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Integrated PSO-SQP technique for Short-term Hydrothermal Scheduling

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***Abstract*—This paper presents short-term fixed and variable head hydrotherml scheduling. An integrated PSO-SQP technique is applied to obtain the optimum scheduling of power generation. PSO is used as a global search optimization technique which explores the search space. Sequential quadratic programming (SQP) is used as a local search optimization technique used for exploitation of the results obtained from PSO. The validity and effectiveness of proposed algorithms has been tested with standard hydrothermal test systems.**

***Index Terms*—heuristic search, hydrothermal, integrated, power demand**

I. INTRODUCTION

Optimal scheduling of power generation has a great importance in the electric power supply systems. The objective of the Short-term hydrothermal scheduling (STHTS) is to determine the optimum power generation by each thermal and hydro committed units in such a way that it minimizes the total fuel cost of thermal units while satisfying various equality and inequality constraints [1]. Several optimization techniques are used to minimize the operating cost of a thermal unit. Several classical methods are used to find the optimum power generation of hydrothermalunits such as dynamic programming [1], mixed integer programming [2], lagrangian relaxation method [3] and newton's method [4] etc.. Most of the classical techniques use several assumptions that may lead to premature convergence. In the past decades, the use of heuristic search techniques increases rapidly because of their advantages over classical techniques. Heuristic search technique has the advantages like parallelism, robust, no requirement of gradient, fast, less memory requirement and reliable [11]. Several heuristic search technique are there such as genetic algorithm [5, 6], hopfield neural networks technique [7], simulated annealing [8], PSO [9], differential evolution (DE) [10] applied by various researchers on STHTS. Narang*et al*. [11] applied predator prey optimization technique, in which PSO technique is combined with predator effects, which introduce diversity in the swarm to avoid any local sub-optimal convergence. Basu [12] applied artificial immune technique for optimum scheduling. A. Bhattacharya [13] *et al*. applied gravitational search technique (GSA) on STHTS in which agents are objects and convergence of GSA is based on the object's masses. All the masses attract each other and thus the global moment is towards heavier mass. A.I. Selvakumar [14] applied civilized swarm optimization which is based on the behavior of a civilized society. T.T. Nguyen [15] applied cuckoo search algorithm on STHTS problem. Sometimes the results of heuristic search technique may trap into local minima and not reaches near the global minima. The integration of local search and heuristic search avoids any local convergence and hence better solution may obtain. S. Sivasubramani [16] *et al*. applied hybrid DE-SQP on the STHTS problem.

In this paper PSO and SQP are integrated together to find the optimum scheduling of short-term fixed and variable head hydrothermal scheduling. Initially PSO is used for exploration of the search space while SQP is used for exploitation of the result obtained from PSO.

II. PROBLEM FORMULATION

The basic aim of the STHTS problem is to minimize the cost of fuel used in thermal units while satisfying several constraints like water availability constraint, Power generation demand equality constraint, generator operating limits etc. [21].

A. Thermal model

The generating cost of thermal units is generally given by the sum of quadratic function and a sinusoidal function. The sinusoidal function indicates the valve point loading. The fuel cost is mathematically formulated as [11]:

$$F = \sum_{k=1}^{T} \sum_{i=1}^{N} t_k \left(a_{1i} P_{ik}^2 + a_{2i} P_{ik} + a_{3i} + a_{4i} \sin\left\{ a_{5i} \left(P_i^{min} - P_{ik} \right) \right\} \right) (1)$$

where, F is the fuel cost, a_{1i} , a_{2i} , a_{3i} , a_{4i} and a_{5i} are fuel cost coefficients of i^{th} thermal unit, P_{ik} is generated power of i^{th} thermal unit during k^{th} subinterval.P_i^{min} is lower limit of

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the i^{th} thermal unit, t_k is the time duration of the k^{th} interval. N and T are the number of thermal units and total scheduling time, respectively.

B. Short-term hydro model

The water discharge rate is the function of hydro power (P_{mk}) and net head (h_{jk}) which is given by Glimn-Kirchmayer model [21]. The discharge rate of j^{th} hydro unit at k^{th} subinterval is given as:

$$q_{jk} = K_j \boldsymbol{\Phi}(P_{mk})\, \psi(h_{jk})\ \text{(j=1,2,….,M; m = j+N; k=1,2,….,T)} \quad (2)$$

where, M is the number of hydro units, **Φ** and ψ are the function of hydro power and effective head of reservoir, respectively. K_j is proportionality constant. The functions **Φ** and ψ are represented as:

$$\psi(h_{jk}) = x_{1j} h_{jk}^2 + x_{2j} h_{jk} + x_{3j} \quad \text{(j=1,2,….,M;k=1,2,….,T)} \quad (3)$$

$$\boldsymbol{\Phi}(P_{mk}) = y_{1j} P_{mk}^2 + y_{2j} P_{mk} + y_{3j}\ \text{(j=1,2,….,M; m = j+N; k=1,2,….,T)} \quad (4)$$

where, x_{1j} , x_{2j} , x_{3j} are head variation coefficient and y_{1j} , y_{2j} , y_{3j} are discharge rate coefficient of j^{th} hydro unit, respectively. For a fixed head reservoir head is fairly constant, hence discharge rate equation can be rewritten as:

$$q_{jk} = K_j^{'} \boldsymbol{\Phi}(P_{mk}) \quad \text{(j=1,2,….,M; m = j+N; k=1,2,….,T)} \quad (5)$$

For a variable head reservoir effective head at k^{th} subinterval is given by effective head continuity equation:

$$h_{j(k+1)} = h_{j(k)} + \frac{t_k}{S_j} (I_{kj} - q_{jk})\text{(j=1,2,….,M; k=1,2,….,T)} \quad (6)$$

where, S_j is the surface area of the reservoir of j^{th} unit, I_{kj} is inflow rate.

C. Short-term hydrothermal scheduling problem

The objective of STHTS is to determine the optimal power generation of hydrothermal units so as to minimize the total fuel cost of thermal units while satisfying several operational constraints.

Objective:

Minimize

$$F = \sum_{k=1}^{T} \sum_{i=1}^{N} t_k \left(a_{1i} P_{ik}^2 + a_{2i} P_{ik} + a_{3i} + a_{4i} \sin\left\{a_{5i}\left(P_i^{min} - P_{ik}\right)\right\}\right)(7)$$

Equality constraints

(i) load demand constraint during each subinterval

$$\sum_{i=1}^{N+M} P_{ik} = P_{Dk} + P_{Lk} \quad \text{(k=1, 2,…., T)} \quad (8)$$

(ii) Water discharge of each hydro unit over a period should balance the available volume

$$\sum_{k=1}^{T} t_k q_{jk} = R_j \quad \text{(j=1, 2,…., M)} \quad (9)$$

Inequality constraints

(i) Discharge limits on hydro units are

$$q_j^{min} \le q_{jk} \le q_j^{max} \quad \text{(j=1,2,….,M; k=1,2,….,T)} \quad (10)$$

(ii) Hydro and thermal power generator limit

$$P_i^{min} \le P_{ik} \le P_i^{max} \quad \text{(i=1,2,….,N+M; k=1,2,….,T)} \quad (11)$$

where, P_{Dk} and P_{Lk} is power demand and loss during k^{th} subinterval, respectively. P_i^{min} and P_i^{max} are the limits on generated power. q_i^{min} and q_i^{max} are limits on water discharge rate. R_j is predefined volume of water available for j^{th} hydro unit.

III. CONSTRAINT HANDLING

In fixed and variable head hydrothermal scheduling power demand equality constraint in each interval and available water equality constraint of each hydro unit are two equality constraints and limits on water discharge rate of each hydro plant is only inequality constraint. Decision variables for fixed and variable head short-term hydrothermal scheduling problem are thermal and hydro power.

A. Equality constraint

During the search of decision variables if the equality constraints are not satisfied then both the equality constraints are handle by generating errors and an exterior penalty is applied to each error.

Error from power demand equality constraint is calculated as $e_1 = \sum_{i=1}^{N+M} P_{ik} - P_{Dk} - P_{Lk}(13)$

Error from available water equality constraint is calculated as $e_2 = \sum_{k=1}^{T} t_k q_{jk} - R_j(14)$

B. Inequality constraint

Water discharge rate inequality constraint can violate either by exceeding the upper limit or by falls below the lower limit

(i) If the water discharge rate exceeds the upper limit
then, error is calculated as $(e_3) = q_j^{max} - q_{jk}(15)$

(ii) If the water discharge rate falls below the lower limit then, error is calculated as(e_3) = $q_{jk} - q_j^{min}$ (16)

The objective function is made by adding these errors to the fuel cost, mathematically

obj. = F + $r_p \times (e_1^2 + e_2^2 + e_3^2)$(17)

where, obj. is the objective function, r_p is exterior penalty factor and value of r_p is very large.

IV. PARTICLE SWARM OPTIMIZATION

The PSO was originally introduced by Kennedy and Eberhart [17] in 1995. It was motivated by the dynamics of social interaction between birds, initially influenced by work in simulation of coordinated flight in flocks of birds. It uses a number of particles which fly in the search space to obtain the best solution. Each particle considers own best solutions as well as the best solution in history. Each particle in PSO should consider thecurrent position, the current velocity, the distance to pbest, and the distance to gbest to modify its position. PSO was mathematically formulated as:

$$V_{ij}^{t+1} = w \times V_{ij}^t + C_1 \times rand(1) \times \left(Pbest_{ij}^t - x_{ij}^t\right) + C_2 \times rand(2) \times (Gbest_j^t - x_{ij}^t) \quad (18)$$

$$x_{ij}^{t+1} = x_{ij}^t + V_{ij}^{t+1} \quad \text{(i = 1, 2,…., NP; j = 1, 2,….,N+M)} \quad (19)$$

where, NP is number of particles in a group, N+M is number of members in a particle, c_1 and c_2 are acceleration constant generally set to 2, rand(1) and rand(2) are uniform random numbers between 0 and 1,V_{ij}^t is the velocity of the j^{th} particle at t^{th} iteration which is limited between minimum and maximum value of velocity, as given below

$$V_j^{min} \le V_{ij}^t \le V_j^{max} \quad (20)$$

w is inertia weight factor which is continuously decreasing from $w^{max} = 0.9$ to $w^{min} = 0.4$, mathematically given as

$$w = w^{max} - \left(\frac{w^{max} - w^{min}}{IT^{MAX}}\right) \times IT \quad (21)$$

where, *IT* is iteration, IT^{Max} is maximum number of iterations.

V. SEQUENTIAL QUADRATIC PROGRAMMING

The SQP is one of the best nonlinear programming for practical optimization problems in terms of accuracy, efficiency and convergence rate [18]. The method is closely related to newton's method for constrained optimization problems. In each iteration hessian matrix is updated then a quadratic program is solved to find the search direction. These search directions are used to update the decision variables.
SQP can be described as [18]

Minimize the following

$$\frac{1}{2}(d^t)^T B^t d^t + \nabla f(x^t)^T d^t \quad (22)$$

Subjected to

$$g_i(x^t) + [\nabla g(x^t)]^T g^t = 0 \text{(i = 1, 2,……..,}m_c\text{)} \quad (23)$$

$$g_i(x^t) + [\nabla g(x^t)]^T g^t \le 0 \text{ (i = }m_c\text{+1,……., m)} \quad (24)$$

where,

B^t is the hessian matrix of the lagrangian function defined by

L(x, λ) = f(x) + $\lambda^T g_i(x)$ at, x = x^t(25)

d^t is search direction at t^{th} iteration, λ is lagrange multiplier, f(x) is objective function, g(x) is constraints, m is number of all constraints, m_c is number of equality constraints.
SQP consists of three main stages as follows

(1) Update the hessian matrix

At each iteration k hessian matrix is calculated using BFGS quasi-newton method as shown below

$$B^{t+1} = B^t + \frac{q^t (q^t)^T}{(q^t)^T (x^{t+1} - x^t)} - \frac{(B^t (x^{t+1} - x^t))(B^t (x^{t+1} - x^t))^T}{(x^{t+1} - x^t)^T B^t (x^{t+1} - x^t)} \quad (26)$$

(2) Quadratic programming problem
At each iteration t, a search direction d^t can be obtained by solving the quadratic programming sub-problem given in equation (22).

(3) Line search calculation
The search direction d^t is used to find a new iteration

$$x^{t+1} = x^t + \alpha d^t \quad (27)$$

The step lengthα calculated so as to produce a significant decrease in the objective function.

VI. DEVELOPMENT OF PROPOSED TECHNIQUE

In this section, an integrated PSO-SQP technique is discussed for scheduling of hydrothermal plants with fixed and variable head reservoirs. The algorithm starts with random initialization. For a hydrothermal system having N+M number of generating units, position of i^{th} particle is initializes randomly within the feasible region according to equation (11) which can be represented as

X_l^0 = ($P_{l1}^0, P_{l2}^0, \ldots\ldots\ldots\ldots\ldots\ldots, P_{lN+M}^0$) ($l$ =1, 2,……, NP)(28)

where, NP is number of population.
Now, the velocity is also randomly generated for each particle according to equation (20) as,

V_l^0 = ($V_{l1}^0, V_{l2}^0, \ldots\ldots\ldots\ldots\ldots\ldots, V_{lN+M}^0$)($l$ =1, 2,……, NP) (29)

V_j^{max} is set to 10-15% of the dynamic range of the decision variable while V_j^{min} was set to 5-10% of the dynamic range of the decision variable but always with the negative sign [21].
Now, algorithm can be described as:
Step(1): Read data; viz. Maximum iteration, population size, limits of velocity and other algorithm constants.
Step(2): Randomly initialize the velocity of particles and position of particles within the search space.
Step(3): For each particle, calculate the objective function using eq.(17).
Step(4): Update position and velocity of each particle according to eq.(18) and (19), respectively.
Step(5): Update the Pbest for each particle and choose the particle with minimum objective function as Gbest.
Step(6): If the maximum number of iteration reached, go to step 7 otherwise go to step 4.
Step(7): Obtained Gbest is the initial values of the decision variables(x) for SQP.
Step(8): Read data for SQP; viz. Maximum number of iteration, initial hessian matrix, step length.
Step(9): Obtain search direction by solving quadratic programming sub-problem given in eq.(22).
Step(10): Update the Gbest according to eq. (27).
Step(11): If maximum number of iteration reached, go to step(12), otherwise update the hessian matrix according to eq.(26) and go to step 9.
Step(12): The value of Gbest obtained is the final result.

VII. TEST SYSTEMS AND RESULTS

In order to validate the performance and capability of the proposed technique, three standard hydrothermal test system are used which are basically divided into two cases-

Case1: short-term fixed head hydrothermal scheduling

Test system1: Two thermal and two hydro generating units without valve point loading [19].

Test system2: Two thermal and two hydro generating units withvalve point loading [12].

To obtain the optimal solution of STHTS for both the test systems in case1 the parameters of PSOw^{max} , w^{min}, c_1, c_2, NP and IT^{max} are set to 0.4, 0.95, 2, 2, 100 and 200, respectively. For SQP α is set to 0.00001 and IT^{max} is set to 100.

Case2: short-term variable head hydrothermal scheduling

Test system1: Two thermal and two hydro generating units [20].

To obtain the optimal solution of STHTS for test systems1 of case2 the parameters of PSO w^{max} , w^{min}, c_1, c_2, NP and IT^{max} are set to 0.3, 0.7, 1.8, 1.8, 1200 and 80, respectively. For SQP α is set to 0.000001 and IT^{max} is set to 200.

Table1
Comparisonof result of case 1

Test system1		**Test system2**	
Method	**Cost($)**	**Method**	**Cost($)**
RCGA[19]	66,603	AIS[12]	66,117
PSO-SQP	65,437	DE[12]	66,121
		EP[12]	66,198
		PSO-SQP	65,455

Table2
Comparison of result of case 2

Test system1	
Method	**Cost($)**
CFPSO[20]	69801.292
DE[20]	69801.482
PSO-SQP	69398.270

Table3
Result obtained of case 1(testsystem1)

k	Thermal Power(MW)		Hydro Power(MW)		P_{Lk}(MW)
	P_{1k}	P_{2k}	P_{3k}	P_{4k}	
1	278.3205	232.1479	245.003	177.1508	32.6821
2	276.3710	589.6846	274.800	111.6790	52.5919
3	196.5128	527.0331	315.860	103.3655	42.8271

Table4
Result obtained of case 1(testsystem2)

k	Thermal Power(MW)		Hydro Power(MW)		P_{Lk}(MW)
	P_{1k}	P_{2k}	P_{3k}	P_{4k}	
1	114.8830	491.7172	248.4266	73.7439	28.7972
2	299.7984	528.2029	316.6657	108.0782	52.7507
3	183.5332	481.7980	270.5699	207.2086	43.2693

Result obtained of case 1(testsystem2)
Table5-1
Power generation during the period of 24h

k	Thermal Power(MW)		Hydro Power(MW)		P_{Lk}(MW)
	P_{1k}	P_{2k}	P_{3k}	P_{4k}	
1	171.9936	325.8071	319.7966	5.0000	22.5972
2	50.0000	463.7974	200.0000	5.0000	18.795
3	50.0000	358.0365	200.0000	5.0000	13.0374
4	112.3213	175.0000	321.1431	5.0000	13.4661
5	50.0000	175.0000	317.9164	71.6666	14.5799
6	50.0000	300.6256	272.5677	41.9816	15.1748
7	50.0000	395.8609	372.5321	5.0000	23.3963
8	197.5912	556.5898	270.6104	11.7178	36.5100
9	219.0023	788.0652	239.2284	150.7239	67.0195
10	300.0000	612.6535	360.1194	144.3078	67.0800
11	179.6887	688.9982	359.8182	300.0000	78.5057
12	274.8398	698.3476	512.0245	97.3852	82.5932
13	300.0000	657.0685	386.9764	18.596	62.6427
14	111.0483	786.8784	222.4152	300.0000	70.3411
15	276.9609	660.2655	448.5931	30.7082	66.5277
16	199.0284	774.0026	363.1479	103.4818	69.6642
17	299.6305	619.5170	518.5936	89.8156	77.5584
18	300.0000	683.2173	550.0000	128.2850	91.4996
19	185.1089	800.0000	222.0526	300.0000	77.1638
20	269.0111	629.1967	483.0558	34.9849	66.2517
21	299.8409	539.2661	485.2007	5.0000	59.3073
22	219.6056	345.5720	336.6063	300.0000	51.7830
23	127.4627	670.1001	200.0000	41.61175	39.1772
24	130.3012	487.8351	240.4060	70.3080	28.8526

Table5-2
Water discharge rate and head variation during the period of 24h

k	Water discharge rate(m^3/h)		Effective head variation(m)	
	q_{1k}	q_{2k}	h_{1k}	h_{2k}
1	108.13140	6.30787	300.0000	250.0000
2	63.01149	6.30740	299.8919	249.9842
3	62.99826	6.30693	299.8289	249.9685
4	108.58530	6.30645	299.7659	249.9527
5	107.25800	73.4438	299.6573	249.9370
6	89.55162	42.8892	299.5500	249.7533
7	129.51950	6.29725	299.4605	249.6461
8	88.74232	12.82428	299.3310	249.6304
9	76.99277	159.3328	299.2422	249.5983
10	124.2204	151.8009	299.1652	249.2000
11	124.0444	339.7611	299.0410	248.8205
12	191.4642	99.75327	298.9170	247.9711
13	135.2883	19.38357	298.7255	247.7217
14	70.71571	337.9120	298.5902	247.6732
15	162.0413	31.13521	298.5195	246.8285
16	125.1408	105.6462	298.3575	246.7506
17	194.1368	91.08619	298.2323	246.4865
18	209.0869	132.0877	298.0382	246.2588
19	70.40737	335.1218	297.8291	245.9286
20	177.2494	35.06208	297.7587	245.0908
21	178.1321	6.15978	297.5815	245.0031
22	113.9198	333.6281	297.4033	244.9877
23	62.46981	41.39901	297.2894	244.1536
24	76.91048	70.03805	297.2269	244.0501

VIII. CONCLUSION

The integrated PSO-SQP technique has been successfully applied to the STHTS problem. Results obtained are compared with other available technique and found better. The integration of local search technique SQP will avoid the trapping of result in the local minima and pushes the solution towards global minima.

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