Short Term Optimal Generation Scheduling of Narmada Cascaded Hydro Electric System

Amita Mahor and Saroj Rangnekar


Amita Mahor Saroj Rangnekar

Abstract: Generation scheduling of cascaded hydropower plants at same stream of river is imperative to harness river water energy in an optimal manner. Along with hydropower, multipurpose hydropower plants are also fulfilling irrigation requirement of nearby zones. Irrigation requirements from immediate plants, natural inflows from tributaries and evaporation losses between successive reservoirs affects water levels in both reservoirs and operating heads. In this paper all of the above factors are included in water continuity equations for optimization problem formulation of a real operated cascaded hydroelectric system located on the Narmada river in Madhya Pradesh, India. Time Varying Acceleration Coefficients PSO (TVAC_PSO) have been used to determine the optimal generation schedule of the above system. The results obtained are compared with Novel Self Adaptive Inertia Weight PSO (NSAIW_PSO), and are found to give a better solution.

Key words: Hydroelectric power generation; Novel Self Adaptive Inertia Weight PSO; Linearly Decreasing Inertia Weight PSO; Time Varying Acceleration Coefficient PSO; short term generation scheduling: Narmada river, Madya Pradesh (India).

Nomenclature

t, T Time index & total scheduled Horizon.

E Objective Function.

E^t Hourly deviation between load demand and generated power through all hydropower plants of NCHES.

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_i^t , Head for the j^{th} hydropower 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 .

O_i^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.

Introduction

In India, Madhya Pradesh (MP) state is highly blessed with river-based hydro resources; hence, power installed capacity of the state is dominated by hydropower plants. At present, 2,810 MW hydropower plants are located in cascade mode on the main stream of the Narmada river. Apart from this, a 400 MW Maheshwar purely hydropower project is to be commissioned shortly, which will further enhance the power installed capacity of the state. Currently, these hydroelectric power plants are operating at nominal output power values in spite of optimal operation. Therefore, proper operation policy in terms of optimal hydroelectric generation scheduling of these power plants plays an important role in power generation. Hydroelectric scheduling means utilizing water resources of reservoirs in such a way that water resources of a river can be effectively utilized without spilling at downstream. The scheduling problem becomes a more difficult optimization problem when a hydro systems is of an inter-connected multiple reservoirs type. In such a system, due to hydrological interdependence of the plants the operation of any plant affects water level and storage at other plants in the same system. The non-conventional meta- heuristic Particle Swarm Optimization

(PSO) technique has gained popularity as the preeminent solution algorithm to determine the optimal generation schedule of hydropower plants.

Significant research has been done and is going on to improve the performance of PSO. Researchers have shown improvement in performance of PSO by a random number generation technique (Coelho and Lee 2008), introduction of particle repulsion (Selvakumar and Thanushkodi 2008), craziness (Ranjit and Ghosal 2008; Titus and Jeyakumar 2007), mutation (Pichet 2008), time varying acceleration coefficients (Chaturvedi, Pandit and Shrivastava 2008; Ratnaweera, Halgamuge and Waston 2004), inertia weight variation (Panigrahi, Ravikumar and Das 2008; Park et al 2008). 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.

The rest of the paper is organized in seven sections. Section 2 described 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 is discussed in Section 4. Detail algorithm of the TVAC_PSO is described in Section 5. And, results and discussions are dealt with in Section 6, followed by Conclusions in Section 7.

Problem Formulation

The short term scheduling of cascaded hydroelectric systems means to find out the water discharge, water storage and spillages for each reservoir j at each hour of scheduled horizon over 24 hrs to minimize objective function subjected to all physical and operational constraints.

Objective Function

The scheduling of cascaded hydroelectric systems differs from thermal power plants as cascaded hydroelectric system reservoir storage varies with time as per water continuity equation. In the present work, reservoir storage of each hydropower project updated as per water continuity equation at a discrete interval of one hour and updated reservoir storage is the maximum storage limit for the successive hour. Hence, objective function E, i.e., the deviation between load demand and generation through hydroelectric power plants of NCHES for time horizon of one day expressed as:

$$E = Min \sum_{t=1}^{T} E^t \quad (1)$$

Where E^t is the hourly deviation between load demand and generated power as given below.

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

The power generated from hydropower 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 (Naresh 2002) as given in eq. (3) within bounds of head/storage and discharges.

$$P_j^{\ t} = A_1 \times (H_j^{\ t})^2 - A_2 \times (U_j^{\ t})^2 - A_3 \times (H_j^{\ t}) \times (U_j^{\ t}) + A_4 \times (H_j^{\ t}) + A_5 \times (U_j^{\ t}) + A_6 \quad (3)$$

Constraints

The optimal value of 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 periods of one hour.

Equality Constraints

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:

$$X_j^{\ t+1} - X_j^{\ t} + U_{up}^{\ t-\delta} \quad S_{up}^{\ t-\delta} \quad I_j^t - U_j^{\ t} - S_j^{\ t} \quad EL_j^t \quad IR_j^t \quad (4)$$

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.

Reservoir storage bounds

$$X_j^{\min} \le X_j^t \le X_j^{\max} \tag{5}$$

Water discharge bounds

$$U_j^{\min} \le U_j^t \le U_j^{\max} \tag{6}$$

Power generation bounds

$$P_j^{\min} \le P_j^t \le P_j^{\max} \tag{7}$$

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:

$$S_j^t = Q_j^t - U_j^{\max} \text{ if } Q_j^t > U_j^{\max} \tag{8}$$
$$= 0 \quad \text{otherwise}$$

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.

$$X_j^T = X_j^{end} \qquad X_j^T = X_j^{end} \tag{9}$$

Overview of Particle Swarm Optimization

Particle Swarm Optimization is inspired from the collective behavior exhibited in swarms of social insects (Kennedy and Eberhart 1995). Amongst various versions of PSO, the most familiar was proposed by Shi and Eberhart (2007). The key attractive feature of PSO is its simplicity, as it involves only two model eq. (10) and eq. (11). In PSO, the co-ordinates of each particle represent a possible solution called particles associated with position and velocity vector. At each iteration the particles move 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 $p_i = [p_{i1}, p_{i2}..............p_{id}]$ and $v_i = [v_{i1}, v_{i2,}..............v_{id}]$ in the PSO algorithm.

Let $P\_best(i) = [p_{i1pbest}, p_{i2pbest} ....p_{idpbest}$ $G\_best = [p_{1gbest}, p_{2gbest} .....p_{dgbest}]$

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:

$$v_i^{k+1} = v_i^k \times \omega + C_1 \times R_1 \times (P\_best(i) - p_i^k) + C_2 \times R_2 \times (G\_best - p_i^k) \tag{10}$$

$$p_i^{k+1} = p_i^k + v_i^{k+1} \tag{11}$$

$$\omega = \omega_{\max} - ((\omega_{\max} - \omega_{\min}) \text{ iter}) / \text{it\_max} \tag{12}$$

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. (12).

Novel Self Adapting Inertia Weight PSO (NSAIW_PSO)

In a simple PSO method, the inertia weight is made constant for all particles in one generation. In the NSAIW_PSO (Chen, Gaofeng and Zhenyi 2008) 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 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. (13).

$$\omega = \left(3 - \exp(-PS/200) + (r/100)^2\right)^{-1} \tag{13}$$

Time Varying Acceleration Coefficients PSO (TVAC_PSO)

In PSO, search towards optimum solution is guided by the two stochastic acceleration components (cognitive and social component). Therefore, the proper control of these components is very necessary. Kennedy and Eberhart (1995) 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, a time varying acceleration coefficients concept has been introduced by Halgamuge and Waston (2004) that enhances 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. (14) & eq. (15)

$$C_1 = ((C_{1f} - C_{1i}) \times (iter / it\_\max)) + C_{1i} \tag{14}$$

$$C_2 = ((C_{2f} - C_{2i}) \times (iter / it\_\max)) + C_{2i} \tag{15}$$

Description of Narmada Cascaded Hydroelectric System (NCHES)

NCHES is located on the interstate river Narmada in India. This system is characterized by a cascade flow network, with water transport delay between successive reservoirs and variable natural inflows. This system has five major hydropower projects, namely: Rani Avanti Bai Sagar (RABSP), Indira Sagar (ISP), Omkareshwar (OSP), and Maheshwar (MSP), located in the state pf Madhya Pradesh, and India and Sardar Sarovar (SSP) terminal project in the state of Gujarat. All projects are located on the main stream of the river, hence a hydraulic coupling exists amongst them as shown in Figure 1, especially between ISP, OSP and MSP. The tailrace level of the ISP is matched with the full

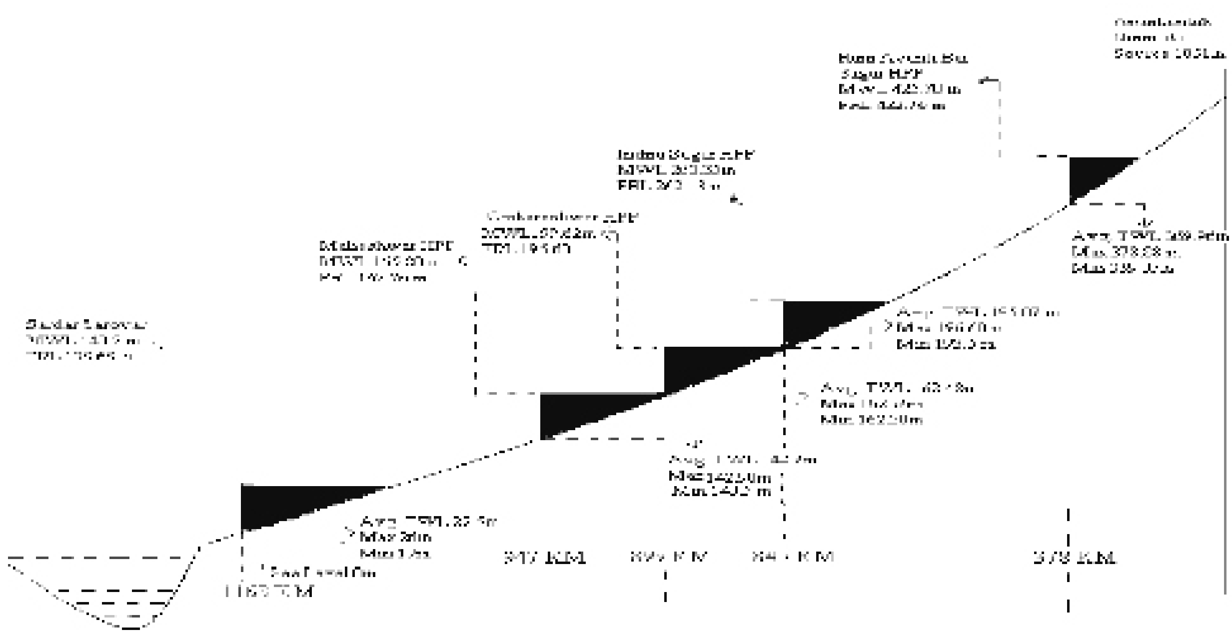


Figure 1: Hydraulic Coupling in NCHES

reservoir level of OSP. and similarly between OSP and MSP.

The present work is carried out based on data reported in Mahor, Prasad and Rangnekar (2009). Water traveling time between successive reservoirs is mentioned in Table 1. The hourly load demand, irrigation requirement, natural inflows and evaporation losses considered for the scheduling of NCHES have been given in Table 1, 2, 3, 4 and 5, respectively.

Plant	Travel time	Plant	Travel time	Plant	Travel time
RABS	52 hrs	ISP	4 hrs	OSP	3 hrs
MSP	17 hrs	SSP	0 hrs		

Table 1. Water Traveling Time Between Consecutive Reservoirs

Hour	Demand	Hour	Demand	Hour	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

Table 2. Hourly Load Demand (MW)

Hour	Irrigation Requirement			
	RABS	ISP	OSP	SSP
1-3	52.94	65.48	51.97	311.2
4-6	60.81	56.72	102.8	329.8
7-9	43.40	45.3	41.54	222.2
10-12	14.81	37.72	49.98	447.45
13-15	60.31	63.2	51.3	451.2
16-18	35.6	55.28	65.75	500.54
19-21	50.67	65.48	51.96	600.67
22-24	25.5	40.67	80.51	370.1

Table 3. Hourly Irrigation Requirement (m^3/s)

Evaporation Loss m^3/s				
RABS	ISP	OSP	MSP	SSP
14.02	13.13	9	7.10	16.1

Table 4. Average Hourly Evaporation Loss (m^3/s)

Natural Inflows m^3/sec				
RABS	ISP	OSP	MSP	SSP
59.21	80.5	25.45	20	442

Table 5. Average Hourly Natural Inflows (m^3/s)

TVAC_PSO Algorithm of NCHES Generation Scheduling

To get the optimal value of objective function, hourly deviation between load demand and generated power through hydropower plants of NCHES E^t should be minimized. The steps involved in optimization to minimize E^t are as follows:

Step 1: Initialize velocity of discharge particles between $-v_j^{max}$ to $+v_j^{max}$ as $v_j^{max} = (U_j^{max} - U_j^{min})/10$
Step 2: 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. (4).
Step 7: Check whether 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:

$$f(X_j^t, U_j^t) = 1/[1 + Min((1/2) \times (P_D^t - \sum_{j=1}^{5} P_j^t)^2)] \tag{16}$$

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 (it_max) reached?

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

Step12: Calculate acceleration coefficients using eq. (14) & eq. (15).
Step 13: Update velocity of discharge particle using eq. (10).
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

Results and Discussion

The solution of NCHES optimal generation scheduling has been done by Time Varying Acceleration Coefficients PSO (TVAC_PSO) on an hourly basis, assuming all reservoirs full at starting of schedule horizon. The above problem was also approached by NSAIW_PSO with the same population size, PSO parameters as given in Table 6 and load demand. The program was coded in MATLAB and the performance of both algorithms was 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 three criteria. The first is the probability to get best solution or objective function (robustness). The second is the solution quality. And, the third is dynamic convergence characteristics. Dynamic convergence behavior has been analyzed by the mean and standard deviation of swarm as given in eq. (17) & eq. (18) at each generation. Hourly optimal generation schedules are obtained on succession basis. Ten trials of each individual hour have been done and best results are chosen based on above criteria.

Mean $$\mu_{iter} = \left(\sum_{p=1}^{PS} E\right) / PS \tag{17}$$

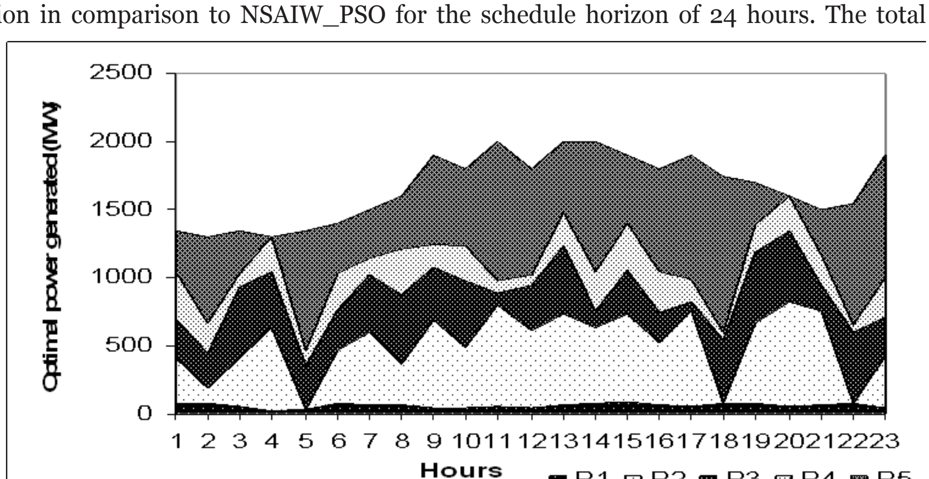
Standard deviation $$\sigma_{iter} = \sqrt{\left[(1/PS) \times \sum_{p=1}^{PS} (E - \mu_{iter})^2\right]} \tag{18}$$

Parameter	Value
Population size, Max. No. of Iterations	10, 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

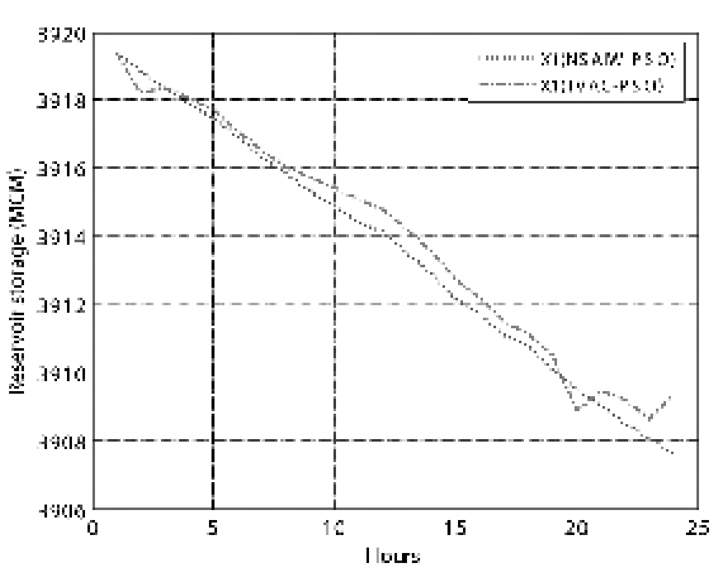
Table 6. PSO Parameter Settings

The final optimal hourly power generation through hydropower plants of NCHES is shown in Figure 3(a) and (b). The number subscript in increasing order with parameters P, X and Q in Figure 3, Figure 4(a) to (e) and Figure 5(a) to (e) for parameters related to Rani Avanti Bai Sagar, Indira Sagar, Omkareshwar and Sardar Sarovar hydropower plant respectively.

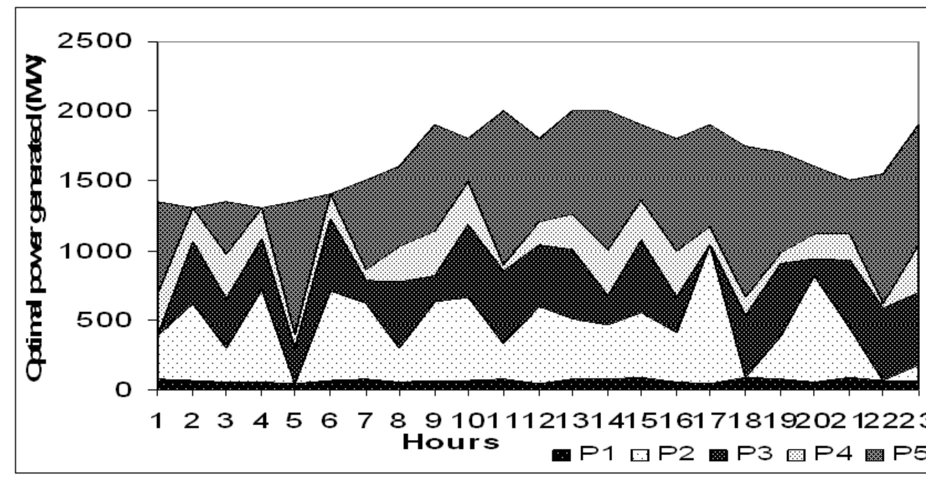
Results of both algorithms are summarized in Table 7. It clearly shows that TVAC_PSO is giving the best suitable objective function in comparison to NSAIW_PSO for the schedule horizon of 24 hours. The total discharge from



(a) TVAC_PSO

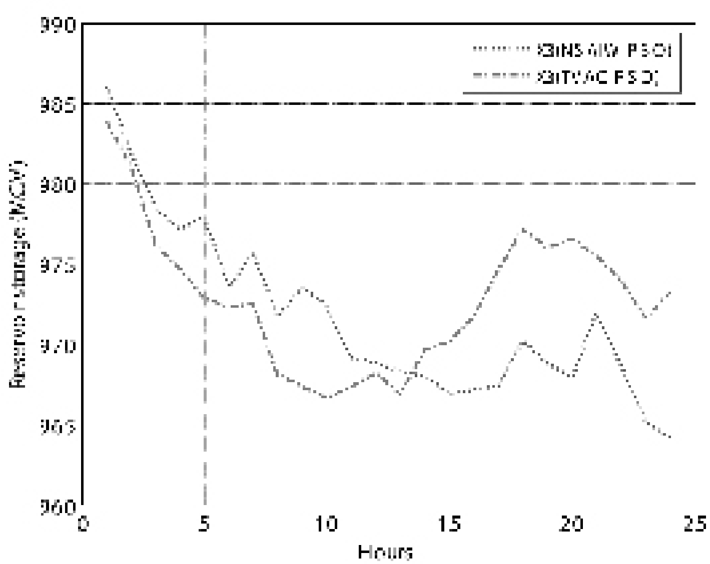


(a) Reservoir Storage Trajectories: Rani Avanti Bai Sagar

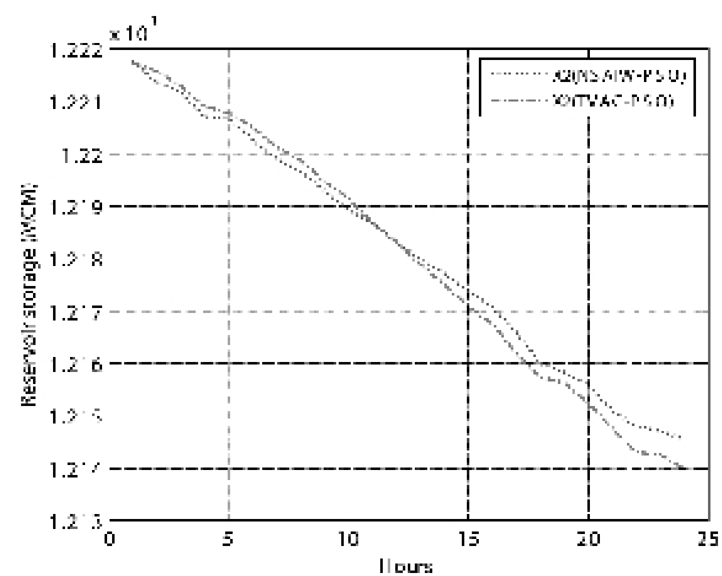


(b) NSAIW_PSO

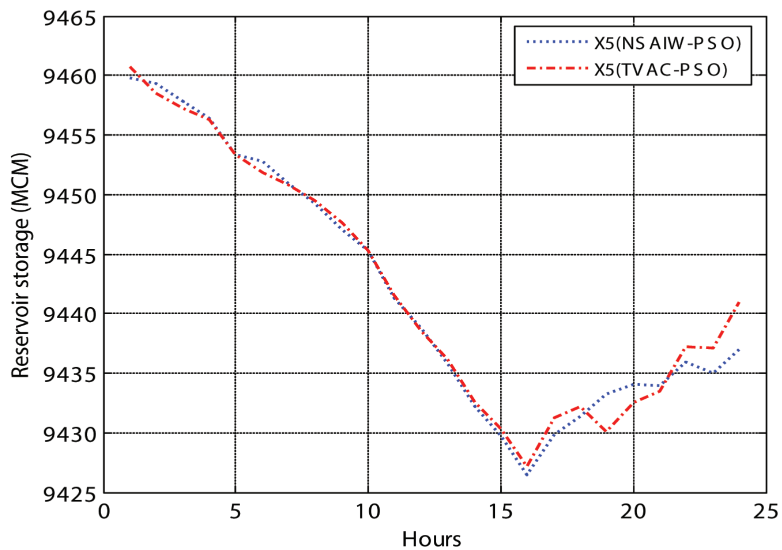
Figure 3(a)-(b). Hourly Optimal Generation Schedule from Hydro Plants of NCHES Using TVAC_PSO



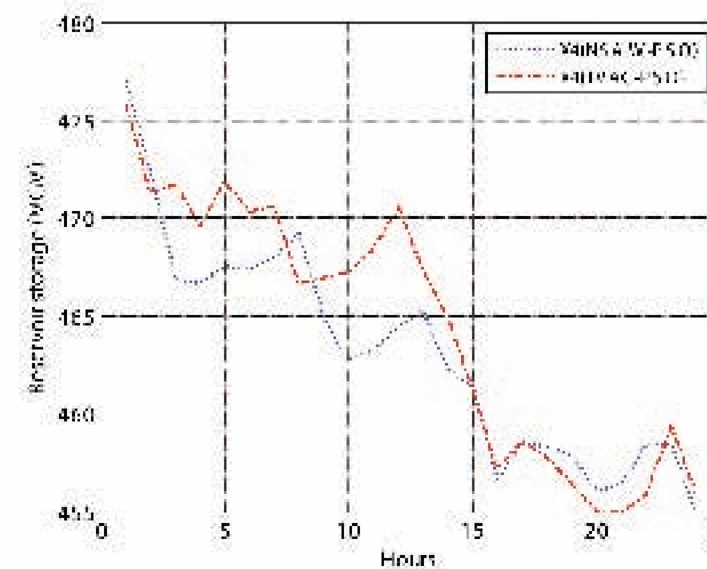
(c) Reservoir Storage Trajectories: Omkarehswar



(b) Reservoir Storage Trajectories: Indira Sagar

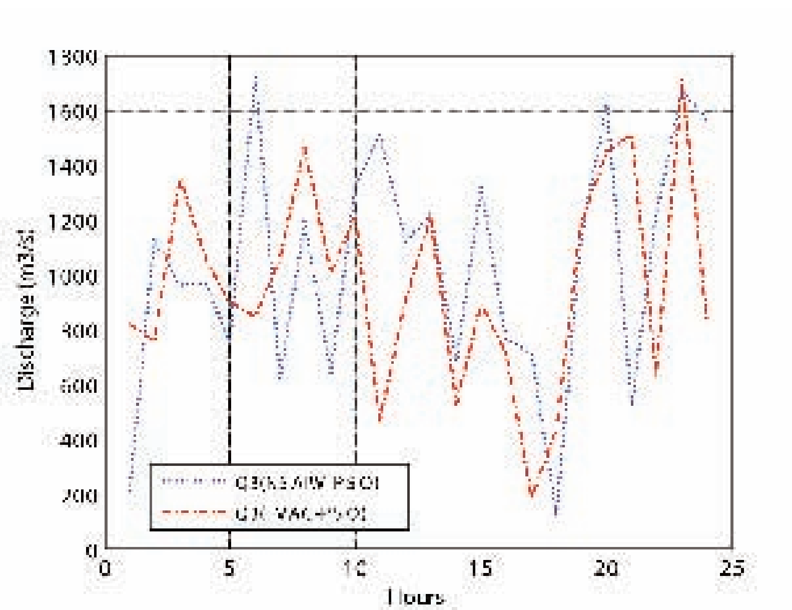


(e) Reservoir storage trajectories: Sardar Sarovar

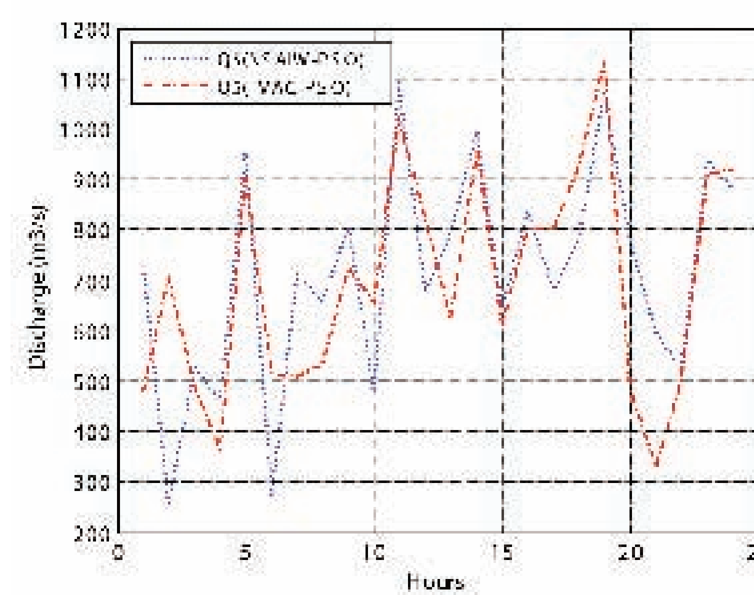


(d) Reservoir Storage Trajectories: Maheshwar

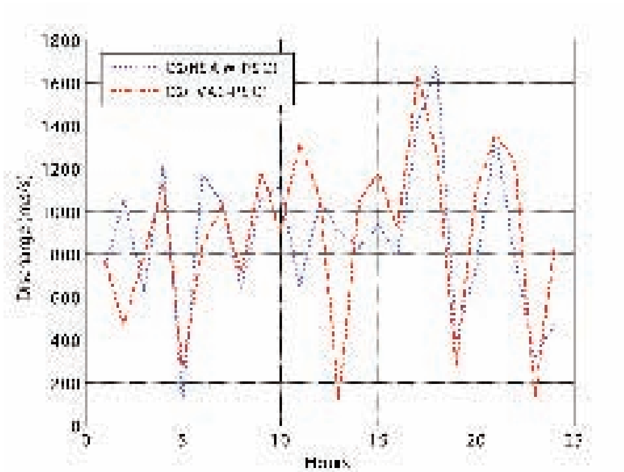
Figure 4(a)-(e). Hourly Reservoir Storage Trajectories of Hydropower Plants Using TVAC_PSO and NSAIW_PSO



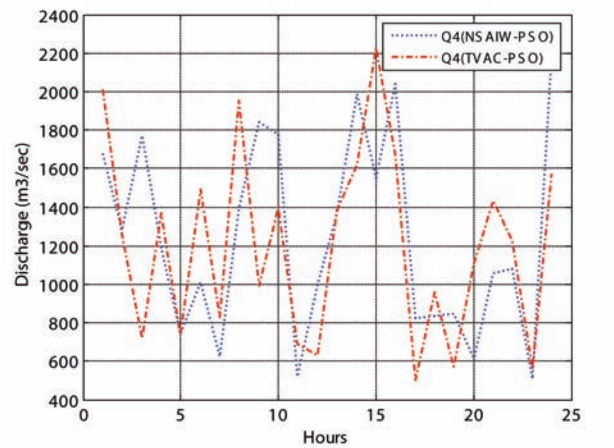
(b) Discharge Trajectories: Omkareshwar



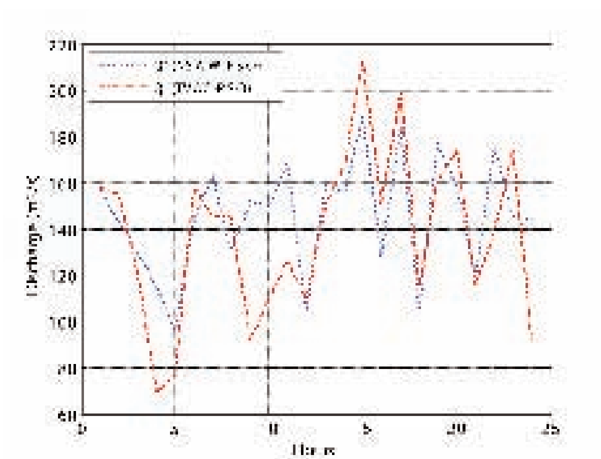
(a) Discharge Trajectories: Sardar Sarovar



(c) Discharge Trajectories: Indira Sagar



(d) Discharge Trajectories: Maheshwar



(e) Discharge Trajectories: Rani Avanti Bai

Figure 5 (a)-(e). Hourly discharge trajectories of hydropower plants using TVAC_PSO & NSAIW_PSO

the hydropower plants of NCHES using TVAC_PSO is 336.84 MCM, which is less in comparison to 345.11 MCM through NSAIW_PSO.

Particulars		NSAIW_PSO	TVAC_PSO
Objective function		3.89E-01	4.45E-05
Discharge through hydropower plants of NCHES in MCM for schedule horizon of 24 Hours	Q_1	11.94	11.94
	Q_2	75.64	77.41
	Q_3	88.88	83.31
	Q_4	106.99	104.04
	Q_5	61.66	60.14
	Total	345.11	336.84

Table 7. Comparison of Numerical Results of NCHES Using NSAIW_PSO and TVAC_PSO

Conclusions

Hydropower plants are generally multipurpose projects, hence irrigation requirements, natural inflows and evaporation losses are considered during optimization problem formulation. TVAC_PSO is used to determine the optimal generation schedule of hydropower plants of NCHES and results thus obtained are compared with NSAIW_PSO results. TVAC_PSO has shown superior results in terms of objective function and total discharge through all hydropower plants of NCHES in comparison to NSAIW_PSO as it addresses the problem of premature convergence by striking proper balance between global and local exploration. Dynamic convergence characteristics and the frequency of getting better solution are also superior in case of TVAC.

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Amita Mahor *is a full time PhD research scholar in the Department of Energy at Maulana Azad National Institute of Technology (MANIT), Bhopal, India. She did her B.E. in Electrical Engineering and M. Tech in Heavy Electrical Equipments. Her research area is Optimal Generation Scheduling of Cascaded Hydro Power Plants.*

Corresponding address: amitamahor@ yahoo.co.in

Dr. Saroj Rangnekar *is Professor in the Department of Energy, Energy Centre at MANIT, Bhopal. India. She has 32 years of teaching a research experience and has received three National awards. Her field of interest includes Hydroelectric System, Control Systems and Integrated Renewable Energy System, its modeling and optimization.*

Corresponding address: saroj6@yahoo.com or rangnekars@manit.ac.

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A Jug of Water

If we go on using the Earth uncaringly and without replenishing it, then we are just greedy consumers. We should take from the Earth only what are our absolute and basic necessities: things without which we cannot survive. The Earth has an abundance of everything, but our share in it is only what we really need.

There is a story to illustrate this.

Mahatma Gandhi was staying with the first Indian Prime Minister, Mr. Nehru, in the city of Allahabad. In the morning Gandhi was washing his face and hands. Mr. Nehru was pouring water from the jug as they talked about the problems of India. As they were deeply engaged in serious discussion, Gandhi forgot that he was washing; before he had finished washing his face, the jug became empty. So Mr. Nehru said, "Wait a minute and I will fetch another jug of water for you. Gandhi said, "What! You mean I have used all that jugful of water without finishing washing my face? How wasteful of me! I use only one jug of water every morning.

He stopped talking; tears flowed from his eyes. Mr. Nehru was shocked. "Why are you crying, what has happened, why are you worried about the water? In my city of Allahabad there are three great rivers, the Ganges, the Jummar and the Saraswati, you don't need to worry about water here!

Gandhi said, "Nehru, you are right, you have three great rivers in your town, but my share in those rivers is only one jug of water a morning and no more.

Satish Kumar
Jonathon Porritt
Save the Earth
London, Dorling Kindersley, 1991