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ORIGINAL ARTICLE

Harmony Search Algorithm For Solving Economic Load Dispatch With Valve Point Effect

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ABSTRACT: A hybrid method based on Harmony Search Algorithm (HAS) and Fuzzy Mechanism (FM) has been presented in this paper for solving Economic Load Dispatch (ELD) problem by considering the valve point in power system. The ELD plays an important role in the operation of power system, and several models by using different techniques have been used to solve these problems. For practical generator operation, many nonlinear constraints of the generator, such as ramp rate limits, prohibited operating zone, generation limits, transmission line loss and non-smooth cost functions are all considered using the proposed technique. The purpose of this paper is to find out the advantages of application of the proposed algorithm in particular to the economic load dispatch problem. Here, an attempt has been made to find out the minimum cost by using HSA using the data of six and forty generating units.

Keywords: ELD Problem, Valve Point Effect, Practical Constrains, HAS, FM.

Introduction

As an engineer is always worried with the price of products and services, the efficient optimum economic operation and planning of electric power production system have always engaged an important role in the electric power industry. With big interconnection of the electric grids, the energy crisis in the world and continuous rise in prices, it is so important to decrease the running charges of the electric energy. A saving in the operation of the system of a small percent shows an important reduction in operating value as well as in the quantities of fuel consumed. The classic problem is the economic power flow of generating systems to achieve minimum operating cost [1].

The basic objective of ELD of electric power production is to schedule the committed generating unit outputs, so as to meet the load demand at min operating value cost while satisfying all unit and system equality and inequality constraints. The ELD problem has been overcome by many scientifics in the past [1-3]. ELD problem involves different problems. The first is pre-dispatch or unit commitment problem where in it is required to select optimally out of the available producing sources to operate to meet the expected load and provide a specified margin of operating reserve over a specified time. In nest step of ELD is on-line economic dispatch where in it is required to distribute the load between the generating sources actually parallel with the system in such a manner as to minimize the total cost of supplying power. In ELD problem, The productions are not fixed but they are allowed to take values again within determined limits so as to meet a special load demand with minimum fuel consumption.

Complex constrained ELD is addressed by intelligent algorithm. Between these models, some of them are Genetic Algorithm (GA) [1], Dynamic Programming (DP) [2], Tabu Search [3], hybrid EP [4], Particle Swarm Optimization (PSO) [5], etc. For calculation simplicity, existing methods use second step fuel cost functions that involve probability evaluation and constraints are handled separately, although sometimes valve-point effects are considered. Harmony Search Algorithm (HAS) is a new optimization algorithm which is applied to solve the above problem. HSA is a recently developed powerful evolutionary algorithm, inspired by the improvisation process of musicians, for finding the best point in single or multi-objective optimization problems. However, the authors propose higher order cost objectives for (a) better curve fitting of running cost, (b) less approximation, (c) more practical, accurate and reliable results, and proposed model is presented to evaluate the optimum dispatch of the proposed higher order cost polynomials. Constraint management is incorporated in the HSA and no extra concentration is needed for the higher order cost functions of fuel units in the proposed model.

The Eld Formulation

The problem of ELD has been introduced in 1960s as an expanded of classical economic dispatch to determine the optimal set of control variables while subject to different equality and inequality limitations. In conventional power flow the values of control variables are pre-specified unlike an ELD amount of some control parameters need to be found to optimize an objective function [2]. So, the ELD is one of the most sensitives optimization strategies for power system managing and nonlinear programming problem. The ELD planning performs the optimal production dispatch among the operating units to satisfy different limitations that change from solution to other solution [6, 7]. In this paper, the ramp rate limits and prohibited operating zone are considered as essential operation limitations of generators for 6 unit system and valve-point loading effects without transmission loss is examined to 40 unit system.

Actually, the adjustments of the power output are instantaneous that is one of the infeasible assumptions. So, generator units are constrained because of ramp rate limits where, generation may increase or decrease based on upper and downward ramp rate limits [9]. Therefore, the operating range of all online units is considered by their ramp rate limits which are defines as:

- Power generation increasing

$P_i - P_i^0 \le UR_i$

- Power generation decreasing

$P_i^0 - P_i \le DR_i$

Where,
P_i: The current is output power of i_{th} unit
P_i^0: previous output power
UR_i: The up ramp constrain of the i_{th} generator
DR_i: The down ramp constrain of the i_{th} generator

According to this fact that, the prohibited operating area in the input/output curve of generator are due to vibration in a shaft bearing/steam amount operation it should be considered that, finding the actual prohibited zone by actual performance testing /operating records is very hard. That cause to getting the best economy by avoiding operation in areas [7]. So, adjustment of the production output of a unit must avoid operation in the prohibited zones. For this purpose, the practical operating area of generators are described as:

$$A_{ai} = \left| \begin{array}{l} P_i^{\min} \le P_i \le P_{i,1}^l \\ P_{i,j-1}^u \le P_i \le P_{i,j}^l,\ j = 2,3,\ldots,n_i, i = l,\ldots,m \\ P_{i,ni}^u \le P_i \le P_i^{\max} \end{array} \right.$$

Where, A_{ai}= Feasible operating zones of i^{th} unit

Due to minimizing fuel cost is the preliminary concern of operation planning; the objective of ELD problem in this study is to minimizing whole generator fuel cost. Which can be expressed as:

$$F_t = \sum_{i=1}^{m} F_i(P_i) \qquad (1)$$

Where,

$$F_i(P_i) = \sum_{i=1}^{m} (a_i P_i^2 + b_i P_i + c_i), i = 1,\ldots, m \qquad (2)$$

For the mentioned equation, the F_t is the total generation cost and F_i is the cost function of the i^{th} generator. a_i, bi and c_i present the cost coefficients in i^{th} generator. Furthermore, the electrical production of the i^{th} generator is shown by P_i and m is the number of generators committed to the operating model. This limited ELD problem is subjected to a variety of constraints depending upon assumptions and feasible concepts [6-7]. These constraints are discussed as follows. Constrained conditions are:

Power Balance

This limitation is according to the principle of equilibrium between total system generation ($\sum_{i=1}^{m} P_i$) and total system loads (P_D) and losses (P_L) that is

$$\sum_{i=1}^{m} P_i = P_D + P_L, i = 1,\ldots, m \qquad (3)$$

P_L: Obtained using B-coefficients, given by:

$$P_L = \sum_{i=1}^{m}\sum_{j=1}^{m} P_i B_{ij} P_j + \sum_{i=1}^{m} B_{0i} P_i + B_{00}$$

Generator Operation Constraints

$$P_i^{\min} \le P_i \le P_i^{\max} \max(P_i^{\min}, P_i^0 - DR_i) \le P_i$$
$$\le \min(P_i^{\max}, P_i^0 + UR_i) P_i \in A_{ai} \qquad (4)$$

Where, P_i^{min} and P_i^{max} are lower and upper bounds for power outputs of the i_{th} generating unit.

Line Flow Constraints

$$\left|P_{Lf,k}\right| \le P_{Lf,k}^{\max}, k = l,\ldots, L \qquad (5)$$

Where, $P_{Lf,k}$ is the real power flow of line k; $P_{Lf,k}^{max}$ is the power flow up limit of line k and L is the number of transmission lines.

Proposed Algorithm

Harmony Search Algorithm

The summary process steps of harmony search for solving optimization problems are described in five steps as:
This process can be presented as Fig. 2.

Step 1: Evaluate objective function and Equality & Inequality constraints in the following form:

$$\begin{array}{l} Minmize : \{f(x), x \in X\} \\ s.t \\ g(x) \ge 0 \\ h(x) = 0 \end{array} \qquad (6)$$

where, f(x) is the objective function. X_i is the feasible set. x_i is the randomly selected parameter. g(x) is the inequality limitation. h(x) is the equality limitations [6].

Step 2: Initialize Harmony Memory (HM) [7].

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \ldots & x_{N-1}^1 & x_N^1 \\ x_1^1 & x_2^2 & \ldots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \ldots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \ldots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \frac{\Delta y}{\Delta x} \qquad (7)$$

Step 3: Initialization of harmony memory

The New Harmony invention is applied in this step and consists of two stages of HMCR and PAR in literature as;

Step 3.1:.1 Harmony Consider Rated (HMCR)

$$x_i^{'} \leftarrow \left\{ \begin{array}{l} x_i^{'} \in \left\{x_i^1, x_i^2, \ldots, x_i^{HMS}\right\} (HMCR) \\ x_i^{'} \in X_i (1 - HMCR) \end{array} \right\} \qquad (8)$$

Where x́ᵢ is new value of x_i and HMCR is probability of choosing x_i' which PR means the probability function.

Step 3.2: pitch adjust rate (PAR)

$$x_i' \leftarrow \begin{Bmatrix} Yes, \Pr(PAR) \\ No, \Pr(1-PAR) \end{Bmatrix} \tag{9}$$

Where, PAR is probability to shift x_i

$$x_i' \leftarrow x_i' \pm rand() \times bw \tag{10}$$

Where bw is range of x_i, rand is random number during 0-1.

Step 4: Update HM and check the stopping criterion Find value of f (x_i') from substitute x_i' [8].

Step 5: To check the stopping criterion, set the NI (Number of iteration) before starts to run the program; HS can stop calculation instantaneously when NI is reached.

Fuzzy Mechanism

Upon having the Pareto-optimal value of non-dominated way, the proposed approach presents one solution to the decision maker as the suitable compromise way. Because of the imprecise nature of the decision maker's judgment, the ith objective function is shown by a membership function μi defined as [9]:

$$\mu_i(p_{gi}) = \frac{f_i^{\max} - f_i(p_{gi})}{f_i^{\max} - f_i^{\min}} \tag{11}$$

Where, f_i^{max} and f_i^{min} are the max and min amount of ith objective, respectively.

$$FDM_i(p_{gi}) = \begin{cases} 0 & \mu_i(p_{gi}) \le 0 \\ \mu_i(p_{gi}) & 0 < \mu_i(p_{gi}) < 1 \\ 1 & \mu_i(p_{gi}) \ge 1 \end{cases} \tag{12}$$

For each non-dominated solution k, the normalized membership function FDM^k is:

$$FDM^k = \left[\frac{\sum_{i=1}^{2} FDM_i^k(p_{gi})}{\sum_{j=1}^{M} \sum_{i=1}^{2} FDM_i^j} \right] \tag{13}$$

The best compromise solution of congestion management problem is the one having the maximum value of FDM^k as fuzzy decision making relation where M defines the total value of non-dominated solutions [9]. Then, all the solutions are arranged in descending order based on their membership function values which will guide the decision makers with a previous list of non-dominated way in view of the current operating conditions. Fig. 1 shows the membership structure μ_c for the fuzzy logical variable signifying total fuel cost $f_i(P_{gi})$.

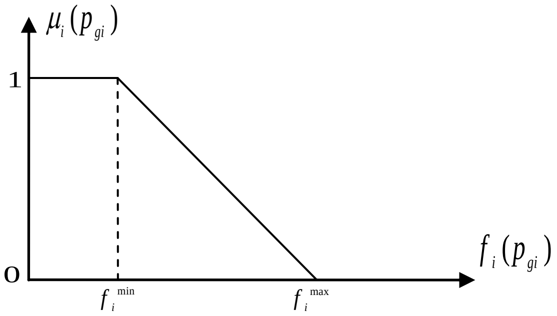

Figure 1. Membership function of fuzzy fuel cost.

Simulation And Results

In order to illustrate the efficiency of the proposed HSA algorithm for the solution of the ELD problems, two power systems, including 6 and 40 generating unit are evaluated as test systems. In these case, the ramp rate limits and prohibited area of the units were taken into account in the practical application. The found results are compared with the represented results of PSO [10], IPSO [11], Hybrid GAPSO [12], Chaotic PSO (CPSO) [13], Self organizing hierarchical PSO (SOH-PSO) [14], New PSO [15] and BBO [16] methods in the literature. The HSA technique is implemented in MATLAB software. In each test system, 20 independent runs were made for each of the optimization methods. In order to acquire better application, max cycle value, colony size amount and limit value are chosen as 60, 70 and 20 to different studies system, respectively for HSA.

Scenario 1: 6-Unit System

The system contains six thermal generating limits, 26 buses and 46 transmission lines. The load demand is considered 1263 MW. The required system data are given in [17]. The network losses are calculated by B matrix loss formula [10]. The optimal results using the proposed HSA method in comparison than the other heuristic methods are shown in Table I that satisfies the generator constraints. It can be apparent from this Table that the proposed model calculate better numerical results compared with other reported evolutionary algorithm methods.

Scenario 3: 40-Unit System

The system contains 40 thermal units with valve-point loading whose characteristics are given in [17]. The load demand of the system is 10500 MW. The cost coefficients along with valve-point loading coefficient were shown in [17]. The numerical simulation results using the HSA method in comparison with the other approached are shown in Table II that also satisfies the system constrains. It can be seen that the HSA demonstrates its better performance in computational complexity, success rate and solution quality than the other recently published methods in the literature.

Convergence Characteristics

A convergence characteristic of the 6 and 40 generator systems in case of HSA algorithm are shown in Figs. 1 and fig 2, respectively. It can be seen that the HSA algorithm has high-quality convergence property, thus resulting in better evaluation amount and low generation cost. After some iteration the HSA characteristics shows signs of premature convergence trend and settle to close the optimal results.

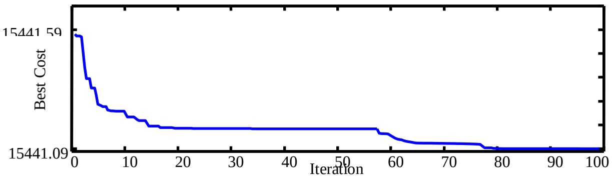

figure 2. Convergence characteristic of HSA technique for 6-units

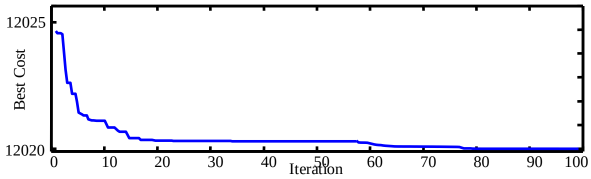

Figure 3. Convergence characteristic of HSA technique for 40-units

Table 1. Best simulation results of 6-unit system. Pd = 1263 mw

Unit	GA	NPSO_LRS	NPSO	PSO_LRS	PSO	New MPSO	SOH_PSO	BBO	HSA
P1 (MW)	474.81	446.96	447.4734	447.4440	447.50	446.71	438.21	447.3997	442.4699
P2 (MW)	178.64	173.3944	173.1012	173.3430	173.32	173.01	172.58	173.2392	174.7586
P3 (MW)	262.21	262.3436	262.6804	263.3646	263.47	265.00	257.42	263.3163	262.6245
P4 (MW)	134.28	139.5120	139.4156	139.1279	139.06	139.00	141.09	138.0006	135.9562
P5 (MW)	151.90	164.7089	165.3002	165.5076	165.48	165.23	179.37	165.4104	165.3031
P6 (MW)	74.18	89.0162	87.9761	87.1698	87.13	86.78	86.88	87.07979	86.1821
Total power output (MW)	1276.03	1275.94	1275.95	1275.95	1276.01	1275.7	1275.55	1275.446	1276.8
P_{loss} (MW)	13.022	12.9361	12.9470	12.9571	12.958	12.733	12.55	12.446	12.35
Generation cost ($/h)	15459.0	15450.0	15450.0	15450.0	15450.0	15447.0	15446.02	15443.0963	15442.04
CPU Time iteration (s)	0.22	NA	NA	NA	0.06	0.0379	0.0638	0.0325	0.0121
Maximum	15,524	15,452	15,454	15,455	15,492	15,455	15609.64	15443.0963	15442.05
Minimum	15,459	15,450	15,450	15,450	15,450	15,447	15446.02	15443.0966	15442.0655
Average	15,469	15450.5	15,452	15,454	15,454	15,447	15497.35	15443.0964	15442.2467

Comparative Discussions

The obtained results for generation cost using different methods for 6-unit and 40-unit power systems are shown in Tables III-IV, respectively. Effectiveness of the proposed HSA method is investigated in terms of solution quality and computation efficacy to illustrate its robustness as follows: From the Tables III-IV, it is evident that the HSA algorithm can provide lower fuel generation cost than the recent studied methods in the literature. Also, these Tables show that the average cost produced by this method is least compared to the other reported approaches. Since the average cost of generation in HSA method is better for small as well as large system; it only reveals its capability to reach global minima in a consistent manner. Hence, it can be concluded that the proposed HSA method has the stronger ability to find the superior quality solution and its convergence characteristic is also better.

Table 2. Best simulation results of 40-unit system. Pd = 10500 mw

Unit	SPSO	PSO_LRS	PC_PSO	NPSO	NPSO_LRS	SOH_PSO	BBO	HSA
P_{1}(MW)	113.97	111.9858	113.98	113.9891	113.9761	110.80	110.8158	113.05
P_{2}(MW)	114.00	110.5273	114.00	113.6334	113.9986	110.80	111.0896	112.85
P_{3}(MW)	109.19	98.5560	97.26	97.5500	97.4241	97.40	97.40261	120.0000
P_{4}(MW)	179.77	182.9266	179.51	180.0059	179.7327	179.73	179.7549	177.1917
P_{5}(MW)	97.00	87.7254	89.38	97.0000	89.6511	87.80	88.20832	91.0000
P_{6}(MW)	91.01	139.9933	105.20	140.0000	105.4044	140.00	139.9886	140.0000
P_{7}(MW)	259.87	259.6628	259.55	300.0000	259.7502	259.60	259.5935	261.7323
P_{8}(MW)	286.99	297.7912	286.90	300.0000	288.4534	284.60	284.6174	284.4338
P_{9}(MW)	284.09	284.8459	284.71	284.5797	284.6460	284.60	284.6479	285.7547
P_{10}(MW)	204.05	130.0000	206.24	130.0517	204.8120	130.00	130.0298	130.0000
P_{11}(MW)	168.40	94.6741	166.52	243.7131	168.8311	94. 00	94.01459	165.0455
P_{12}(MW)	94.00	94.3734	94.00	169.0104	94.0000	94.00	94.26367	164.1900
P_{13}(MW)	212.30	214.7369	214.56	125.0000	214.7663	304.52	304.5153	218.0000
P_{14}(MW)	393.76	394.1370	392.76	393.9662	394.2852	304.52	394.264	390.0148
P_{15}(MW)	303.62	483.1816	306.24	304.7586	304.5187	394.28	304.5057	300.5027
P_{16}(MW)	392.05	304.5381	394.88	304.5120	394.2811	394.28	394.2472	300.0103
P_{17}(MW)	489.49	489.2139	489.26	489.6024	489.2807	489.28	489.3273	486.5363
P_{18}(MW)	489.35	489.6154	489.82	489.6087	489.2832	489.28	489.3047	491.7410
P_{19}(MW)	512.39	511.1782	510.62	511.7903	511.2845	511.28	511.3087	511.5635
P_{20}(MW)	511.21	511.7336	511.68	511.2624	511.3049	511.27	511.2495	512.2868
P_{21}(MW)	522.61	523.4072	523.52	523.3274	523.2916	523.28	523.3217	525.0000
P_{22}(MW)	523.65	523.4599	523.26	523.2196	523.2853	523.28	523.3144	524.5506
P_{23}(MW)	523.06	523.4756	523.98	523.4707	523.2797	523.28	523.3629	522.1635
P_{24}(MW)	520.72	523.7032	523.21	523.0661	523.2994	523.28	523.2883	520.2756
P_{25}(MW)	524.86	523.7854	523.54	523.3978	523.2865	523.28	523.2989	526.0000
P_{26}(MW)	525.22	523.2757	523.10	523.2897	523.2936	523.28	523.2802	526.0000
P_{27}(MW)	10.00	10.0000	10.00	10.0208	10.0000	10.00	10.02817	10.0000
P_{28}(MW)	10.00	10.6251	10.00	10.0927	10.0001	10.00	10.00321	10.0000
P_{29}(MW)	10.00	10.0727	10.00	10.0621	10.0000	10.00	10.0288	10.0000
P_{30}(MW)	87.64	51.3321	89.05	88.9456	89.0139	97.00	88.14595	90.0000
P_{31}(MW)	190.00	189.8048	190.00	189.9951	190.0000	190.00	189.9913	190.0000
P_{32}(MW)	190.00	189.7386	190.00	190.0000	190.0000	190.00	189.9888	190.0000
P_{33}(MW)	190.00	189.9122	190.00	190.0000	190.0000	190.00	189.9998	190.0000
P_{34}(MW)	200.00	199.3258	200.00	165.9825	199.9998	185.20	164.8452	167.8706
P_{35}(MW)	167.18	199.3065	164.78	172.4153	165.1397	164.80	192.9876	200.0000
P_{36}(MW)	172.12	192.8977	172.89	191.2978	172.0275	200.00	199.9876	200.0000
P_{37}(MW)	110.00	110.0000	110.00	109.9893	110.0000	110.00	109.9941	110.0000
P_{38}(MW)	110.00	109.8628	110.00	109.9521	110.0000	110.00	109.9992	110.0000
P_{39}(MW)	95.58	92.8751	94.24	109.8733	93.0962	110.00	109.9833	110.0000
P_{40}(MW)	510.85	511.6883	511.36	511.5671	511.2996	511.28	511.2794	511.5000
Maximum	124091.16	123461.6794	122867.55	122995.0976	122981.5913	122446.30	121688.6634	120345.75
Minimum	122049.66	122035.7946	121767.90	121704.7391	121664.4308	121501.14	121479.5029	120305.58
Average	122327.36	122558.4565	122461.30	122221.3697	122209.3185	121853.57	121512.0576	120304.74

Table 3. Different methods results comparison for 6-unit system

Method	Generation		
	Minimum	Average	Maximm
GA	15459	15469	15524
NPSO-LRS	15450	15450.5	15452
NPSO	15450	15452	15454
PSO-LRS	15450	15454	15455
IPSO	15490	15454	15492
New MPSO	15447	15447	15455
SOH-PSO	15446.02	15497.35	15468.2
BBO	15443.090	15443.096	15443.09
HSA	15442.04	15442.02	15442.14

Table 4. Different methods results comparison for 40-unit system

Method	Generation		
	Minimum	Average	Maximum
SPSO	122049.66	122327.36	124091.1
PSO-LRS	122035.794	122558.45	123461.67
PC-PSO	121767.90	122461.30	122995.09
NPSO	121704.739	122221.36	122981.59
NPSO-LRS	121664.430	122209.31	122981.59
SOH-PSO	121501.14	121853.57	122446.3
BBO	121479.502	121512.05	121688.66
HSA	120205.26	120205.45	120248.14

Conclusions

The ELD problems are the important problems in the electric power system operation. In this paper, the ELD problem has been solved considering transmission losses, valve point effects. The problem has been formulated by the modified form of constraint method. The ELD problem is converted into an optimization problem which is solved by the HSA technique with competing objectives of fuel cost and loss transmission. Numerical results for some test system have been presented to demonstrate the performance, found to converge to optimum in a faster rate and applicability of the proposed method. The proposed algorithm applied to 30-bus 6-generator IEEE test system, and 40 units system with valve point effects. The convergence speed of this algorithm is higher than other heuristics algorithms and thus the high precision and efficiency are achieved.

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