_{Gi\max})}{E_{gasi}(P_{Gi\max})} \ \$/ton \quad i = 1,...,ng$$

The steps to determine the price penalty factor for a particular load demand are:

1. Find the ratio between maximum fuel cost and maximum emission of each generator.
2. Arrange P_{fgasi} in ascending order.
3. Add the maximum capacity of each unit $P_{Gi\max}$ one at a time, starting from the smallest P_{fgasi} until $\sum_i P_{Gi\max} \ge P_d^t$.
4. In this stage, P_{fgas}^t associated with the last unit in the process is the price penalty factor of the given load.

Once the value of P_{fgas}^t is known, then equation (8) can be rewritten in terms of known coefficients and the unknown output of the generators.

$$(10) \quad Min\left[\sum_{t=1}^{24}\sum_{i=1}^{ng}(A_i^t {P_{Gi}^t}^3 + B_i^t {P_{Gi}^t}^2 + C_i^t P_{Gi}^t + D_i^t)\right]$$

where

$$A_i^t = a_i + \sum_{gas} P_{fgas}^t a_{gasi} \ , \ B_i^t = b_i + \sum_{gas} P_{fgas}^t b_{gasi}$$

$$C_i^t = c_i + \sum_{gas} P_{fgas}^t c_{gasi} \ , \ D_i^t = d_i + \sum_{gas} P_{fgas}^t d_{gasi}$$

Transmission losses formula

Active power losses can be determined by various methods. It can simply be computed as RI^2. The power loss in a line can also be calculated by taking the algebraic sum of the total power flows in either direction and the total loss would be the sum of all the line losses.

The other method used to calculate losses is using B-losses coefficients, which express the transmission losses as a function of the outputs of all the generation/power plants.

The B matrix loss formula was originally introduced in the early 1950s as a practical method for loss and incremental loss calculations. In this method, the results of power flow are used to account for power transmission losses in the power system. It is important in terms of the economic dispatch problem to express the system losses in terms of active power generations only. This is commonly referred to as the loss formula or B-coefficient method.

The simplest form of loss equation is George's formula[10], which is:

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n} P_{Gi} B_{ij} P_{Gj}$$

A more general formula is given in reference [11] where the real power losses are a function of real power injection P_i^t and reactive power Q_i and voltage nodes. Their expression is given by:

$$(11) \quad P_L(P_{Gi}^t) = \sum_{\substack{i=1\\j=1}}^{n} [a_{ij}(P_i^t P_j^t + Q_i Q_j) + b_{ij}(Q_i P_j^t - P_i^t Q_j)]$$

where $a_{ij} = \frac{r_{ij}}{|V_i|.|V_j|}\cos(\theta_{ij})$, $b_{ij} = \frac{r_{ij}}{|V_i|.|V_j|}\sin(\theta_{ij})$

$P_i^t = P_{Gi}^t - P_{Di}^t$ and $Q_i = Q_{Gi} - Q_{Di}$

n is the total bus number.

P_{Di}^t is the active power demand at bus i.

Q_{Di} is the reactive demand at bus i.

r_{ij} are the real components of bus impedance matrix .

The voltages nodes V_i (in module $|V_i|$ and phase θ_i) and the reactive power injection are assumed constant. In this case, the power transmission losses can be expressed in terms of active power generations by assuming that the demand for power remains constant during dispatch period. This expression is given by:

$$(12) \quad P_L(P_{Gi}^t) = \sum_{\substack{i=1\\j=1}}^{n} a_{ij} P_{Gi}^t P_{Gj}^t - 2\sum_{\substack{i=1\\j=1}}^{n}(b_{ij} Q_j + a_{ij} P_{Di}^t) P_{Gi}^t + K^t$$

where

$$K^t = \sum_{\substack{i=1\\j=1}}^{n} [a_{ij}(P_{Di}^t P_{Dj}^t + Q_i Q_j) + b_{ij}(P_{Di}^t Q_j - Q_i P_{Dj}^t)]$$

Harmony Search Algorithm

Harmony search algorithm (HSA) is based on natural musical performance processes that occur when a musician searches for a better state of harmony, such as during jazz improvisation. This process was first adapted into engineering optimization problems by Geem et al. [12]. The engineers seek for a global solution as determined by an objective function, just like the musicians seek to find musically pleasing harmony as determined by an aesthetic. The harmony search (HS) algorithm includes a number of optimization operators, such as the harmony memory (HM), the harmony memory size (HMS), the harmony memory considering rate (HMCR), and the pitch adjusting rate (PAR). The harmony memory (HM) stores the feasible vectors, which are all in the feasible space. The harmony memory size determines how many vectors it stores. A new vector is generated by selecting the components of different vectors randomly in the harmony memory. Undoubtedly, the new vector does not violate the variables boundaries, but it is not certain if it violates the problem-specific constraints. When it is generated, the harmony memory will be updated by accepting this new vector if it gets a better solution and deleting the worst vector. The solution of an optimization problem using HSA is performed based on the following four steps:

1. Initialization : HM is filled with randomly generated solution vectors and their corresponding objective function values;
2. generate a new solution vector from HM (memory consideration) or generate a solution vector from the possible random range;
3. replace a decision variable with a new one which is close to the current one (pitch adjusting);
4. update harmony memory.

The optimization algorithm continues to be executed until the given termination criteria are satisfied. Different termination criteria can be used to stop the computation. These may be: Stopping the computation after a given number of iterations; reaching a specific objective function value; or no improvement in the objective function value for a specified number of passed iterations. In this study, stopping the computation after a given number of iterations is used as the termination criterion.

Case Studies

The proposed algorithm is applied to IEEE-30 bus system to verify its effectiveness. The system has six thermal units. Generators characteristics, that is, cost and emission coefficients and generation limits, are taken from [1] and its detailed data are given in [6, 13].

The generator fuel cost, and NO_x, SO_2, and CO_2 emissions functions are given in Tables 1, 2, 3 and 4.

Table 1. The generator fuel cost

BUS	$P_{G\min}$ (MW)	$P_{G\max}$ (MW)	$F(P_{Gi}^t) = a_i P_{Gi}^{t\,3} + b_i P_{Gi}^{t\,2} + c_i P_{Gi}^t + d_i$			
			a_i	b_i	c_i	d_i
1	50	200	0.0010	0.092	14.5	-136
2	20	80	0.0004	0.025	22.0	-3.50
5	15	50	0.0006	0.075	23.0	-81.0
8	10	50	0.0002	0.100	13.5	-14.5
11	10	50	0.0013	0.120	11.5	-9.75
13	12	40	0.0004	0.084	12.5	75.6

Table 2. The NOx emission function

$E_{NO_xi}(P_{Gi}^t) = a_{NO_xi} P_{Gi}^{t\,3} + b_{NO_xi} P_{Gi}^{t\,2} + c_{NO_xi} P_{Gi}^t + d_{NO_xi}$				
BUS	a_{NO_xi}	b_{NO_xi}	c_{NO_xi}	d_{NO_xi}
1	0.0012	0.052	18.5	-26.0
2	0.0004	0.045	12.0	-35.0
5	0.0016	0.050	13.0	-15.0
8	0.0012	0.070	17.5	-74.0
11	0.0003	0.040	8.50	-89.0
13	0.0014	0.024	15.5	-75.0

Table 3. The SO2 emission function

$E_{SO_2i}(P_{Gi}^t) = a_{SO_2i} P_{Gi}^{t\,3} + b_{SO_2i} P_{Gi}^{t\,2} + c_{SO_2i} P_{Gi}^t + d_{SO_2i}$				
BUS	a_{SO_2i}	b_{SO_2i}	c_{SO_2i}	d_{SO_2i}
1	0.0005	0.150	17.0	-90.0
2	0.0014	0.055	12.0	-30.5
5	0.0010	0.035	10.0	-80.0
8	0.0020	0.070	23.5	-34.5
11	0.0013	0.120	21.5	-19.75
13	0.0021	0.080	22.5	25.6

Table 4. The CO2 emission function

$E_{CO_2i}(P_{Gi}^t) = a_{CO_2i} P_{Gi}^{t\,3} + b_{CO_2i} P_{Gi}^{t\,2} + c_{CO_2i} P_{Gi}^t + d_{CO_2i}$				
BUS	a_{CO_2i}	b_{CO_2i}	c_{CO_2i}	d_{CO_2i}
1	0.0015	0.092	14.0	-16.0
2	0.0014	0.025	12.5	-93.5
5	0.0016	0.055	13.5	-85.0
8	0.0012	0.010	13.5	-24.5
11	0.0023	0.040	21.0	-59.0
13	0.0014	0.080	22.0	-70.0

The daily load demands of IEEE 30-bus system are shown in fig. 1. [14]

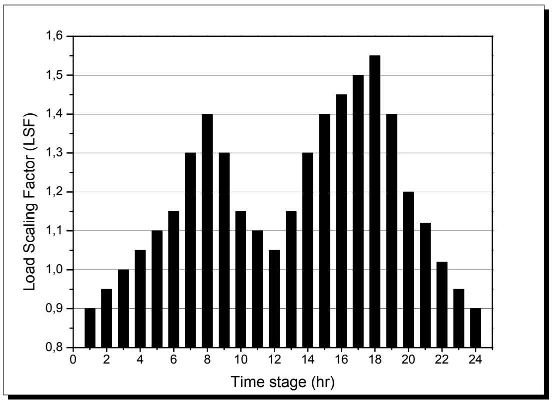

Fig. 1. Daily load curve of IEEE 30-bus system

The total system load of IEEE 30-bus system is 283.4 MW. The corresponding load scaling factor (LSF) is 1.0 and the corresponding coefficients losses are:

$$a_{ij}=10^{-2}\begin{bmatrix} 1.186 & 0.193 & -0.358 & -0.534 & -0.413 & -0.258 \\ 0.193 & 0.618 & -0.084 & -0.466 & -0.354 & -0.268 \\ -0.358 & -0.084 & 2.302 & -0.411 & -0.311 & -0.386 \\ -0.534 & -0.466 & -0.411 & 1.471 & 0.486 & 0.189 \\ -0.413 & -0.354 & -0.311 & 0.486 & 1.046 & -0.207 \\ -0.258 & -0.268 & -0.386 & 0.189 & -0.207 & 2.213 \end{bmatrix}$$

$$K = 0.03782$$

and

$$-2\sum_{\substack{i=1\\ j=1}}^{n=1}(bijQ_j + aijP_{Dj}) = \begin{bmatrix} 0.01965 \\ 0.01101 \\ -0.03447 \\ -0.00819 \\ -0.00732 \\ -0.00193 \end{bmatrix}$$

The SO2, NOx, and CO2 price penalty factors are given in Table 5.

Table 5. The SO2, NOx, and CO2 price penalty factors.

Dispatch periods	P_{fNOx}	P_{fSO_2}	P_{fCO_2}	Dispatch periods	P_{fNOx}	P_{fSO_2}	P_{fCO_2}
1	1.093	1.085	0.782	13	1.387	1.085	1.133
2	1.093	1.085	0.782	14	1.497	1.085	1.190
3	1.093	1.085	0.782	15	1.497	1.085	1.190
4	1.387	1.085	1.133	16	1.497	1.085	1.190

5	1.387	1.085	1.133	17	2.171	2.105	1.436
6	1.387	1.085	1.133	18	2.171	2.105	1.436
7	1.497	1.085	1.190	19	1.497	1.085	1.190
8	1.497	1.085	1.190	20	1.497	1.085	1.190
9	1.497	1.085	1.190	21	1.387	1.085	1.133
10	1.387	1.085	1.133	22	1.093	1.085	0.782
11	1.387	1.085	1.133	23	1.093	1.085	0.782
12	1.387	1.085	1.133	24	1.093	1.085	0.782

The HSA parameters are taken as follow:

$$Par = 0.7,\ HMCR = 0.9\ and\ HMS = 10.$$

Fig. 2., fig. 3. And fig.4. plot respectively total fuel cost, transmission losses, NOx, SO2 and CO2 emissions with respect of the time stage.

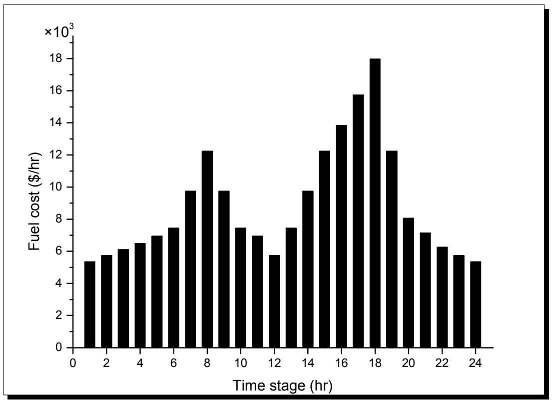

Fig. 2. Fuel cost.

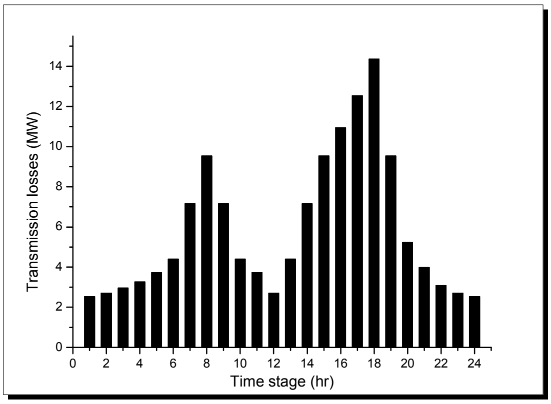

Fig. 3. Transmission losses.

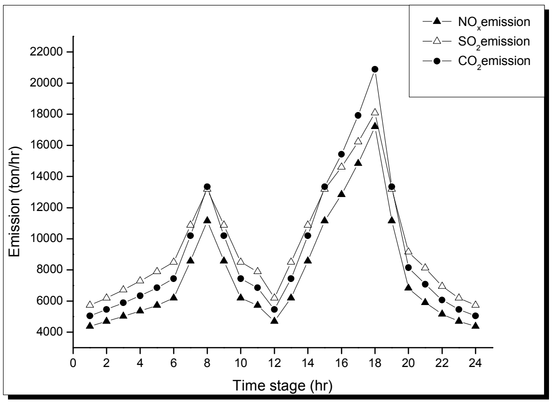

Fig. 4. Gas emission

It is clearly shown that total fuel cost, transmission losses and NOx, SO2 and CO2 emissions increase by increasing the power demand.

Table 6 address optimal generated power.

Table 6. Optimal generated power

Dispatch period	LSF	Optimal power output					
		Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
1	0.90	50.000	53.762	46.465	36.469	37.891	33.005
2	0.95	50.000	56.846	49.273	39.447	40.506	35.863
3	**1.00**	**50.000**	**60.533**	**50.000**	**42.971**	**43.628**	**39.229**
4	1.05	50.000	65.095	50.000	48.021	47.714	40.000
5	1.10	51.274	74.186	50.000	50.000	50.000	40.000
6	1.15	60.316	80.000	50.000	50.000	50.000	40.000
7	1.30	105.573	80.000	50.000	50.000	50.000	40.000
8	1.40	136.294	80.000	50.000	50.000	50.000	40.000
9	1.30	105.573	80.000	50.000	50.000	50.000	40.000
10	1.15	60.316	80.000	50.000	50.000	50.000	40.000
11	1.10	51.274	74.186	50.000	50.000	50.000	40.000
12	1.05	50.000	56.846	49.273	39.447	40.506	35.863
13	1.15	60.316	80.000	50.000	50.000	50.000	40.000
14	1.30	105.573	80.000	50.000	50.000	50.000	40.000
15	1.04	136.294	80.000	50.000	50.000	50.000	40.000
16	1.45	151.873	80.000	50.000	50.000	50.000	40.000
17	1.50	167.635	80.000	50.000	50.000	50.000	40.000
18	1.55	183.628	80.000	50.000	50.000	50.000	40.000
19	1.40	136.294	80.000	50.000	50.000	50.000	40.000
20	1.20	75.309	80.000	50.000	50.000	50.000	40.000
21	1.12	54.078	77.308	50.000	50.000	50.000	40.000
22	1.02	50.000	62.321	50.000	44.685	45.141	40.000
23	0.95	50.000	56.846	49.273	39.447	40.506	35.863
24	0.90	50.000	53.762	46.465	36.469	37.891	33.005

In order to demonstrate the performance of the proposed algorithm, a comparison for the power demand of 283.4 MW emerges between HSA and Fuzzy Multi-objective Optimal real Power Flow FMOPF [1], as are shown in table 7 and fig. 4.

Table 7. Comparison results

Method	Fuel cost ($/hr)	NOx emission (ton/hr)	SO2 emission (ton/hr)	CO2 emission (ton/hr)
HSA	6097.875	5023.850	6713.957	5888.548
FMOPF	6068.144	5018.074	6822.925	5889.963

From the results, it is obvious that the proposed algorithm is performing well in the solution of combined economic emission dispatch. Our results are similar to those obtained in reference [1], moreover the emission of the most toxic gas (SO2) is consequently reduced.

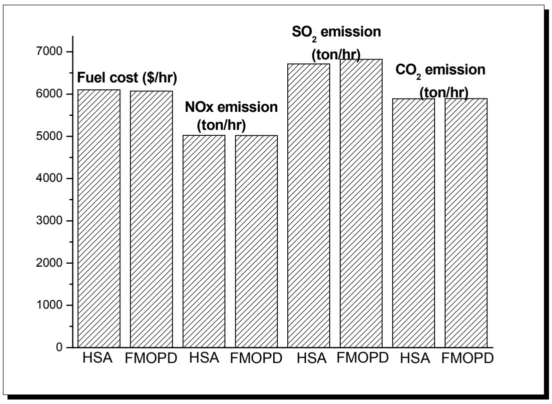

Fig. 4. Results of different objective functions.

Conclusion

In this paper the Dynamic Combined Economic Emission Dispatch problem is solved by Harmony Search Algorithm to minimize the fuel cost, NOx, SO2 and CO2 emissions.

Satisfactory results are obtained by adapting HSA to six generators system and found that those results are very similar to those obtained in [1].

The advantage of using HSA to minimize the Combined Economic Emission Dispatch objective function is its simplicity and no necessity of gradients.

Thus, the proposed algorithm is simple tool for the power industry to aid in curbing pollution and protect our environment.

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