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Short Term Optimal Generation Scheduling of Multi-Chain Hydrothermal System Using Constriction Factor Based Particle Swarm Optimization Technique (CFPSO)

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Abstract- In this paper, the particle swarm optimization technique with constriction factor is proposed to solve short term multi chain hydrothermal scheduling problem with non smooth fuel cost objective functions. The performance of the proposed algorithm is demonstrated on hydrothermal test system comprising of three thermal units and four hydro power plants. A wide range of thermal and hydraulic constraints such as power balance constraint, minimum and maximum limits of hydro and thermal units, water discharge rate limits, reservoir volume limits, initial and end reservoir storage volume constraint and water dynamic balance constraint are taken into consideration. The simulation results of the proposed technique are compared with those obtained from other methods such as, simulated annealing (SA) and evolutionary programming (EP) to reveal the validity and verify the feasibility of the proposed method. The test results show that the proposed algorithm achieves qualitative solution with less computational time when compared to the other methods.

Index Terms- Hydrothermal Generation Scheduling, Valve Point Loading Effect, Particle Swarm Optimization (PSO), Constriction Factor.

I. INTRODUCTION

The hydrothermal generation scheduling plays an important role in the operation and planning of a power system. Since the operating cost of thermal power plant is very high compared to the operating cost of hydro power plant, the integrated operation of the hydro and thermal plants in the same grid has become the more economical [1]. The main objective of the short term hydro thermal scheduling problem is to determine the optimal generation schedule of the thermal and hydro units to minimize the total production cost over the scheduling time horizon (typically one day or one week) subjected to a variety of thermal and hydraulic constraints. The hydrothermal generation scheduling is mainly concerned with both hydro unit scheduling and thermal unit dispatching. The hydrothermal generation scheduling problem is more difficult than the scheduling of thermal power systems. Since there is no fuel cost associated with the hydro power generation, the problem of minimizing the total production cost of hydrothermal scheduling problem is achieved by minimizing the fuel cost of thermal power plants under the constraints of water available for the hydro power generation in a given period of time [2]. In short term hydrothermal scheduling problem, the reservoir levels at the start and the end of the optimization period and the hydraulic inflows are assumed known. In addition, the generating unit limits and the load demand over the scheduling interval are known. Several mathematical optimization techniques have been used to solve short term hydrothermal scheduling problems [3]. In the past, hydrothermal scheduling problem is solved using classical mathematical optimization methods such as dynamic programming method [4-5], lagrangian relaxation method [6-7], mixed integer programming [8], interior point method [9], gradient search method and Newton raphson method [2]. In these conventional methods simplifying assumptions are made in order to make the optimization problem more tractable. Thus, most of conventional optimization techniques are unable to produce optimal or near optimal solution of this kind of problems. The computational time of these methods increases with the increase of the dimensionality of the problem. The most common optimization techniques based upon artificial intelligence concepts such as evolutionary programming [10-11], simulated annealing [12-14], differential evolution [15], artificial neural network [16-18], genetic algorithm [19 -22] and particle swarm optimization [23-27] have been given attention by many researchers due to their ability to find an almost global or near global optimal solution for short term hydrothermal scheduling problems with operating constraints. Major problem associated with these techniques is that appropriate control parameters are required. Sometimes these techniques take large computational time due to improper selection of the control parameters. The PSO is a population based optimization technique first proposed by Kennedy and Eberhart in 1995. In PSO, each particle is a candidate solution to the problem. Each particle in PSO makes its decision based on its own experience together with other particles experiences. Particles approach to the optimum solution through its present velocity, previous experience and the best experience of its neighbours [28]. Compared to other evolutionary computation techniques, PSO can solve the problems quickly with high quality solution and stable convergence characteristic, whereas it is easily implemented.

II. PROBLEM FORMULATION

The main objective of short term hydro thermal scheduling problem is to minimize the total fuel cost of thermal power plants over the optimization period while satisfying all thermal and hydraulic constraints. The objective function to be minimized can be represented as follows:

$$FT=\sum_{t=1}^{T}\sum_{i=1}^{N} ntFit(Pgit) \quad (1)$$

In general, the fuel cost function of thermal generating unit i at time interval t can be expressed as a quadratic function of real power generation as follows:

$$Fit(Pgit)=aiP^{2}git+biPgit+ci \quad (2)$$

Where P_{git} is the real output power of thermal generating unit i at time interval t in (MW), Fit (Pgit) is the operating fuel cost of thermal unit i in ($/hr), FT is the total fuel cost of the system in ($), T is the total number of time intervals for the scheduling horizon, nt is the numbers of hours in scheduling time interval t, N is the total number of thermal generating units, a_i, b_i and ci are the fuel cost coefficients of thermal generating unit i.

The generating units with multi-valve steam turbines exhibit a greater variation in the fuel cost function. The valve opening process of multi-valve steam turbines result in ripples in fuel cost curve [29]. Due to the valve point effects, the real input-output characteristic contains higher order non linearity and discontinuity which result in non smooth and non convex fuel cost functions. The valve point effects are taken into consideration by adding rectified sinusoidal cost function to the original fuel cost function described in (2). The fuel cost function of thermal power plant with valve point loading effect can be expressed as:

$$Fit^{v}(Pgit)=aiP^{2}git+biPgit+ci+\left|ei\times\sin(fi\times(Pgit^{min}-Pgit))\right| \quad (3)$$

Where Fit^{v} (Pgit) is the fuel cost function of thermal unit i including the valve point loading effect and fi, ei are the fuel cost coefficients of generating unit i with valve point loading effect.

The minimization of the objective function of short term hydrothermal scheduling problem is subject to a number of thermal and hydraulic constraints. These constraints include the following:

1) Real Power Balance Constraint:

For power balance, an equality constraint should be satisfied. The total active power generation from the hydro and thermal plants must equal to the total load demand plus transmission line losses at each time interval over the scheduling period.

$$\sum_{i=1}^{N} Pgit+\sum_{j=1}^{M} Phjt=PDt+PLt \quad (4)$$

Where, PDt is the total load demand during the time interval t in (MW), Phjt is the power generation of hydro unit j at time interval t in (MW), Pgit is the power generation of thermal generating unit i at time interval t in (MW), M is the number of hydro units and PLt represents the total transmission line losses during the time interval t in (MW). For simplicity, the transmission power loss is neglected in this paper.

2) Thermal Generator Limit Constraint:

The output power generation of thermal power plant must lie in between its minimum and maximum limits. The inequality constraint for each thermal generator can be expressed as:

$$Pgi^{min} \le Pgit \le Pgi^{max} \quad (5)$$

Where Pgi^{min} and Pgi^{max} are the minimum and maximum power outputs of thermal generating unit i in (MW), respectively. The maximum output power of thermal generator i is limited by thermal consideration and minimum power generation is limited by the flame instability of a boiler.

3) Hydro Generator Limit Constraint:

The output power generation hydro power plant must lie in between its minimum and maximum bounds. The inequality constraint for each hydro generator can be defined as:

$$Phj^{min} \le Phjt \le Phj^{max} \quad (6)$$

Where Phj^{min} is the minimum power generation of hydro generating unit j in (MW) and Phj^{max} is the maximum power generation of hydro generating unit j in (MW).

4) Reservoir Storage Volume Constraint:

The operating volume of reservoir storage limit must lie in between the minimum and maximum capacity limits.

$$Vhj^{min} \le Vhjt \le Vhj^{max} \quad (7)$$

Where Vhj^{min} is the minimum storage volume of reservoir j and Vhj^{max} is the maximum storage volumes of reservoir j.

5) Water Discharge Rate Limit Constraint:

The water Discharge rate of hydro turbine must lie in between its minimum and maximum operating limits.

$$qhj^{min} \le qhjt \le qhj^{max} \quad (8)$$

Where qhj^{min} and qhj^{max} are the minimum and maximum water discharge rate of reservoir j, respectively

6) Initial and End Reservoir Storage Volume Constraint:

This constraint implies that the desired volume of water to be discharged by each reservoir over the scheduling period should be in limit.

$$Vhjt^{0}=Vhj^{begin}=Vhj^{max} \quad (9)$$

$$Vhjt^{T}=Vhj^{end} \quad (10)$$

Where Vhj^{begin} and Vhj^{end} are the initial and final storage volumes of reservoir j, respectively

7) Water Dynamic Balance Constraint:

The water continuity equation relates the previous interval water storage in reservoirs with the current storage including delay in water transportation between successive reservoirs. The water continuity equation can be represented as:

$$Vhjt=Vhj,t-1+Ihjt-qhjt-shjt+\sum_{u=1}^{R_{uj}}(qu,t-\tau_{uj}+Su,t-\tau_{uj}) \qquad (11)$$

Where I_{hjt} is water inflow rate of reservoir j at time interval t, S_{hjt} is the spillage from reservoir j at time interval t, τuj is the water transport delay from reservoir u to reservoir j and Ruj is the number of upstream hydro reservoirs directly above the reservoir j.

8) Hydro Plant Power Generation Characteristic:

The hydro power generation is a function of the net hydraulic head, water discharge rate and the reservoir volume. This can be expressed as follows:

$$Phjt=f(qhjt,vhjt) \text{ and } vhjk=f(hjk) \qquad (12)$$

The hydro power generation can be expressed in terms of reservoir volume instead of using the reservoir effective head, and the frequently used functional is:

$$Phjt=c1jV^{2}hjt+c2jq^{2}hjt+c3jVhjtqhjt+c4jVhjt+c5jqhjt+c6j \qquad (13)$$

Where c_{1j}, c_{2j}, c_{3j}, c_{4j}, c_{5j} and c_{6j} are the Power generation coefficients of hydro generating unit j

III. PARTICLE SWARM OPTIMIZATION WITH CONSTRICTION FACTOR

A. Overview of Particle Swarm Optimization

Particle swarm optimization (PSO) is a population based stochastic optimization technique, inspired by social behavior of bird flocking or fish schooling. It is one of the most modern heuristic algorithms, which can be used to solve non linear and non continuous optimization problems. PSO shares many similarities with evolutionary computation techniques such as genetic algorithm (GA). The system is initialized with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evolution operators such as mutation and crossover. The PSO algorithm searches in parallel using a group of random particles. Each particle in a swarm corresponds to a candidate solution to the problem. Particles in a swarm approach to the optimum solution through its present velocity, its previous experience and the experience of its neighbors. In every generation, each particle in a swarm is updated by two best values. The first one is the best solution (best fitness) it has achieved so far. This value is called Pbest. Another best value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best and called gbest. Each particle moves its position in the search space and updates its velocity according to its own flying experience and neighbor's flying experience. After finding the two best values, the particle update its velocity according to equation (14).

$$V_i^{k+1}=\omega\times V_i^{k}+c_1\times r_1\times(Pbest_i^{k}-X_i^{k})+c_2\times r_2\times(gbest^{k}-X_i^{k}) \qquad (14)$$

Where V_i^k is the velocity of particle i at iteration k, X_i^k is the position of particle i at iteration k, ω is the inertia weight factor, $c_1$and c_2 are the acceleration coefficients, $r_1$and r_2 are positive random numbers between 0 and 1, $Pbest_i^k$ is the best position of particle i at iteration k and $gbest^k$ is the best position of the group at iteration k.

In the velocity updating process, the acceleration constants c_1, c_2 and the inertia weight factor are predefined and the random numbers $r_1$and r_2 are uniformly distributed in the range of [0,1]. Suitable selection of inertia weight in equation (14) provides a balance between local and global searches, thus requiring less iteration on average to find a sufficiently optimal solution. A low value of inertia weight implies a local search, while a high value leads to global search. As originally developed, the inertia weight factor often is decreased linearly from about 0.9 to 0.4 during a run. It was proposed in [30]. In general, the inertia weight ω is set according to the following equation:

$$\omega=\omega_{max}-\frac{\omega_{max}-\omega_{min}}{Iter_{max}}\times Iter \qquad (15)$$

Where ω_{min} and ω_{max} are the minimum and maximum value of inertia weight factor, $Iter_{max}$ corresponds to the maximum iteration number and Iter is the current iteration number.

The current position (searching point in the solution space) can be modified by using the following equation:

$$X_i^{k+1}=X_i^{k}+V_i^{k+1} \qquad (16)$$

The velocity of particle i at iteration k must lie in the range:

$$V_{i\ min}\le V_i^{k}\le V_{i\ max} \qquad (17)$$

The parameter V_{max} determines the resolution or fitness, with which regions are to be searched between the present position and the target position. If V_{max} is too high, the PSO facilitates a global search and particles may fly past good solutions. Conversely, if V_{max} is too small, the PSO facilitates a local search and particles may not explore sufficiently beyond locally good solutions. In many experiences with PSO, V_{max} was often set at 10-20% of the dynamic range on each dimension.

The constants c_1 and c_2 in equation (14) pull each particle towards Pbest and gbest positions. Thus, adjustment of these constants changes the amount of tension in the system. Low values allow particles to roam far from target regions, while high values result in abrupt movement toward target regions.

Figure 1 shows the search mechanism of particle swarm optimization technique using the modified velocity, best position of particle i and best position of the group.

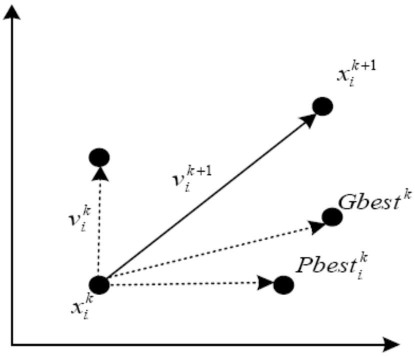

Fig.1. Updating the position mechanism of PSO technique

B. Constriction Factor Approach

After the original particle swarm proposed by Kennedy and Eberhart, a lot of improved particle swarms were introduced. The particle swarm with constriction factor is very typical. Recent work done by Clerc [31] indicates that the use of a constriction factor may be necessary to insure convergence of the particle swarm optimization algorithm. In order to insure convergence of the particle swarm optimization algorithm, the velocity of the constriction factor approach can be represented as follows:

$$V_i^{k+1}=K\times[\omega\times V_i^k+c_1\times r_1\times(Pbest_i^k-X_i^k)+c_2\times r_2\times(gbest^k-X_i^k)] \quad (18)$$

Where K is the constriction factor and given by:

$$K=\frac{2}{\left|2-\varphi-\sqrt{\varphi^2-4\varphi}\right|} \quad (19)$$

Where: $\varphi=c_1+c_2$, $\varphi>4$

The convergence characteristic of the particle swarm optimization technique can be controlled by φ. In the constriction factor approach, φ must be greater than 4.0 to guarantee the stability of the PSO algorithm. However, as φ increases the constriction factor decreases and diversification is reduced, yielding slower response. Typically, when the constriction factor is used, φ is set to 4.1 (i.e. $c_1 = c_2 = 2.05$) and the constant multiplier k is 0.729. The constriction factor approach can generate higher quality solutions than the basic PSO technique.

IV. ALGORITHM FOR SHORT TERM HYDROTHERMAL SCHEDULING PROBLEM USING CFPSO TECHNIQUE

The sequential steps of solving short term hydro thermal scheduling problem by using constriction factor based PSO algorithm are explained as follows:

Step 1: Read the system input data, namely fuel cost curve coefficients, power generation limits of hydro and thermal units, number of thermal units, number of hydro units, power demands, power generation coefficients of hydro power plants, upper and lower limits of reservoir volumes, discharge rate limits and water inflow rate through the hydro turbines.

Step 2: Initialize a population of particles with random positions according to the minimum and maximum operating limits of each unit (upper and lower bounds of power output of thermal generating units and upper and lower bounds of water discharge rate of hydro units). These initial particles must be feasible candidate solutions that satisfy the practical operation constraints of all thermal and hydro units.

Step 3: Initialize the velocity of particles in the range between $[-Vi^{\max},+Vi^{\max}]$.

Step 4: Calculate the reservoir storage of j^{th} hydro power plant in the dependent interval by using the water balance continuity equation defined in (11).

Step5: Check the inequality constraint of reservoir storage volume by the following equation:

$$V_{hjt}=\begin{cases} V_{hjt} & \text{if } V_{hj}^{\min}\le V_{hjt}\le V_{hj}^{\max} \\ V_{hj}^{\min} & \text{if } V_{hjt}\le V_{hj}^{\min} \\ V_{hj}^{\max} & \text{if } V_{hjt}\ge V_{hj}^{\max} \end{cases} \quad (20)$$

Step 6: Calculate the hydro power generation from the equation given in (13).

Step 7: Calculate the thermal demand by subtracting the generation of hydro units from the total load demand. The thermal demand (total load – hydro generation) must be covered by the thermal units. The thermal generations are calculated from the power balance equation given in (4).

Step 8: Check the inequality constraint of thermal power generated according to the following equation:

$$P_{git}=\begin{cases} P_{git} & \text{if } P_{gi}^{\min}\le P_{git}\le P_{gi}^{\max} \\ P_{gi}^{\min} & \text{if } P_{git}\le P_{gi}^{\min} \\ P_{gi}^{\max} & \text{if } P_{git}\ge P_{gi}^{\max} \end{cases} \quad (21)$$

Step 9: Evaluate the fitness value of each particle in the population using the objective function given in equation (1).

Step 10: If the evaluation value of each particle is better than the previous Pbest, then set Pbest equal to the current value.

Step 11: Select the particle with the best fitness value of all the particles in the population as the gbest.

Step 12: Update the velocity of each particle according to equation (18).

Step 13: Check the velocity of each particle according to the following equation:

$$V_i^{k+1} = \begin{cases} V_i^{k+1} & \text{if } V_i^{\min} \le V_i^{k+1} \le V_i^{\max} \\ V_i^{\min} & \text{if } V_i^{k+1} \le V_i^{\min} \\ V_i^{\max} & \text{if } V_i^{k+1} \ge V_i^{\max} \end{cases} \qquad (22)$$

Step 14: The position of each particle is modified according to equation (16).

Step 15: Check the inequality constraints of the modified position.

Step 16: If the stopping criterion is reached (i.e. usually maximum number of iterations) go to step 17, otherwise go to step 4.

Step 17: The particle that generates the latest gbest is the optimal generation power of each unit with minimum total fuel cost of the thermal power plants.

Step 18: Print the outputs of hydrothermal scheduling and stop.

V. CASE STUDY AND SIMULATION RESULTS

To verify the feasibility and effectiveness of the proposed algorithm, a hydrothermal power system consists of a multi chain cascade of four hydro units and three thermal units were tested. The effect of valve point loading has been taken into account in this case study to illustrate the robustness of the proposed method. The transport time delay between cascaded reservoirs is also considered in this case study. The scheduling time period is one day with 24 intervals of one hour each. The data of test system are taken from [17] and [18]. The multi chain hydro sub system configuration is shown in figure 2. The water time transport delays between connected reservoirs are given in table I. In this case study, the output power of hydro power plants is represented as a function of the reservoir storage and the water discharge rates. The hydro power generation coefficients are given in table II. The reservoir storage limits, discharge rate limits, initial and end reservoir storage volume conditions and the generation limits of hydro power plants are shown in table III while table IV shows the reservoir inflows of multi chain hydro power plants. The fuel cost coefficients and the minimum and maximum limits of three thermal generating units are given in table V. The load demand over the 24 hours is given in table VI. The proposed algorithm has been implemented in MATLAB language and executed on an Intel Core i3, 2.27 GHz personal computer with a 3.0 GB of RAM. The control parameters of CFPSO algorithm used to solve short term hydro thermal scheduling problem are given in table VII. The optimal solution obtained from the proposed algorithm is achieved in 50 trial runs. The resultant optimal schedule of thermal and hydro power plants obtained from the CFPSO technique for each time interval is shown in table VIII. Table IX presents the fuel cost of each thermal unit and the total fuel cost of thermal power plants obtained from the proposed algorithm for each time interval while table X shows the optimal hourly water discharge of hydro power plants obtained from the CFPSO method. The optimal hourly storage volumes of hydro reservoirs obtained from the proposed algorithm are given in table XI.

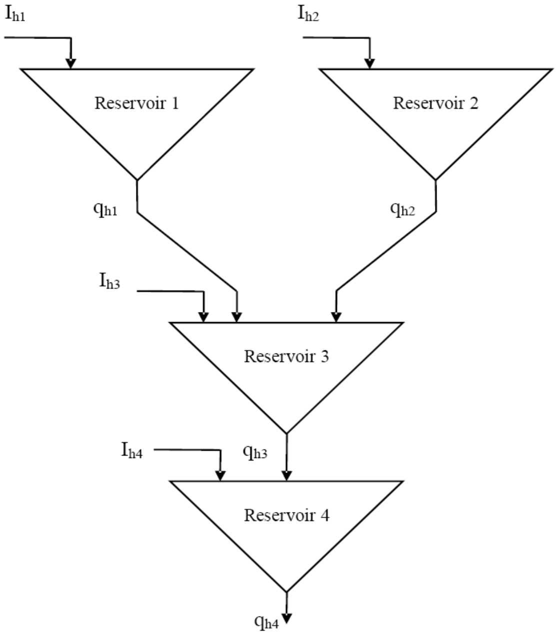

Fig.2. Multi chain hydro sub system networks

Table I: Water time transport delays between connected reservoirs

Plant	**1**	**2**	**3**	**4**
R_u	0	0	2	1
τ_u	2	3	4	0
Ru : Number of upstream hydro power plants τu : Time delay to immediate downstream hydro power plant				

Table II: Hydro power generation coefficients

Plant	**C_1**	**C_2**	**C_3**	**C_4**	**C_5**	**C_6**
1	-0.0042	-0.4200	0.0300	0.9000	10.000	-50.000
2	-0.0040	-0.3000	0.0150	1.1400	9.5000	-70.000
3	-0.0016	-0.3000	0.0140	0.5500	5.5000	-40.000
4	-0.0030	-0.3100	0.0270	1.4400	14.000	-90.000

Table III: Reservoir storage capacity limits, plant discharge limits, plant generation limits and reservoir end conditions ($\times 10^4 m^3$)

Plant	**V_h^{min}**	**V_h^{max}**	**V_h^{ini}**	**V_h^{end}**	**q_h^{min}**	**q_h^{max}**	**P_h^{min}**	**P_h^{max}**
1	80	150	100	120	5	15	0	500
2	60	120	80	70	6	15	0	500
3	100	240	170	170	10	30	0	500
4	70	160	120	140	13	25	0	500

Table IV: Reservoir inflows of multi chain hydro plants ($\times 10^4 m^3$)

Hour	**Reservoir**				**Hour**	**Reservoir**			
	1	**2**	**3**	**4**		**1**	**2**	**3**	**4**
1	10	8	8.1	2.8	13	11	8	4	0
2	9	8	8.2	2.4	14	12	9	3	0
3	8	9	4	1.6	15	11	9	3	0
4	7	9	2	0	16	10	8	2	0
5	6	8	3	0	17	9	7	2	0
6	7	7	4	0	18	8	6	2	0
7	8	6	3	0	19	7	7	1	0
8	9	7	2	0	20	6	8	1	0
9	10	8	1	0	21	7	9	2	0
10	11	9	1	0	22	8	9	2	0
11	12	9	1	0	23	9	8	1	0
12	10	8	2	0	24	10	8	0	0

Table V: Fuel cost coefficients and operating limits of thermal units

Unit	**ai**	**bi**	**ci**	**e_i**	**f_i**	**P_{gi}^{min}**	**$P_{gi,}^{max}$**
1	0.0012	2.45	100	160	0.038	20	175
2	0.0010	2.32	120	180	0.037	40	300
3	0.0015	2.10	150	200	0.035	50	500

Table VI: Load demand for 24 hour

Hour	**P_D (MW)**	**Hour**	**P_D (MW)**	**Hour**	**P_D (MW)**	**Hour**	**P_D (MW)**
1	750	7	950	13	1110	19	1070
2	780	8	1010	14	1030	20	1050
3	700	9	1090	15	1010	21	910
4	650	10	1080	16	1060	22	860
5	670	11	1100	17	1050	23	850
6	800	12	1150	18	1120	24	800

Table VII: Control parameters of particle swarm optimization

CFPSO parameters	**Value**
Population size	50
Maximum number of generations	300
Acceleration coefficients(c_1/c_2)	2.05
Minimum inertia weight (ω_{min})	0.4
Minimum inertia weight (ω_{max})	0.9
Constriction factor (k)	0.729

Table VIII: Hourly optimal hydrothermal schedule using constriction factor based particle swarm optimization (CFPSO)

Hour	**Thermal generation (MW)**			**Hydro generation (MW)**			
	P_{g1}	**P_{g2}**	**P_{g3}**	**P_{h1}**	**P_{h2}**	**P_{h3}**	**P_{h4}**
1	102.3522	209.8194	57.6422	60.1722	80.3207	38.6494	201.0440
2	20.0000	126.8176	230.7566	73.0700	79.3509	55.3298	194.6751
3	105.4454	130.2316	139.7551	54.0153	55.8002	42.4402	172.3121
4	25.1898	128.3247	141.6169	86.1289	65.3077	48.1490	155.2830
5	123.6643	116.0352	140.8527	54.2512	43.3706	23.7179	168.1081
6	20.2832	300.0000	144.4642	54.0606	73.2636	41.5883	166.3402
7	32.7205	300.0000	230.9010	88.9708	71.1724	55.5877	170.6477
8	101.6320	296.3523	234.4262	77.8782	70.3955	54.2548	175.0610
9	104.6402	295.1020	365.9320	56.0490	37.4051	44.0579	186.8139
10	110.1216	300.0000	319.4361	64.1774	44.9308	40.0597	201.2744
11	102.9433	299.8210	324.6830	96.2948	46.6031	38.5205	191.1343
12	29.9546	300.0000	410.6102	102.7084	56.2583	57.3524	193.1162
13	20.0000	294.0590	408.0650	87.5439	45.7874	54.3512	200.1934
14	20.1798	294.8191	319.1150	81.9074	51.3624	52.8587	209.7574
15	65.0533	297.0703	229.3150	94.6490	50.6550	49.3154	223.9421
16	116.1536	139.0801	406.3149	84.1369	53.9792	42.2257	218.1095
17	103.0538	209.8115	317.8150	99.4313	47.9614	52.1143	219.8126
18	35.3345	298.2462	320.2436	102.2590	69.0529	60.3747	234.4891
19	102.0183	211.1061	321.2727	84.0163	40.2404	52.7194	258.6312
20	100.0383	212.6210	313.3650	58.2941	42.5457	50.6354	272.5005
21	29.9704	295.1772	140.3611	79.0149	64.9985	37.0795	263.3983
22	109.9750	134.5710	232.0451	57.9149	42.6570	42.0930	240.7441
23	103.0293	125.5876	230.0580	65.3415	42.4109	45.5238	238.0490
24	22.6076	209.6222	140.0572	67.0476	49.5320	42.4138	268.7197

Table IX: Hourly fuel cost of each thermal unit and total fuel cost of the system using CFPSO technique

Hour	F1 ($/hr)	F2 ($/hr)	F3 ($/hr)	FT ($/hr)
1	365.2875	650.8290	328.8924	1345.009
2	149.4800	443.0075	723.1182	1315.606
3	388.5058	474.3245	472.8158	1335.646
4	193.8263	456.8758	490.4691	1141.171
5	535.8437	460.7023	483.1984	1479.744
6	151.9094	940.9172	517.4616	1610.288
7	255.8136	940.9172	724.5312	1921.262
8	367.7239	906.2017	758.9062	2032.832
9	381.4544	894.2413	1318.932	2594.627
10	429.0324	940.9172	974.9719	2344.922
11	366.5683	939.2243	1027.5630	2333.356
12	233.5563	940.9172	1276.1740	2450.648
13	149.4800	893.1142	1263.5300	2306.124
14	151.0224	891.5338	974.0437	2016.600
15	422.8659	913.0624	711.8716	2047.800
16	479.1878	552.1295	1269.9400	2301.257
17	367.5381	650.8123	979.1672	1997.518
18	276.1141	924.2753	983.0938	2183.483
19	366.4173	662.9219	993.4389	2022.778
20	373.0982	677.1374	996.4685	2046.704
21	233.6855	894.9607	478.5194	1607.165
22	427.7779	513.3079	735.7177	1676.804
23	367.3231	431.6617	716.2805	1515.265
24	171.8302	651.5545	475.6256	1299.011

Table X: Hourly hydro plant discharge using CFPSO technique

Hour	Hydro plant discharges ($\times 10^4 m^3/hr$)			
	q_{h1}	q_{h2}	q_{h3}	q_{h4}
1	5.7990	12.9505	20.5398	13.1229
2	7.4559	14.9805	12.8725	13.9983
3	5.0000	8.2127	17.9687	13.0000
4	9.6117	10.3248	16.4797	13.0000
5	5.0528	6.1585	22.5614	13.4225
6	5.0000	14.3987	18.7684	13.2641
7	10.1422	14.1917	11.5845	13.0000
8	8.1422	13.8035	15.0767	13.0000
9	5.1849	6.0528	19.1534	13.0000
10	6.0564	6.9771	20.4840	14.0564
11	11.1414	7.0141	20.9517	13.0528
12	13.5567	8.7984	13.7150	13.0000
13	9.4322	6.8451	16.3067	13.0000
14	8.3885	7.5845	17.3808	13.1585
15	10.6153	7.2676	19.0765	13.8979
16	8.6736	7.7958	20.6765	13.1849
17	11.8519	6.7976	18.0101	13.0000
18	13.4021	12.1095	13.0102	14.2676
19	8.9637	6.1907	18.3101	17.0670
20	5.4306	6.3603	19.0075	18.9034
21	8.1710	10.8396	22.3957	17.3716
22	5.3689	6.2854	21.1805	14.6610
23	6.1983	6.0528	19.9457	13.8475
24	6.3625	7.0287	20.5701	17.4578

Table XI: Hourly storage volume of hydro reservoirs using CFPSO technique

Hour	Reservoir storage volume ($\times 10^4 m^3$)			
	V_{h1}	V_{h2}	V_{h3}	V_{h4}
0	100.0000	80.0000	170.0000	120.0000
1	104.2010	75.0495	157.5602	109.6771
2	105.7451	68.0690	152.8877	98.0788
3	108.7449	68.8563	138.9190	86.6788
4	106.1334	67.5315	143.1888	73.6789
5	107.0806	69.3730	146.0638	80.7961
6	109.0805	61.9743	144.5081	80.4045
7	106.9384	60.0000	155.8601	85.3732
8	106.7962	60.0000	154.9947	88.8529
9	111.6113	61.9472	156.2400	98.4143
10	116.5549	63.9701	161.0899	103.1263
11	117.4135	65.9560	163.0839	101.6580
12	113.8568	65.1576	162.6066	103.7347
13	115.4264	66.3125	163.3334	109.8881
14	119.0379	67.7280	167.1081	117.2136
15	120.4226	69.4604	173.3867	124.2674
16	121.7490	69.6646	170.9875	124.7975
17	118.8971	69.8670	170.9504	128.1042
18	113.4950	63.7575	177.8232	131.2175
19	111.5313	64.5668	176.9825	133.2270
20	112.1007	66.2065	177.6245	135.0001
21	110.9297	64.3669	182.7404	135.6386
22	113.5608	67.0815	178.7143	133.9877
23	116.3625	69.0287	171.5595	138.4503
24	120.0000	70.0000	170.0000	140.0000

In order to verify and validate the effectiveness of the proposed technique, its simulation results will be compared with the results obtained from the simulated annealing and evolutionary programming techniques. Table XII shows the comparison of total fuel cost and computation time of the proposed methods among other methods. From table XII, it is observed that the constriction factor based PSO algorithm give high quality solution with less computation time compared to other methods. Figure 3 shows the hourly hydro plant power generation including total hydro generation by using proposed method, the hourly thermal plant power generation including total thermal generation is given in figure 4, the hourly hydro plant discharges using proposed technique are shown in figure 5 while figure 6 presents the hourly reservoir storage volumes using proposed algorithm.

Table XII: comparison of total fuel cost and computation time of the proposed technique among GA, SA and EP techniques

Method	Total fuel cost ($)	CPU Time (Sec)
CFPSO	44925.62	183.64
SA [27]	45466.000	246.19
EP [27]	47306.000	9879.45

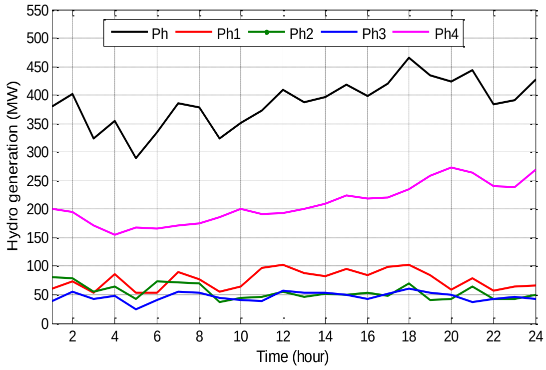

Fig.3. Hourly hydro plant power generation

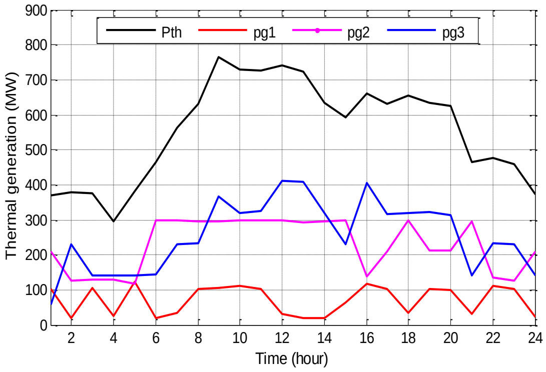

Fig.4. Hourly thermal plant power generation

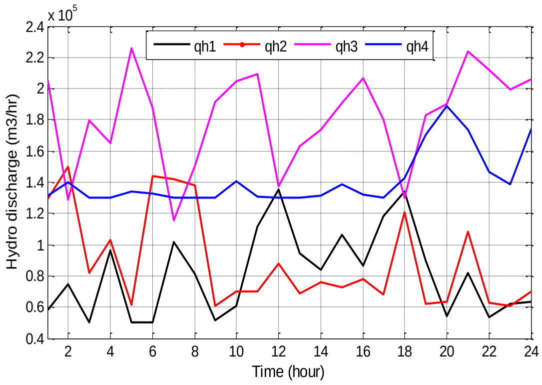

Fig.5. Hourly hydro plant discharge trajectories

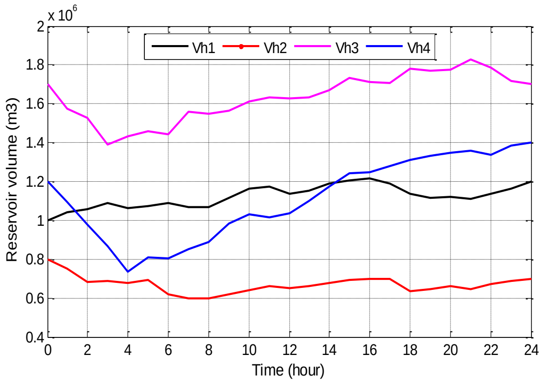

Fig.6. Hourly hydro reservoir storage volume trajectories

VI. CONCLUSIONS

In this paper, particle swarm optimization technique with constriction factor has been proposed for solving short term multi chain hydrothermal scheduling problem. To demonstrate the performance efficiency of the proposed algorithm, it has been applied on test system consists of a multi chain cascade of four hydro units and three thermal units. The effect of valve point loading is considered in this paper to demonstrate the robustness of the proposed technique. The results obtained by the proposed technique have been compared with other evolutionary computation techniques such as simulated annealing (SA) and evolutionary programming (EP) to verify the feasibility of the proposed method. The numerical results show that the proposed algorithm give a cheaper total fuel cost than those obtained from the other techniques. From the tabulated results, it is clear that the computational time of the proposed algorithm is much less than the other methods. Thus, the proposed approach can converge to the minimum fuel cost faster than the other approaches. Finally, the Simulation results demonstrate that the proposed method is a powerful optimization tool for solving hydrothermal scheduling problems with non smooth objective functions.

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