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Short term generation scheduling of cascaded hydro electric system using time varying acceleration coefficients PSO

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Abstract
The hydrological interdependence of plants in cascaded hydroelectric system means that operation of any plant has an effect on water levels and storage at other plants in the system. Hydro-logically efficient operation of power plants in such cascaded system requires that water resources should be managed efficiently, so that it can dispatched to predicted demand considering all physical and operational constraints. Meta-heuristic optimization techniques particularly Particle Swarm Optimization (PSO) and its variants have been successfully used to solve such problem. In this paper Time Varying Acceleration coefficients PSO (TVAC_PSO) has been used to determine the optimal generation schedule of real operated cascaded hydroelectric system located at Narmada river in state Madhya Pradesh, India. Results thus obtained from TVAC_PSO are compared with Novel Self Adaptive Inertia Weight PSO (NSAIW_PSO) and found to give better solution.

Keywords: Hydroelectric power generation, Novel self adaptive inertia weight PSO, Linearly decreasing inertia weight PSO, Time varying acceleration coefficient PSO, Short term generation scheduling.

1. Introduction
The restructuring of electrical industry has created highly vibrant and competitive market that altered many aspects of the power industry. In this changed scenario, scarcity of energy resources, increasing power generation cost, environmental concern and ever growing demand for electrical energy necessitate optimal utilization of hydro resources. The effective utilization of available hydro resources plays an important role for economic operation of hydro project as whole where hydroelectric plants constitute a significant portion of the installed capacity. The objective of hydro generation scheduling is to find out the amount of water to release from each hydro power plant for maximum power generation satisfying various physical and operational constraints.
Hydroelectric generation scheduling is categorized as large scale non-linear, dynamic and non-convex optimization problem. The non-linearity is due to the generating characteristics of hydro plant in which plant output is the non-linear function of head and discharge through turbine. The problem become dynamic for multiple hydro plants at same river arranged in cascade mode where discharge through upstream plant contributes to increase the generation capacity of the downstream plant. Non-convexity is added due to the efficiency variation of hydro turbines. Various conventional methods like Nonlinear Programming [1-2], Mixed integer linear programming [3], Dynamic programming [4], Quadratic programming [5], Lagrange relaxation method [6], Network flow method [7], Bundle method [8] and more are reported in literature for solving such problems. But these conventional methods are unable to

handle the non-linearity nature of the real problems due to sensitivity to initial estimates and stuck into local optimal solution. Modern heuristic optimization techniques based on operational research and artificial intelligence concepts, such as evolutionary programming [9], Hybrid Chaotic Genetic algorithm [10], Simulated annealing [11], Ant colony optimization [12], Tabu Search [13], Neural Network [14-16] Particle swarm optimization (PSO) [17-19] provide the better solution. Each method has its own advantages and dis-advantages; however PSO has gained popularity as the best suitable solution algorithm for such problems.

Upto now, a significant proportion of research has been done and still going on to improve the performance of the PSO. Researchers have shown the improvement in performance of PSO by random number generation Techniques [20], Introduction of particle repulsion [21], Craziness [22, 23], Mutation [24], Time Varying Acceleration Coefficients [25, 26], Inertia weight variation [27, 28]. In this paper Time Varying Acceleration Coefficients Particle Swarm Optimization has been applied for short term hydroelectric generation scheduling of Cascaded hydroelectric system at Narmada river located in Madhya Pradesh, India..

The rest of the paper is organized in seven sections. Section 2 dealt with the optimization problem formulation followed by brief overview of different variants of PSO method in section 3. Description of Narmada cascaded hydroelectric system and its mathematical modeling has been discussed in section 4. Detail algorithm of the TVAC_PSO has been described in section 5. Results and discussions are mentioned in section 6 followed by conclusion in section 7.

2. Problem formulation

The short term scheduling of cascaded hydro electric system means to find out the water discharge, water storage and spillages for each reservoir j at all scheduling time periods (for 24 hrs) to minimize the error between load demand and generation subjected to all constraints.

2.1 Objective function

In hydro scheduling problem, the goal is to minimize the gap between generation and load demand during schedule horizon. Thus objective function to be minimized can be written as

$$E = Min \sum_{t=1}^{T} [(1/2)*(P_D{}^t - \sum_{j=1}^{n} P_j{}^t)^2] \tag{1}$$

The power generated by the reservoir type river bed hydro power plants P_j^t is a function of head and discharges through turbines. Here head has been calculated as a difference of reservoir elevation and tailrace elevation assuming head losses are zero. The power generated through these plants can be expressed as frequently used expression [16] as given in eq. (2) within bounds of head/storage and discharges.

$$P_j{}^t = A_1 \times (H_j{}^t)^2 + A_2 \times (U_j{}^t)^2 + A_3 \times (H_j{}^t) \times (U_j{}^t) + A_4 \times (H_j{}^t) + A_5 \times (U_j{}^t) + A_6 \tag{2}$$

2.2 Constraints

The optimal value of the objective function as given in eq. (1) is computed subjected to constraints of two kinds of equality constraints and inequality constraints or simple variable bounds as given below. The decision is discretized into one hour periods.

2.2.1 Equality constraints

a) Water balance equation

This equation relates the previous interval water storage in reservoirs with current storage including delay in water transportation between reservoirs and expressed as:

$$X_j{}^{t+1} = X_j{}^t + U_{up}{}^{t-\delta} + S_{up}{}^{t-\delta} - U_j{}^t - S_j{}^t \tag{3}$$

2.2.2 Inequality constraints

Reservoir storage, turbine discharges rates, spillages and power generation limits should be in minimum and maximum bound due to the physical limitations of the reservoir and turbine.

a) Reservoir storage bounds

$$X_j^{\min} \le X_j^t \le X_j^{\max} \quad (4)$$

b) Water discharge bounds

$$U_j^{\min} \le U_j^t \le U_j^{\max} \quad (5)$$

c) Power generation bounds

$$P_j^{\min} \le P_j^t \le P_j^{\max} \quad (6)$$

d) Spillage

Spillage from the reservoir is allowed only when water to be released from reservoir exceeds the maximum discharge limits. Water spilled from reservoir j during time t can be calculated as follows:

$$S_j^t = Q_j^t - U_j^{\max} \text{ if } Q_j^t > U_j^{\max} \quad (7)$$

$$= 0 \qquad \text{otherwise}$$

e) Initial & end reservoir storage volumes

Terminal reservoir volumes are generally set through midterm scheduling process. This constraint implies that the total quantity of utilized water for short term scheduling should be in limit so that the other uses of the reservoir are not jeopardized.

$$Xj^0 = X_j^{begin} \qquad X_j^T = X_j^{end} \quad (8)$$

3. Overview of particle swarm optimization

Particle Swarm Optimization is inspired from the collective behaviour exhibited in swarms of social insects. Amongst various versions of PSO, most familiar version was proposed by Shi and Eberhart [29]. The key attractive feature of PSO is its simplicity as it involves only two model eq. (9) and eq. (10). In PSO, the co-ordinates of each particle represent a possible solution called particles associated with position and velocity vector. At each iteration particle moves towards an optimum solution through its present velocity and their individual best solution obtained by themselves and global best solution obtained by all particles. In a physical dimensional search space, the position and velocity of particle i are represented as the vectors of $X_i = [X_{i1}, X_{i2} \ldots\ldots\ldots\ldots X_{id}]$ & $V_i = [V_{i1}, V_{i2,} \ldots\ldots\ldots\ldots V_{id}]$ in the PSO algorithm.

Let $P\_best(i) = [X_{i1pbest}, X_{i2pbest} \ldots X_{idpbest}]$ $G\_best = [X_{1gbest}, X_{2gbest} \ldots X_{dgbest}]$ be the best position of particle i and global best position respectively. The modified velocity and position of each particle can be calculated using the current velocity and the distance from $P\_best(i)$ and G_best as follows:

$$V_i^{k+1} = V_i^k \times \omega + C_1 \times R_1 \times (P\_best(i) - X_i^k) + C_2 \times R_2 \times (G\_best - X_i^k) \quad (9)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (10)$$

$$\omega = \omega_{\max} - ((\omega_{\max} - \omega_{\min})\ \text{iter})\ /\ \text{it\_max} \quad (11)$$

The value of $\omega_{\max}, \omega_{\min}$ ω, C_1, $C_{2,}$ should be determined in advance. The inertia weight ω is linearly decreasing as eq. (11).

3.1 Novel self adapting inertia weight PSO (NSAIW_PSO)

In simple PSO method, the inertia weight is made constant for all particles in one generation. In NSAIW_PSO [31] method movement of the particle is governed as per the value of objective function to increase the search ability. Inertia weight of the most fitted particle is set to minimum and for the lowest fitted particle takes maximum value. Hence the best particle moves slowly in comparison to the worst

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particle. The best particle having smaller rank leads to low inertia weight, whereas the worst particle takes last rank with high inertia weight as per eq. (12).

$$\omega = \left(3 - \exp\left(-PS/200\right) + \left(r/100\right)^2\right)^{-1} \tag{12}$$

3.2 Time varying acceleration coefficients PSO (TVAC_PSO)

In PSO, search towards optimum solution is guided by the two stochastic acceleration components (cognitive & social component).Therefore the proper control of these components is very necessary. Keneddy and Eberhart [30] described that a relatively high value of cognitive component will result excessive wandering of individuals towards the search space. In contrast, a relatively high value of social component may lead particle to rush prematurely towards local optimum solution. Generally in population based algorithm, it is desired to encourage the individuals to wander through the entire search space, without clustering around local optima, during the early stages of optimization. On the other hand, during latter stages, it is important to enhance convergence toward the global optima, to find the optimum solution efficiently. Considering these concerns time varying acceleration coefficients concept is introduced by Asanga [26] which enhance the global search at early stage and encourage the particles to converge towards global optima at the end of search. Under this development, the cognitive component reduces and social component increases, by changing the acceleration coefficients C_1 & C_2 with time as given in eq. (13) & eq. (14)

$$C_1 = ((C_{1f} - C_{1i}) \times (iter / it\_\max)) + C_{1i} \tag{13}$$

$$C_2 = ((C_{2f} - C_{2i}) \times (iter / it\_\max)) + C_{2i} \tag{14}$$

4. Description of narmada cascaded hydroelectric system (NCHES)

TVAC_PSO method is applied to determine the hourly optimal operation of a real operated NCHES located at interstate river Narmada in India. This system is characterized by cascade flow network, water transport delay between successive reservoirs and variable natural inflows. System considered is having five major hydro power projects namely 'Rani Avanti Bai Sagar (RABS)', 'Indira Sagar (ISP)', 'Omkareshwar (OSP)', and 'Maheshwar (MSP)' located in state Madhya Pradesh, India & Sardar Sarovar (SSP) terminal project in state Gujarat. All projects are located at the main stream of river hence a hydraulic coupling exists amongst them as shown in Figure 1 especially between ISP, OSP and MSP. The tailrace level of ISP matched with the full reservoir level of the OSP and similarly between OSP and MSP.

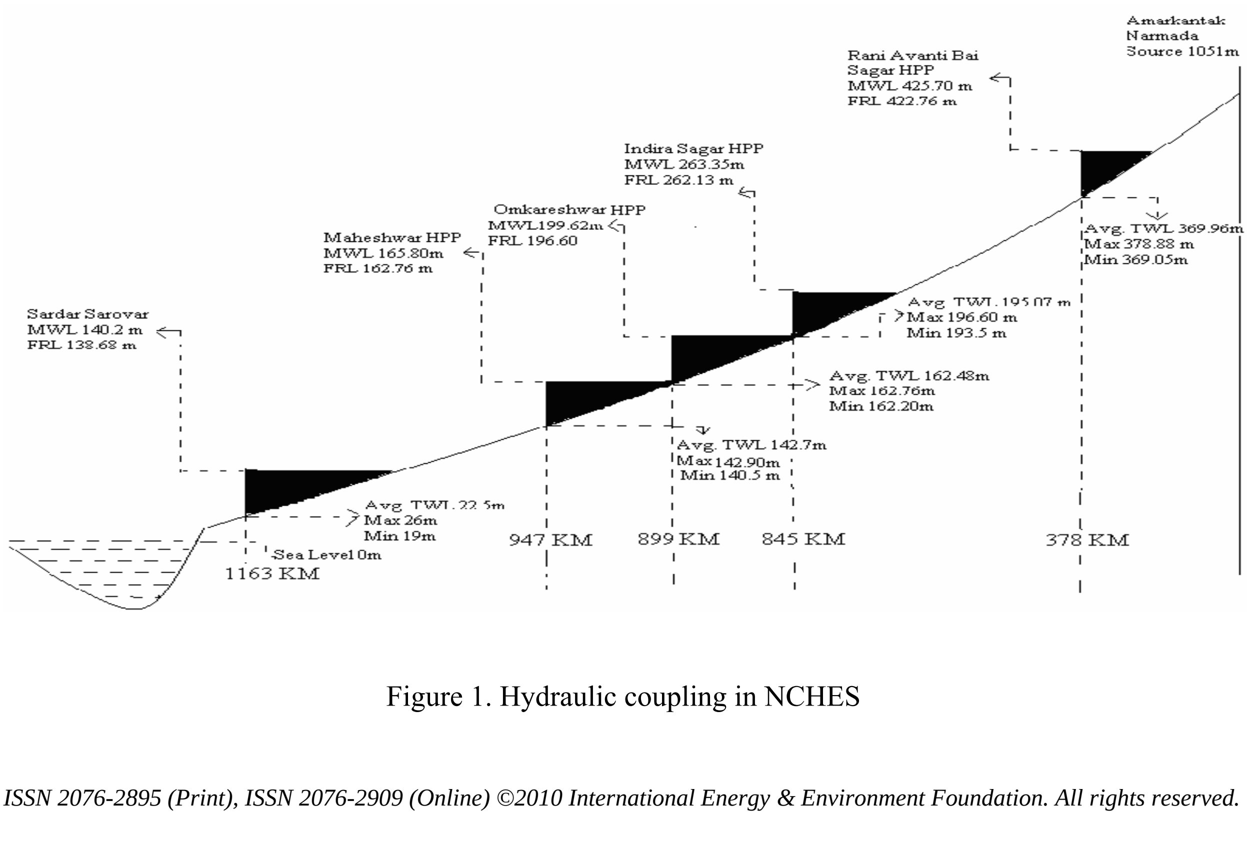

Figure 1. Hydraulic coupling in NCHES

Present work is carried out based on data reported in [32]. Water traveling time between successive reservoirs are mentioned in Table 1. The hourly load demand considered for the scheduling of NCHES have been given in Table 2.

Table 1. Water traveling time between consecutive reservoirs

Plant	Travel time	Plant	Travel time	Plant	Travel time
RABS	62 hrs	ISP	4 hrs	OSP	3 hrs
MSP	17 hrs	SSP	0 hrs		

Table 2. Hourly load demand (MW)

Hour	Load Demand	Hour	Load Demand	Hour	Load Demand
1	1350	9	1900	17	1850
2	1300	10	1800	18	1900
3	1350	11	2000	19	1750
4	1300	12	1800	20	1700
5	1350	13	2000	21	1600
6	1400	14	2000	22	1500
7	1500	15	1900	23	1550
8	1600	16	1900	24	1900

5. TVAC_PSO algorithm of NCHES generation scheduling

The steps involved in optimization are as follows:

Step 1: Initialize velocity of discharge particles between $-V_j^{max}$ to $+V_j^{max}$ as $V_j^{max} = (U_j^{max} - U_j^{min})/10$

Step2: Initialize position of discharge particle between U_j^{min} & U_j^{max} for population size PS.

Step 3: Initialize dependent discharge matrix.

Step 4: Initialize the $P\_best(i)$ and G_best.

Step 5: Set iteration count = 0.

Step 6: Calculate reservoir storage X_j^t with the help of eq. (3).

Step 7: Check whether X_j^t is with in limit X_j^{min}, X_j^{max}.

- If $X_j^t < X_j^{min}$ then $X_j^t = X_j^{min}$
- If $X_j^t > X_j^{max}$ then $X_j^t = X_j^{max}$
- If $X_j^{min} \le X_j^t \le X_j^{max}$ then $X_j^t = X_j^t$

Step 8: Evaluate the fitness function as given below:

$$f(X_j^t, U_j^t) = 1/[1 + Min((1/2) \times (P_D^t - \sum_{j=1}^{5} P_j^t)^2)] \tag{15}$$

Step 9: Is fitness value is greater than $P\_best(i)$?

- If yes, set it as new $P\_best(i)$ & go to step10.
- else go to next step.

Step 10: Is fitness value is greater than G_best ?

- If yes, set it as new G_best & go to next step.
- else go to next step

Step 11: Check whether stopping criteria (max_ iter) reached?

- If yes then got to step 19.
- else go to next step.

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Step12: Calculate acceleration coefficients using eq. (13) & eq. (14).
Step 13: Update velocity of discharge particle using eq. (9).
Step 14: Check whether V_j^t is with in limit V_j^{min}, V_j^{max}.

- If $V_j^t < V_j^{min}$ then $V_j^t = V_j^{min}$
- If $V_j^t > V_j^{max}$ then $V_j^t = V_j^{max}$
- If $V_j^{min} \le V_j^t \le V_j^{max}$ then $V_j^t = V_j^t$

Step 15: Update position of discharge particles using eq. (10).
Step 16: Check whether U_j^t is with in limit U_j^{min}, U_j^{max}.

- If $U_j^t < U_j^{min}$ then $U_j^t = U_j^{min}$
- If $U_j^t > U_j^{max}$ then $U_j^t = U_j^{max}$
- If $U_j^{min} \le U_j^t \le U_j^{max}$ then $U_j^t = U_j^t$

Step 17: Update dependent discharge matrix considering hydraulic coupling.
Step 18: Check for stopping criteria

- If $iter < it\_\max$ then increase iteration count by 1 & go to step 6.
- Else go to step 19.

Step 19: Last G_best position of particles is optimal solution.

6. Results and discussion

The NCHES generation scheduling has been done by Time Varying Acceleration Coefficients PSO (TVAC_PSO) on hourly basis, assuming all reservoirs full at starting of the schedule horizon. The above problem also approached by the NSAIW_PSO with same population size, PSO parameters (as given in Table 3) and load demand. Program has been coded in MATLAB and the performance of both algorithms have been obtained by using MATLAB 7.0.1 on a core 2 duo, 2 GHz, 2.99 GB RAM. The effectiveness of TVAC_PSO & NSAIW_PSO in various trials is judged by the three criteria's first is the probability to get best solution or objective function (robustness), second is the solution quality and third is dynamic convergence characteristics. Dynamic convergence behavior has been analyzed by the mean and standard deviation of swarm as given in eq. (16) & eq. (17) at each generation. Out of 10 trials of each individual hour best results are chosen based on above criteria. The final optimal hourly power generation through hydro power plants of NCHES has shown in Figure 2. The number subscript in increasing order with parameters P, X and Q in Figure 2 to Figure 4 means parameters related to Rani Avanti Bai Sagar, Indira Sagar, Omkareshwar and Sardar Sarovar hydro power plant respectively.

Mean $$\mu_{iter} = (\sum_{p=1}^{PS} E)/PS \tag{16}$$

Standard deviation $$\sigma_{iter} = \sqrt{(1/PS)\times\sum_{p=1}^{PS}(E-\mu_{iter})^2]} \tag{17}$$

Table 3. PSO parameter settings

Parameter	Value
Population size, Max. No. of Iteration	5, 120
Acceleration Coefficients C1 & C2	2 ,2
$C_{1f}, C_{1i}, C_{2f}, C_{2i}$	0.5,2.5,2.5,0.5
$\omega_{min}, \omega_{max}$	0.4,0.9

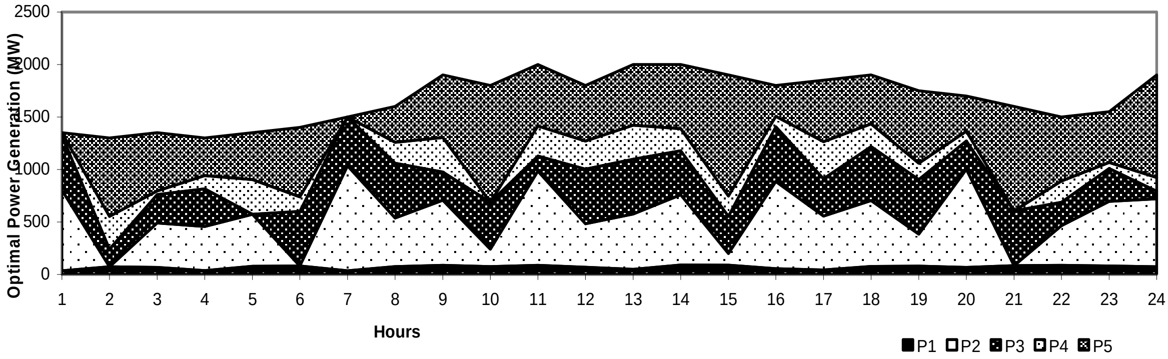
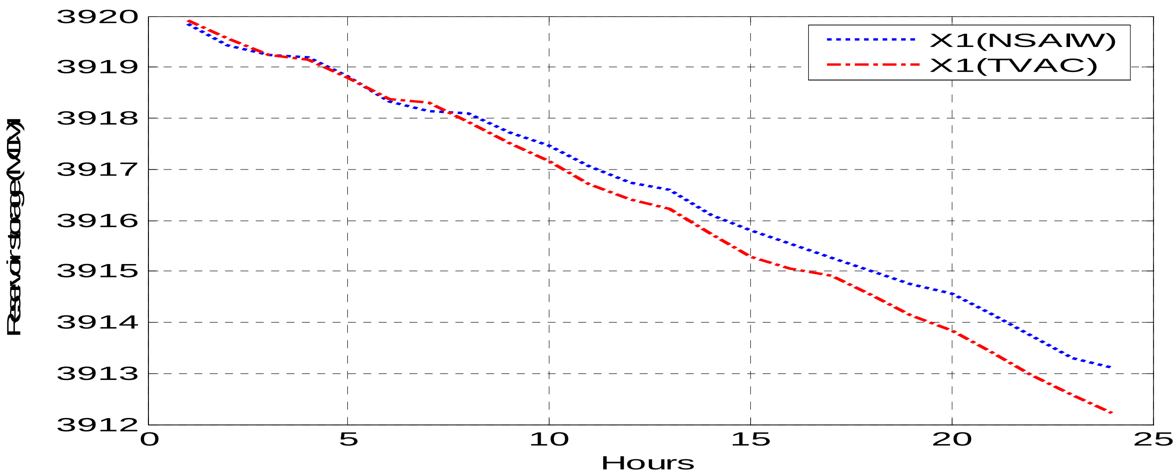
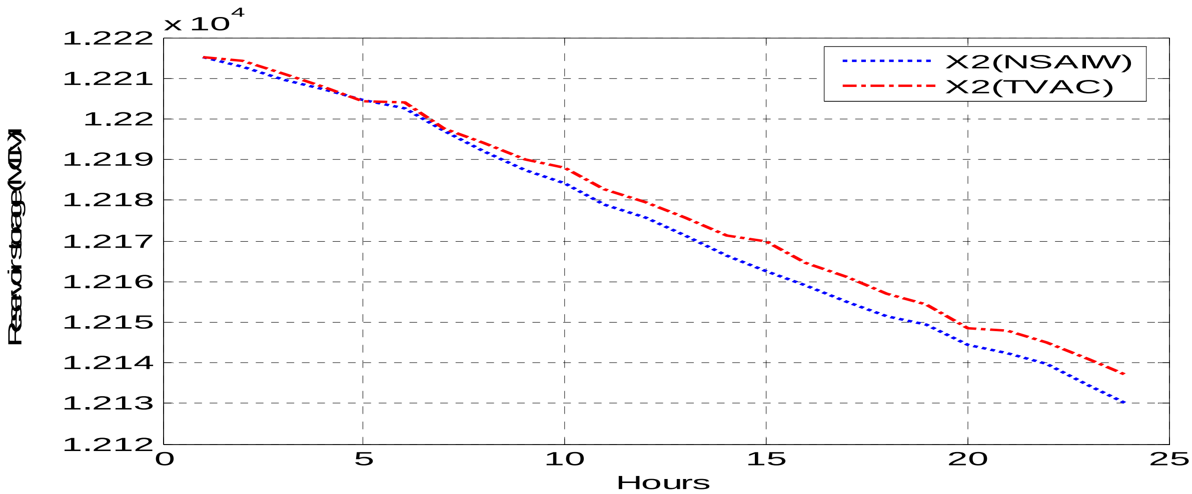


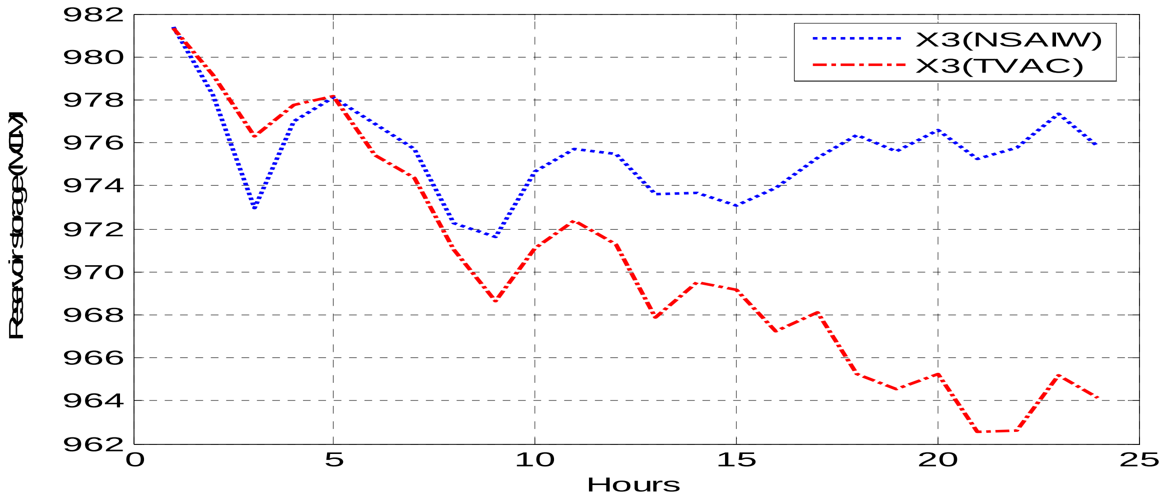
Figure2. Optimal generation schedule from hydro plants of NCHES using TVAC_PSO



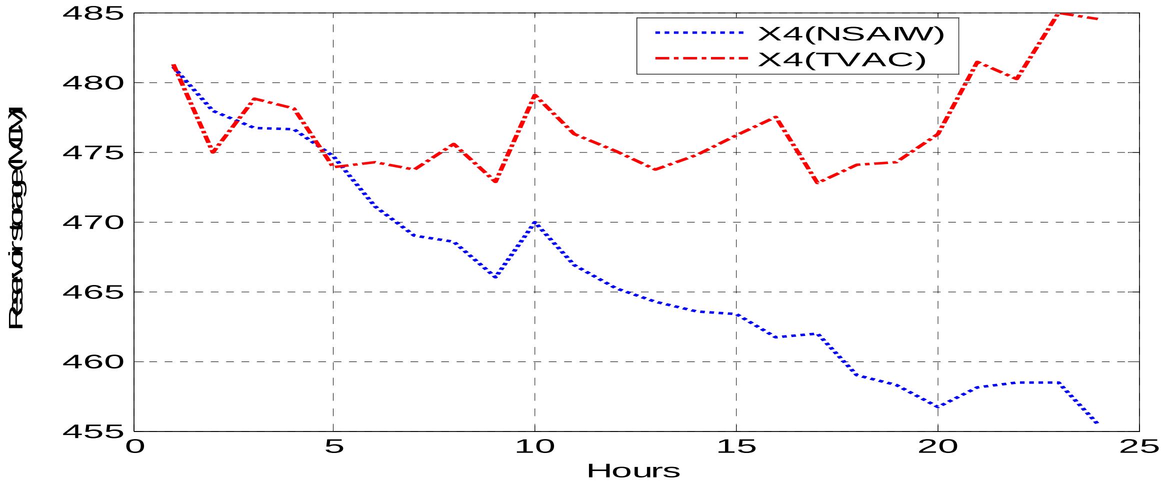
(a) Rani Avanti Bai Sagar HPP



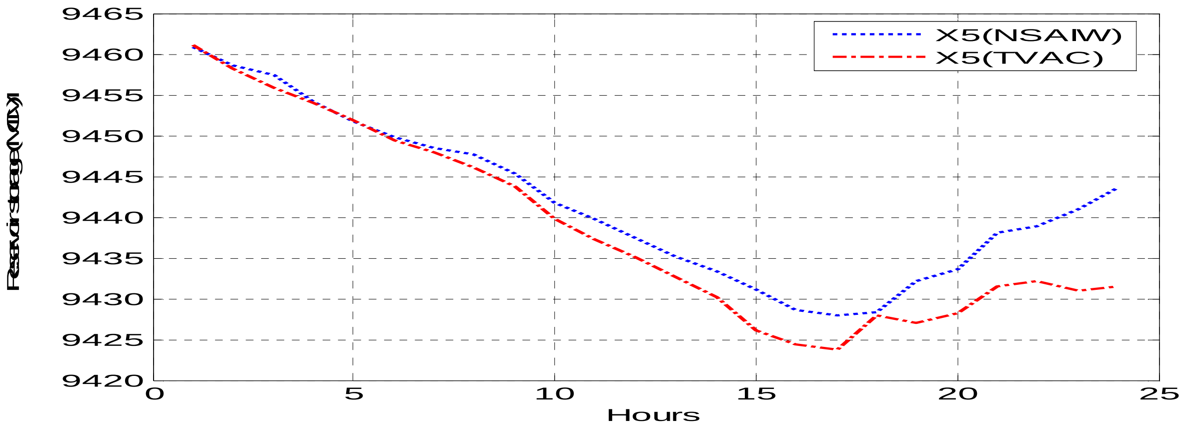
(b) Indira Sagar HPP



(c) Omkarehswar HPP

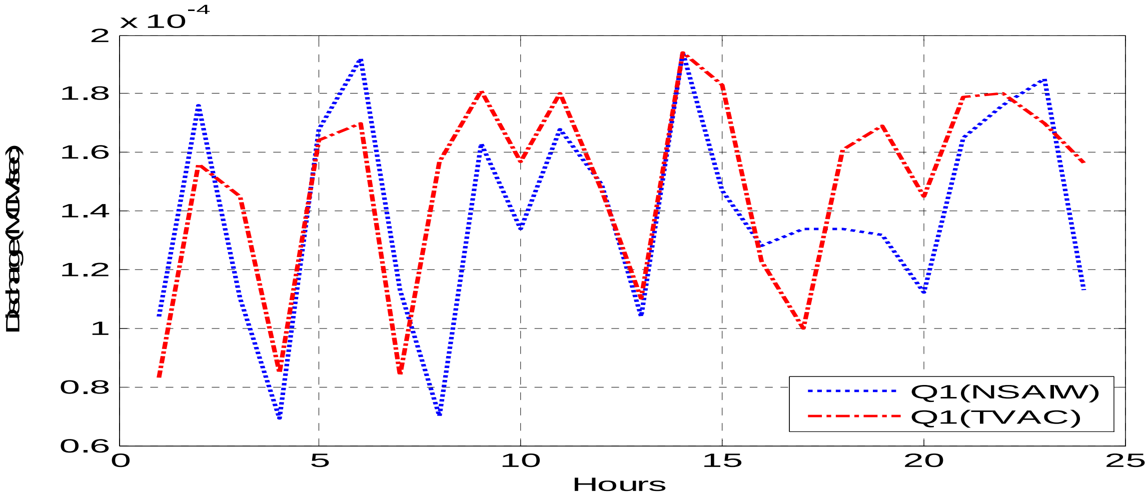


(d) Maheshwar HPP

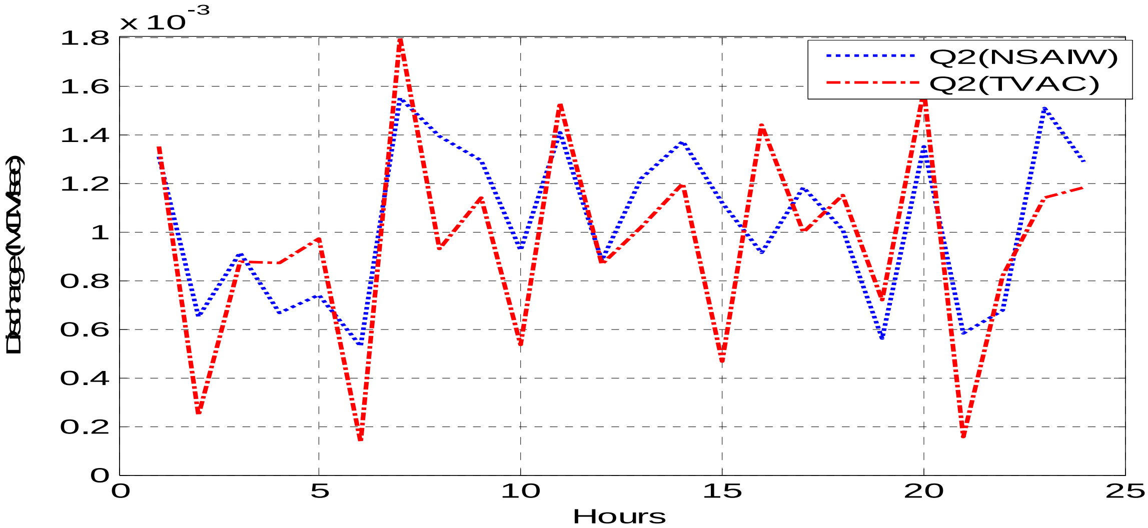


(e) Sardar Sarovar HPP

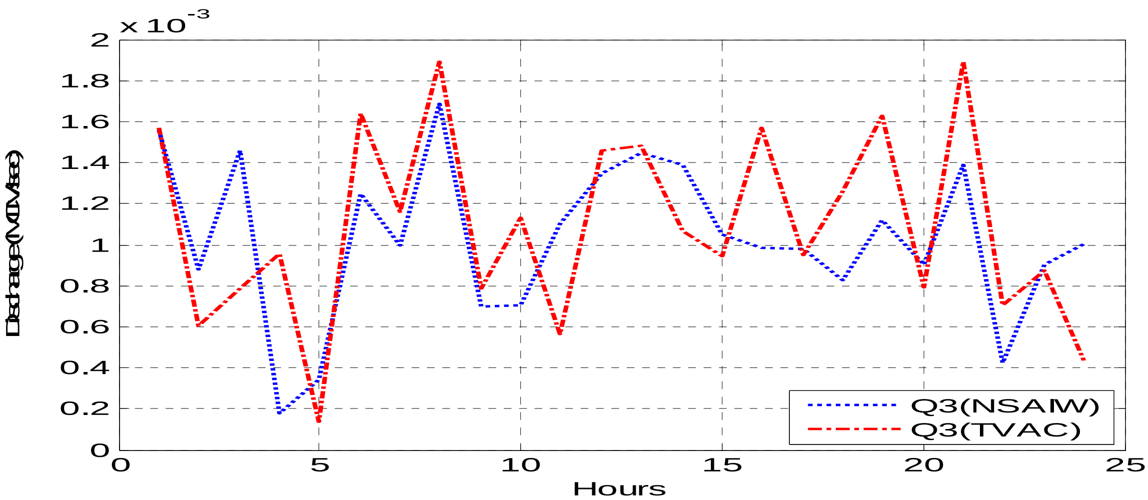
Figure 3. (a-e): Reservoir storage trajectories of hydro plants using TVAC_PSO & NSAIW_PSO



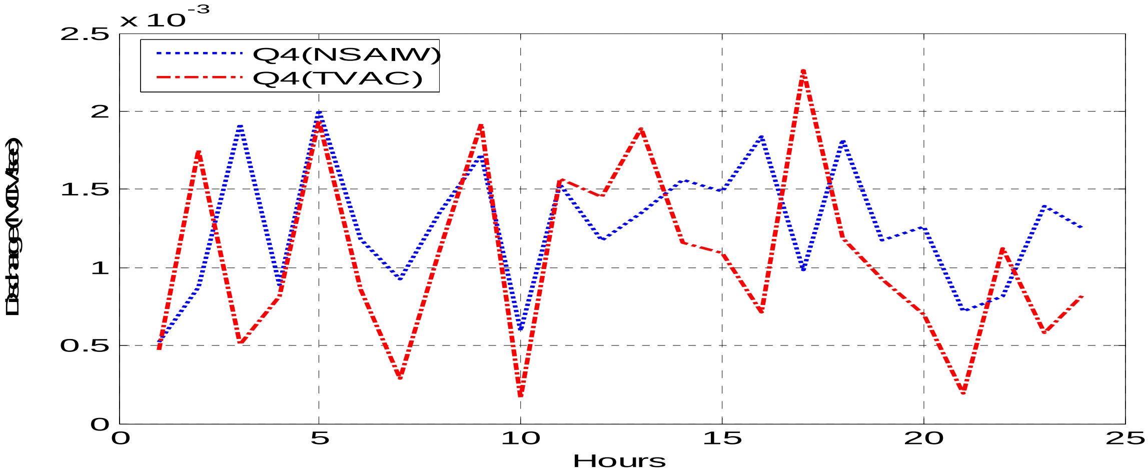
(a) Rani Avanti Bai Sagar HPP



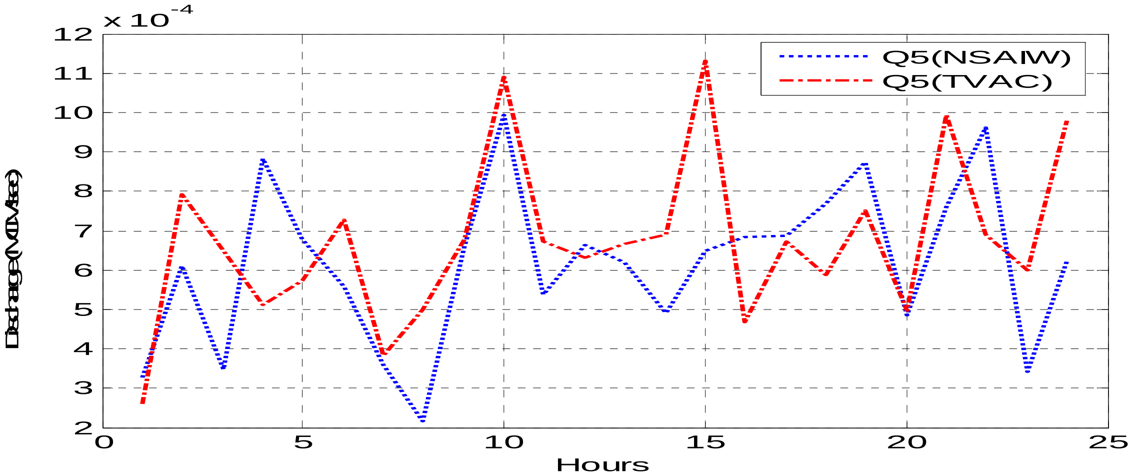
(b) Indira Sagar HPP



(c) Omkareshwar HPP



(d) Maheshwar HPP



(e) Sardar Sarovar HPP

Figure 4. (a-e): Discharge trajectories of hydro plants using TVAC_PSO & NSAIW_PSO

Results of both algorithms are summarized in Table 4. It clearly shows that TVAC_PSO is giving best suitable objective function in comparison to NSAIW_PSO for the schedule horizon of 24 hrs. The total discharge from the hydro power plants of NCHES using TVAC_PSO is 341.53 MCM which is less in comparison to 353.45 MCM through NSAIW_PSO.

Table 4.Comparison of numerical results of NCHES using NSAIW_PSO & TVAC_PSO

Particulars		NSAIW_PSO	TVAC_PSO
Objective Function		4.31E-01	**7.75823E-06**
Discharges through hydro plants of NCHES in MCM in 24 Hours	Q1(MCM)	12.02189557	12.87674831
	Q2 (MCM)	90.16378248	83.2712441
	Q3 (MCM)	88.7430881	94.76693889
	Q4 (MCM)	109.323928	91.90878406
	Q5	53.19838967	58.33005728
	Total	353.4510838	**341.1537726**

Nomenclature

t, T	Time index & total scheduled Horizon.
E	Objective Function
P_D^t	Total load demand at t.
P_j^t	Electrical power generated from j^{th} RBPH plant at t.
X_j^t	Reservoir storage of the j^{th} plant at t .
X_j^{min}	Minimum storage at j^{th} reservoir.
X_j^{max}	Maximum storage at j^{th} reservoir.
H_j^t ,	Head for the j^{th} hydro power plant at t .
U_j^t	Discharge through turbine of j^{th} RBPH at t .
A_i	Hydro turbine model constants for hydro plants.
U_j^{min}	Minimum discharge through turbines of j^{th} plant.
U_j^{max}	Maximum discharge through turbines of j^{th} plant.
S_j^t	Spillage from the j^{th} plant at t .
Q_j^t	Total discharge through plant at t .
δ	Time delay between successive reservoirs.
ω	Inertia weight factor.
C_1 , C_2	Acceleration coefficients.
$C_{1f}, C_{1i}, C_{2f}, C_{2i}$	Time varying acceleration constants.
R_1, R_2	Uniformly distributed random number between 0,1.
X_i^k	Position of particle i at k^{th} iteration.
V_i^k	Velocity of particle i at k^{th} iteration.
$P\_best(i)$	Best position of particle i until iteration k.
G_best	Best position of the group until iteration k.
ω_{min}	Initial value of inertia weight.
ω_{max}	Final value of inertia weight.
iter	Current iteration number.
it_max	Maximum iteration number.
k	Iteration index
up	Index for immediate upstream plant.
n	Total number of plant.
j	Index of hydroelectric power plants.
PS	Population size
r	Rank of particle amongst population.

7. Conclusion

In optimal generation scheduling problem of hydro electric systems, complexity has been introduced by the cascade pattern. This problem becomes more complex when there is high hydraulic coupling between hydro plants of cascade system. This paper adopted TVAC_PSO to determine the optimal generation schedule of NCHES as it addresses the problem of premature convergence by striking proper balance between global and local exploration. Results obtained are compared with the results of NSAIW_PSO and it clearly shows that TVAC_PSO is giving minimum value of objective function in comparison to the NSAIW_PSO with less discharges through hydro power plants of NCHES. Dynamic convergence characteristics and the frequency of getting better solution are also superior in case of TVAC.

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