

Short Term Hydro-Scheduling of Cascaded Narmada Hydroelectric System

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Abstract: This paper presents the optimal short term scheduling of Narmada Cascaded Hydro Electric System (NCHES) situated in central India, which is necessary for determining the optimal generation schedule of real operated cascaded hydroelectric system. 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 deviation between load demand and generation subjected to constraints. Meta-heuristic optimization techniques particularly Particle Swarm Optimization (PSO) and its variants have been successfully used to solve such problem. Double Exponential Distributed PSO (DED_PSO) has been used to determine the efficient generation schedule of real operated cascaded hydroelectric system located at Narmada river in state Madhya Pradesh, India. DED_PSO gives better performance as compared to the other two PSO variants, i.e., Time Varying Acceleration coefficients PSO (TVAC_PSO) and Novel Self Adaptive Inertia Weight PSO (NSAIW_PSO). Also, mathematical modeling of Rani Avanti Bai Sagar, Indira sagar, Omkareshwar, Maheshwar & Sardar Sarovar hydroelectric power plants as a part of cascaded scheme at Narmada river has been presented. These models have been used for the optimization problem of cascade hydro scheduling.

Keywords: Hydro power, scheduling, optimisation technique, etc.

I. Introduction

All over the world there is a huge gap between generation of power & its demand. To fulfil this unremitting increase in demand it is required that the available energy resources should be effectively utilized. Apart from this depletion of fossil fuels, environmental challenges create the threats on power industry to go for the search of alternative solutions. At present general profile of our country dominates by thermal power industry in a ratio of 70/30 with hydro. Although government policies are promoting to increase the hydro power generation. To meet this objective it is require that water resources of the country should be optimally utilized by installing hydropower plants in cascaded mode.

When power plants are connected in cascaded mode there is a hydraulic coupling exists between them. It means

the tail race level of immediate upstream power plant acts as a full reservoir level of the downstream project [3]. In such situation increase on water level than full reservoir level reduces the effective head for the upstream project & ultimately power generation reduces. This necessitates the effective operating mechanism for opening & closing of gates at penstocks of hydro power plants.

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, 3670 MW hydropower plants are located in cascade mode on the main stream of the Narmada river [38]. Currently, these hydroelectric power plants are operating at nominal output power values in spite of optimal operation [39]. Therefore, proper operation policy in terms of optimal hydroelectric generation scheduling of these power plants plays an important role in power generation [40]. 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 [41]. 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 [42].

The optimal scheduling of hydroelectric plants not only reduce the gap between generation and the demand of the Madhya Pradesh, India, but also it can reduce the uses of fossil fuel and vice versa can reduce the uses of fossil fuel and vice versa can reduce the global warming [43]. Modeling of Hydro Electric Plant (HEP) is a very complex task and as such there is no uniform modeling as each one is unique to its location and requirement [44]. The diversity of these design makes its necessary to model each one individually. The main aim in this paper is optimized short term hydro scheduling problem formulation of a real operated cascaded hydroelectric system located on the Narmada river in Madhya Pradesh, India. Particle swarm Optimization Technique has been used to determine the optimal short term generation scheduling of the above system.

The systematic coordination of the operation of a system of hydroelectric generation plans is usually more complex than the scheduling of an all thermal generation

system. The reason is both simple & important. That is, the hydroelectric plants may couples both electrically (i.e., they all serve the same load) and hydraulically (i.e., the water inflow to one or more downstream plants). No two hydroelectric systems in the world are alike. They are all different. The reasons for the differences are the natural differences in the watersheds, the differences in the manmade storage & release elements used to control the water flows, & the very many different types of natural & manmade constraints imposed on the operation of hydroelectric systems. It's very usual now a days to extract multipurpose task from a hydro project. And fulfilling irrigation & water requirement is most common amongst those tasks. Hence installation of Canal Head Power House (CHPH) is very wise decision in every project along with River Bed Power House (RBPH), to extract the potential energy of water released for irrigation utility.

Scheduling of cascaded hydroelectric systems for the generation point of view is always complicated job as water released from the upper reservoir raises the volume of water in lower or subsequent reservoir and cutbacks the actual head for the current plant. This type of problem has been classified as global non-linear, dynamic and non-convex optimization problem. Traditional algorithms like linear, nonlinear, quadratic, integer and geometric programming suffers from uni-directional search, single solution update by point by point approaches, sensitive to initial condition, use of deterministic transition rule, not efficient for discrete search space and stuck into suboptimal solution [2]. Different from traditional search algorithms, non traditional techniques, i.e., evolutionary or non-gradient probabilistic techniques work on a population of potential solutions (points) of the search space and offers an advantages of getting multiple suitable solution in single run, stochastic search, easy to implement, robust, parallel computing and many more [4]. Through cooperation and competition among the potential solutions, these techniques often find optima more quickly when applied to complex optimization problems. Amongst all evolutionary techniques PSO is a comparatively new computation technique which is inspired by natural aspects such as fish schooling, bird flocking and human social relations [1]. It explores global optimal solution through exploiting the particle's memory and swarm memory. PSO has gained incredible recognition during last decade due to convenience of realization, fast convergence and promising optimization ability in various problems. Here also, variants of PSO viz., DED_PSO has been used to determine the efficient generation schedule of real operated cascaded hydroelectric system located at Narmada river in state Madhya Pradesh, India. DED_PSO gives better performance as compared to the other two PSO variants, i.e., TVAC_PSO [11] and NSAIW_PSO [7].

II. Problem Formulation

The important aspect of optimal generation scheduling problem is the formulation of practical problem in a standard mathematical optimization format which is acceptable to the optimization algorithm. This chapter

focused on optimization problem formulation of NCHES subjected to various physical and operation constraints. Here objective function is to minimize the difference between load demand and power generated through five river bed power houses namely RABS, ISP, OSP, MSP and SSP [46] and four irrigation canal head power houses RABS, ISP, OSP and SSP [45]. Equality constraints like water continuity equation, irrigation requirement and inequality constraints power generation limits, reservoir storage limits, discharge limits and spillages have been considered. The purpose of the formulation procedure is to create a mathematical model of the optimal problem, which can be solved using an optimization algorithm. Since an optimization algorithm accepts an optimization problem in a particular format, every optimal problem must be formulated in that format. The development of the optimization problem formulation or model can be divided into five major phases.

- Collection of data - It is an important and fundamental basic of the model building process. The accuracy and ability to evaluate the model depends on the authenticity of available data and its accuracy.
- Problem definition & formulation - This involves the main steps of identification of decision variables, formulation of model objective & constraints. Implementation of above steps necessitates the identification of important elements that the problem consists of, number of independent variables, number of equations required to describe the system, no. of unknown parameters, evaluation of structure and degree of complexity of model and degree of accuracy required of the model.
- Model development - The model development phase is an iterative process that may require returning to problem definition and formulation phase. It includes the mathematical description, parameter estimation, input development and software development.
- Model validation & evaluation of performance - This phase is also an iterative process and may require returning to the problem definition and formulation phase. It consists of validation of assumptions and parameters of the model by standard performance measures like Root Mean Square Error (RMSE), sensitivity analysis.
- Model application & interpretation of results.

A. Objective Function:

Short term hydroelectric power generation scheduling problem for cascaded hydro electric system can be stated to find out the water discharges, water storage in reservoir and the power generated through each hydro power plants at all schedule time periods that minimize the gap between load demand and generation subjected to all physical and operational constraints. These are in form of demand supply balance, flow balance or continuity equation, bounds on reservoir storage, bounds on water release or discharge, limits on spillage, and coupling constraints that put's a boundary condition on the initial and final reservoir

level. Hydro scheduling problems requires an optimization problem formulation. During formulation water travelling time from upstream plant to immediate downstream plant is considered of constant value in spite of varying discharges. In present case of NCHES problem has been formulated considering natural inflows, irrigation requirement and evaporation losses assuming generation through canal head power houses. In this case objective is to minimize the deviation between load demand (including transmission losses) and generation through river bed and irrigation canal head power houses for the scheduled horizon of one day. In present case, it has been assumed that all hydroelectric power plants of cascaded system are directly connected to grid and power generated by them is fed into it. Thus objective function to be minimized can be written as:

$$E = \text{Min} \sum_{t=1}^T E^t$$

where,

$$E^t = \text{Min} (1/2) \times [(P_D^t - \sum_{j=1}^n P_j^t - \sum_{j=1, j \neq 4}^n P_{chj}^t)^2] \quad (1)$$

where, P_D^t, P_j^t and P_{chj}^t represents load demand, power generated through RBPHs and power generated through CHPHs at time t respectively. In all above three cases similar hourly load demand has been taken as given in Table 1.

Table 1: Hourly load demand (in MW).

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

The power generated through reservoir type river bed power houses P_j^t is a nonlinear function of head and discharges through turbines and expressed as eq. (2) within bounds of head / storage and discharges.

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

Above equation is very well satisfying the triplet data sets of the turbine efficiency curve of all RBPH of NCHES. Multiple regression least square technique has been applied to determine the correlation coefficients of these plants. The power generated through RABS, ISP, OSP and SSP canal head power houses P_{chj}^t is dependent on the irrigation discharges and simply expressed either general eq. (2) as above or general eq. (3) given below as per turbine efficiency curve data:

$$P_{chj}^t = C_{chj} \times H_{chj}^t \times U_{chj}^t \quad (3)$$

B. Constraints:

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

1. Equality constraints

a) Water balance equation

Naturally occurring reservoirs are not standard geometric shapes. Generation associated discharge varies with time and there are environmental and weather factors which also contribute directly to change in water level. A reservoir thus has a number of independent inflows and outflows. In case of Narmada cascaded hydroelectric system reservoirs these variables are:

- i) Inflow from upstream power plants
 - a. Discharge through turbines of upstream plant
 - b. Spillway from upstream plant
- ii) Outflow from current power plant
 - a. Discharge through turbines of the current plant
 - b. Spillway from current power plant
 - c. Irrigation requirement at current power plant
- iii) Natural inflows from surrounding catchments area between two consecutive power plants (weather dependent)
- iv) Evaporation loss (weather dependent)

This water continuity equation relates the previous interval water storage in reservoirs with current storage including delay in water transportation between reservoirs for this case has been expressed as:

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

For this case average hourly evaporation loss & natural inflows in reservoirs of NCHES have been taken from the reservoir operation table of the concerned hydro power project and given in Table 2.

Table 2: Average hourly evaporation loss and natural inflows.

Evaporation loss (m ³ /s)					Natural inflows (m ³ /s)				
RA	IS	O	M	SS	RA	IS	OS	M	SS
BS	P	SP	SP	P	BS	P	P	SP	P
14.0	13.	9	7.1	16	59.2	80	25.	20	44
2	13		0	.1	1	.5	45		2

As hydro power plants are connected in cascaded mode, hence the releases from upstream hydro power plant will reach to its immediate downstream plant with appropriate time delay. The delay time between the successive reservoirs of the NCHES have been mentioned in Table 3.

Table 3: Water travel time between consecutive hydroelectric plant of NCHES.

Name of	Travel time	Name of	Travel time	Name of	Travel time

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

b) Irrigation requirement:

Hydro power projects are multipurpose project, hence it is essential that irrigation requirement to be met by the release of reservoir j at time t.

$$Q_{chj}^t = IR_j^t = S_{chj}^t + U_{chj}^t \quad \text{if} \quad IR_j^t > U_{chj}^t$$

$$= U_{chj}^t \quad \text{if} \quad IR_j^t \leq U_{chj}^t \quad (5)$$

In present work Rani Avanti Bai Sagar, Indira Sagar, Omkareshwar and Sardar Sarovar hydro project are the multipurpose projects, hence the irrigation requirement considered for 24 Hrs scheduled horizon have been taken from the reservoir operation table of concerned hydro power plant and mentioned in Table 4.

Table 4: Hourly irrigation requirement.

Hour	Irrigation requirement (m ³ /s)				Hour	Irrigation requirement (m ³ /s)			
	RA BS	ISP	OS P	SS P		RA BS	ISP	OS P	SSP
1	52.94	65.48	51.97	311.2	13	60.31	63.2	51.30	451.4
2	52.94	65.48	51.97	311.2	14	60.31	63.2	51.30	451.4
3	52.94	65.48	51.97	311.2	15	60.31	63.2	51.30	451.4
4	60.81	56.72	102.8	329.8	16	35.628	55.28	65.75	500.54
5	64.81	56.72	102.8	329.8	17	35.628	55.28	65.75	500.54
6	64.81	56.72	102.8	329.8	18	35.628	55.28	65.75	500.54
7	43.40	45.3	41.54	222.2	19	50.67	65.48	51.96	600.67
8	43.40	45.3	41.54	222.2	20	50.67	65.48	51.96	600.67
9	43.40	45.3	41.54	222.2	21	50.67	65.48	51.96	600.67
10	14.81	37.72	49.98	47.45	22	25.567	40.67	80.51	370.1
11	14.81	37.72	49.98	47.45	23	25.567	40.67	80.51	370.1
12	14.81	37.72	49.98	47.45	24	25.567	40.67	80.51	370.1

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 dam and turbine. Reservoir storage before scheduled horizon and at the end of the horizon should be taken from mid-term planning.

a) Reservoir storage bounds

Hydro electric power plants are the multipurpose projects. Hence the min and max reservoir volume should be as per the Indian standard guidelines IS 7323:1994 of reservoir operation. In hydro power plants volume of water stored in reservoir up-to Full Reservoir Level (FRL) is

called the gross storage and it has been considered as maximum bound on reservoir storage. Generally in hydro power plants the volume of water available between the Minimum Draw Down Level (MDDL) and Full Reservoir Level (FRL) which is also called the live storage capacity has been used for power generation. Hence in present research work the minimum bound of reservoir storage are the difference of gross storage and live storage.

$$X_j^{\min} \leq X_j^t \leq X_j^{\max} \quad (6)$$

b) Water discharge bounds

This is a minimum and maximum bound on the releases of the hydro power plant through turbines.

$$U_j^{\min} \leq U_j^t \leq U_j^{\max} \quad (7)$$

c) Power generation bounds

Power generated through hydro power plants should be in minimum and maximum bounds.

$$P_j^{\min} \leq P_j^t \leq P_j^{\max} \quad (8)$$

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:

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

$$= 0 \quad \text{otherwise} \quad (9)$$

e) Initial & end reservoir storage volumes

Terminal reservoir volumes are generally set through mid-term scheduling process. This constraint implies that the total quantity of utilized water for short term scheduling should be in limit so that the user of the reservoir should not be penalized. In present research work it has been assumed that all five reservoirs are filled up-to FRL hence gross storage has been considered as beginning or initial storage in reservoir at the starting of scheduled horizon. Live storage capacity at that time considered as available water for generation for scheduled horizon, i.e., the water storage at the end of scheduled horizon of 24 hrs has been calculated as given below:

$$X_j^0 = X_j^{\text{begin}} \quad X_j^T = X_j^{\text{end}} \quad (10)$$

III. PSO

Particle swarm optimization is a population based stochastic search algorithm which is the most recent developments in the category meta-heuristic optimization. It was first introduced by Kennedy and Eberhart in 1995 as new heuristic method. The original objective of their research was to graphically model the social behaviour of bird flocks and fish schools. But this original version can only handle the non-linear continuous optimization problems. Further, the advancement in this PSO algorithm can explore the global optimal solution of complex problems of engineering and sciences. Amongst various versions of PSO, most familiar version was proposed by Shi and Eberhart [37]. In PSO a number of "particles"

which represent the candidate solution, form the “swarm”. These particles fly in the problem space, and try to find the optimal solution in the space. Thus each particle could be representing by its “position” (variable vector) and “velocity” (in which direction to move in that instant). 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 the particle i are represented as the vectors of $X_i=[X_{i1},X_{i2},\dots,X_{id}]$ and $V_i=[V_{i1},V_{i2},\dots,V_{id}]$ in the PSO algorithm. Let $P_best(i)=[X_{i1pbest}, X_{i2pbest},\dots,X_{idpbest}]$ and $G_best=[X_{1gbest}, X_{2gbest},\dots,X_{ngbest}]$ 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 shown in Figure 1.

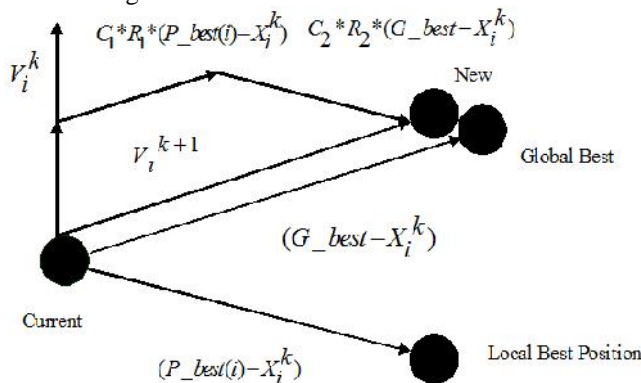


Figure 1: Illustration of PSO.

Mathematically velocity and position of the particles have been updated by the eqs. (8.1) and (8.2) as given below:

$$V_i^{k+1} = K \{ V_i^k \times \omega + C_1 \times R_1 \times (P_best(i) - X_i^k) + C_2 \times R_2 \times (G_best - X_i^k) \}$$

↑ Current Modulation ↑ Particle Memory Influence ↑ Swarm Influence
Inertia Factor Self Confidence Swarm Confidence
Range (0.4 - 0.9) Range (1.5 - 2) Range (2 - 2.5)

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{12}$$

where, $K = 2 \left(\left(2 - C - \sqrt{(C^2 - 4C)} \right) \right)$

where, $C = C_1 + C_2$ (13)

In this velocity updating process, the value of the parameters such as inertia weight ω , cognitive rate C_1 , social rate C_2 , random function between 0 to 1, R_1 & R_2 , constriction factor K should be determined in advance. The inertia weight ω is linearly decreasing as the iteration proceeds and obtained as:

$$\tilde{\omega} = \tilde{\omega}_{max} - ((\tilde{\omega}_{max} - \tilde{\omega}_{min}) \text{iter}) / \text{iter}_{max} \tag{14}$$

The key attractive feature of PSO is its simplicity as it involves only two model eqs. 11 and 12. The first part of eq. 11 represents the previous velocity, which provides the

necessary momentum for particles to roam across the search space. The second part known as “cognitive” component represents the personal thinking of each particle. Cognitive component encourages the particles to move toward their own best positions found so far. The third part is known as the “social” component, which represents the collaborative effect of the particles, in finding the global optimal solution. This social component always pulls the particle towards global best particle so far.

A. Double Exponential Distributed PSO (DED_PSO)

Krohling and Clerc [19] suggested that a possible good choice for the weighting coefficients in the velocity update equation of PSO is between 0.72 to 0.86. This can be achieved through double exponential probability distribution [36] also called Laplace distribution with density function given by:

$$f(x) = (1/2b) \times \exp(|x-a|/b), -\infty \leq x < \infty \text{ \& } a, b > 0 \tag{15}$$

This is the distribution of differences between two independent variates with identical exponential distribution. The variance of such function is controlled by changing the location parameter ‘a’ and scale parameter ‘b’.

The random numbers are generated from absolute value of the exponential distribution thus:

1. Generate uniform random number r_1 & r_2 by rand (0,1)
2. Check if $r_1 > 0.5$ then
 - $E(a, b) = a + b \times \log(r_2)$
 - else $E(a, b) = a - b \times \log(r_2)$
 - end
 - $y = abs(E(a, b))$ where $a=0.30$ & $b=1$

Generating random number using $abs(E(a, b))$ for the stochastic coefficients of PSO may provide a good compromise between the probability of having a large number of small amplitudes around the current points (fine tuning) and a small probability of higher amplitudes, which may allow particle to move away from the current point and escape from local minima. In DED_PSO velocity is updated by eq. (16) and position is updated as eq. (12).

$$V_i^{k+1} = abs(E(a, b)) \times (P_best(i) - X_i^k) + abs(E(a, b)) \times (G_best - X_i^k) \tag{16}$$

The steps involved in optimization are as follows:

- Step1:** Initialize position of discharge particle between U_j^{min} & U_j^{max} for population size PS.
- Step 2:** Initialize velocity of discharge particles between $-V_j^{max}$ to $+V_j^{max}$ where V_j^{max} have been calculated as eq. given below:

$$V_j^{max} = (U_j^{max} - U_j^{min}) / 10 \tag{17}$$
- 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 the dependent reservoir storage X_j^t with the help of eq. (4) for this case.

Step 7: Check whether X_j^t is within the 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 $X_j^{\min} \leq X_j^t \leq X_j^{\max}$, then $X_j^t = X_j^t$

Step 8: Evaluate the fitness function as given below:

$$f(X_j^t, U_j^t, U_{chj}^t) = 1 / [1 + \text{Min}((1/2) \times (P_D^t - \sum_{j=1}^n P_j^t - \sum_{j=1, j \neq 4}^n P_{chj}^t)^2)] \quad (18)$$

Step 9: Is fitness value is greater than $P_best(i)$?

- If yes, set it as new $P_best(i)$ than go to next step10
- Else go to next step

Step 10: Is fitness value is greater than G_best ?

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

Step 11: Check whether stopping criteria max iteration (iter_max) reached?

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

Step 12: Generate absolute value of exponential distributed random numbers as given below:

- Generate uniform random number r_1
=rand (0,1) & r_2 =rand (0,1)

• Check

$$\text{If } r_1 > 0.5$$

$$E(a, b) = a + b \times \log(r_2)$$

Else

$$E(a, b) = a - b \times \log(r_2)$$

End

$$y = \text{abs}(E(A, B))$$

Step 13: Update velocity of discharge particle using eq. (8.11)

Step 14: Check whether V_j^t is within 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 $V_j^{\min} \leq V_j^t \leq V_j^{\max}$ then $V_j^t = V_j^t$

Step 15: Update position of discharge particles using eq. (12)

Step 16: Check whether U_j^t is within 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 $U_j^{\min} \leq U_j^t \leq U_j^{\max}$ then $U_j^t = U_j^t$

Step 17: Update dependent discharge matrix considering hydraulic coupling.

Step 18: Check for stopping criteria

- If $iter < iter_max$ 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.

III. Results Analysis

Hydro electric scheduling means to effectively utilize the water resources of reservoir in such a way that water resources of river can be effectively utilized without spillway at downstream. This scheduling problem becomes more difficult optimization problem when hydro system is inter-connected multiple reservoirs type. In such systems due to hydrological interdependence of the plants, operation of any plant affects water level and storage at other plants of the same system.

In this work as discussed previously NCHES generation scheduling problem has been formulated and solved by proposed DED_PSO for 24 hours on hourly basis to fulfil the load demand. Same problem has also been approached by other two existing variants of PSO, i.e., Time Varying Acceleration Coefficients (TVAC_PSO) and Novel Self Adaptive Inertia Weight PSO (NSAIW_PSO).

A. Testing strategy

During scheduling, it has been assumed that at the starting of schedule horizon all reservoirs are at Full Reservoir Level (FRL) and water available for scheduling period is the live storage capacity. Water travelling time between successive reservoirs of cascaded system are assumed constant, i.e., 52, 4, 3 and 17 hours between RABS to ISP, ISP to OSP, OSP to MSP and MSP to SSP respectively. Hourly load demand and irrigation requirement are mentioned in Tables 1 & 4 in previous section, where as hourly average evaporation losses and natural inflows from tributaries between successive reservoirs have been given in Table 2. Program has been coded in MATLAB. The performance of algorithm has been validated using MATLAB R2012a (7.14.0.739) on a Intel(R) Core(TM) i5-3337U CPU @ 1.80GHz-1.80GHz, 8.00GB RAM 64-bit Operating System, x64-based processor.

B. Experimental settings

The performance of PSO is sensitive to value of its parameters; hence its proper choice is necessary for the better convergence and good quality solution. For the TVAC_PSO and NSAIW_PSO parameters were set as $C_1 =$

$C_2 = 2, C_{1f} = C_{2i} = 0.5, C_{2f} = C_{1i} = 2.5, \min = 0.4$ and $\max = 0.9$. For DED_PSO location parameter 'a' and scale parameter 'b'. To select the best suitable combination, initially 30 trials with population size 10 for the first hour have been done and result thus obtained for E^t are given in Table 5. From results it has been observed that $a = 0.4$ and $b = 0.5$ the probability to get minimum value of E^t is more in case of DED_PSO. Out of 30 trails minimum value of E^t obtained by PSO variants are also presented in Table 5. It clearly shows that solution quality is also good with $a = 0.4$ and $b = 0.5$.

Table 5: Comparison of PSO variants with different value of a & b.

Sl. No.	Value of a, b	PSO Variants	Probability	E^t
1	a = 0.3, b = 1	DED_PSO	6	3.68×10^{-19}
		TVAC_PSO	24	1.08×10^{-16}
		NSAIW_PSO	0	1.70×10^{-06}
2	a = 0.4, b = 0.5	DED_PSO	28	6.21×10^{-21}
		TVAC_PSO	2	5.13×10^{-16}
		NSAIW_PSO	0	7.00×10^{-06}
3	a = 0.5, b = 0.6	DED_PSO	22	6.12×10^{-18}
		TVAC_PSO	8	1.08×10^{-16}
		NSAIW_PSO	0	7.00×10^{-06}
4	a = 0.6, b = 0.7	DED_PSO	19	4.22×10^{-18}
		TVAC_PSO	10	8.69×10^{-18}
		NSAIW_PSO	1	4.22×10^{-18}
5	a = 0.7, b = 0.8	DED_PSO	16	1.82×10^{-19}
		TVAC_PSO	14	8.69×10^{-18}
		NSAIW_PSO	0	4.54×10^{-08}
6	a = 0.8, b = 0.9	DED_PSO	14	7.54×10^{-18}
		TVAC_PSO	16	9.51×10^{-17}
		NSAIW_PSO	0	1.85×10^{-09}

C. Comparison of DED_PSO with NSAIW_PSO & TVAC_PSO

The effectiveness of DED_PSO, TVAC_PSO & NSAIW_PSO in various trials is also judged by the three criteria. First, probability to get best solution or objective

function (robustness), second solution quality and third, dynamic convergence characteristics.

1. Convergence characteristics

The variation of objective value with iteration represents the convergence characteristics.

2. Robustness

Due to the inherent randomness involved in the performance of heuristic search algorithms are judged out of a number of trials. Probability of getting desired objective function value in predefined number of trials proved to be a better algorithm.

3. Solution quality

The dynamic convergence behaviour of the above three methods are also studied by calculating means and standard deviation of particles of the swarm at each iteration as given below:

$$\text{Mean, } \sim_{iter} = \left(\sum_{p=1}^{PS} E^t \right) / PS \quad (19)$$

Standard deviation,

$$\dagger_{iter} = \sqrt{\left[(1/PS) \times \left(\sum_{p=1}^{PS} E^t - \sim_{iter} \right)^2 \right]} \quad (20)$$

Average mean,

$$\sim_{avg} = \left(\sum_{iter=1}^{iter_max} \sim_{iter} \right) / iter_max \quad (21)$$

Average standard deviation,

$$\dagger_{avg} = \sum_{iter=1}^{iter_max} \dagger_{iter} / iter_max \quad (22)$$

4. Comparison of best solution

The best solution for optimal generation scheduling of NCHES for all cases has been judged by the value of objective function.

5. Effect of population size

Eberhart and Shi [22] reported that population size did not affect the performance of the PSO algorithm. Whereas Alrashidi [35] in 2007 reported that random search algorithm PSO are sensitive to population size and related to the problem dimension and complexity. Too large or small population size may not provide minimum value of objective function.

In present work also result are determined for scheduling of NCHES with different population size, i.e., 5, 10, 15, 20, and 25.

IV. Optimal Operation of NCHES

Here, natural inflows from different tributaries & evaporation losses between consecutive reservoirs have been considered. Hydro projects are the multipurpose projects and in present system studied, four projects are fall under this category and fulfilling the irrigation requirement of its nearby zone. Hence irrigation requirement are also

considered from these plants. To harness the potential energy of released water for irrigation, CHPHs are located at the reservoir outlets and power generated through these also contribute to fulfil the load demand

Results are obtained for different population size of 5, 10, 15, 20, and 25 and calculated values of objective function are given in Table 6. For this case also population size of 10 is giving best value of objective function and its corresponding results, i.e., hourly minimum value of E^t and optimal power generated schedule through power plants using all three variants of PSO, i.e., DED_PSO, NSAIW_PSO and TVAC_PSO are shown in Figures 2 to 6. The hourly reservoir storage trajectories and discharge trajectories through individual RBPH obtained by above three variants of PSO are shown in Figures 7 (a) to (e) and Figures 8 (a) to (e) indicate parameters related to RABS, ISP, OSP, MSP and SSP RBPH respectively.

Table 6: Minimum value of objective function at different population size.

No. of Population	Objective Function E		
	DED_PSO	NSAIW_PSO	TVAC_PSO
5	3.46E-13	4.23E-01	2.18E-06
10	7.24E-16	1.96E-01	8.41E-05
15	1.36E-13	6.78E-02	8.95E-05
20	7.32E-16	6.20E-02	4.88E-05
25	3.23E-14	1.96E-02	3.72E-06

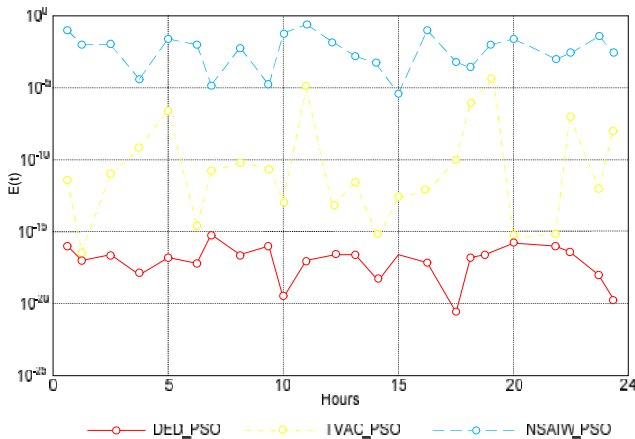


Figure 2: Hourly minimum value of deviation E^t between load demand and generated power from RBPHs using DED_PSO, NSAIW_PSO & TVAC_PSO.

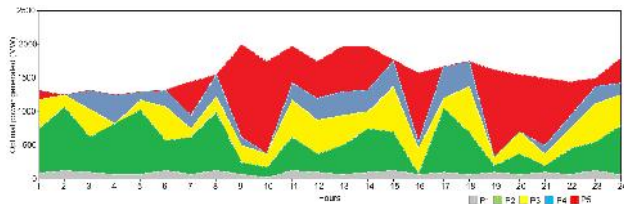


Figure 3: Hourly optimal power generation schedule from RBPHs using DED_PSO.

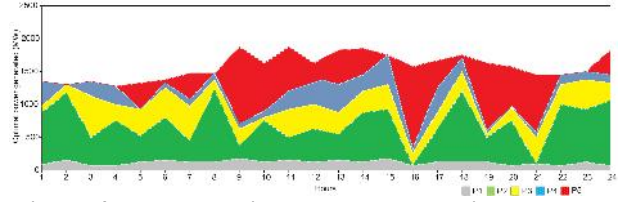


Figure 4: Hourly optimal power generation schedule from RBPHs using TVAC_PSO.

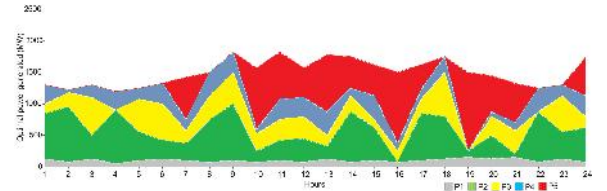


Figure 5: Hourly optimal power generation schedule from RBPHs using NSAIW_PSO for case 3.

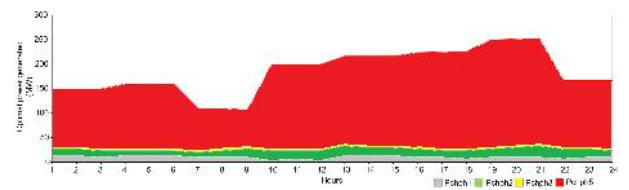


Figure 6: Hourly optimal power generation schedule from CHPHs using DED_PSO, TVAC_PSO & NSAIW_PSO.

From results it has been found that for optimal operation of NCHES the average value of power generated through each RBPH and percentage power generated of its rated capacity, i.e., plant or capacity factor have been mentioned in Table 7. In this case the plant factor of RABS is maximum followed by OSP, ISP, MSP and SSP. The plant factor of RBPHs reflects as per the storage capacity.

Table 7: Average power generated and plant factor of RBPHs.

PSO Variants	RABS_R BPH		ISP_RBP H		OSP_RBP H		MSP_R BPH		SSP_R BPH	
	Average Power (MW)	Plant Factor	Average Power (MW)	Plant Factor	Average Power (MW)	Plant Factor	Average Power (MW)	Plant Factor	Average Power (MW)	Plant Factor
DED_PSO	67.	74.	581.	58.	326.	62.	174	5	57	4
	12	58	200	120	120	71	.64	0.	0.	7.
	63	48	2	02	02	13	9	95	5	8
TVA_C_PSO	67.	74.	568.	56.	307.	59.	168	4	56	4
	32	81	805	805	893	21	.94	9.	2.	6.
	91	01	04	04	6	03	19	4	82	9
NSAIW_PSO	65.	72.	554.	55.	331.	63.	199	4	59	4
	01	23	740	474	820	81	.07	9.	2.	9.
	54	93	4	04	3	16	86	8	65	3

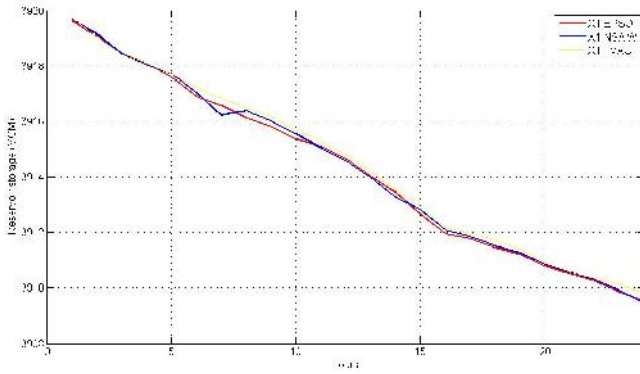


Figure 7(a): Reservoir storage trajectories: Rani Avanti Bai Sagar.

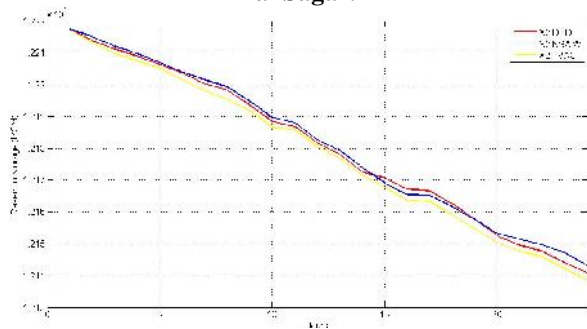


Figure 7(b): Reservoir storage trajectories: Indira Sagar.

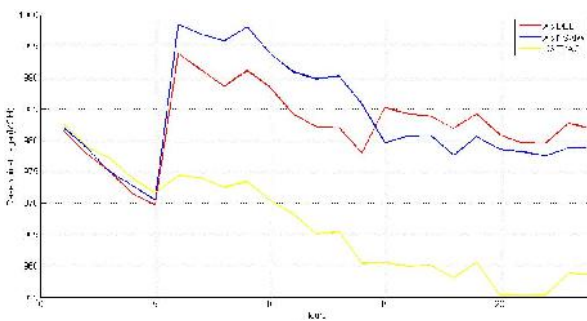


Figure 7(c): Reservoir storage trajectories: Omkareshwar.

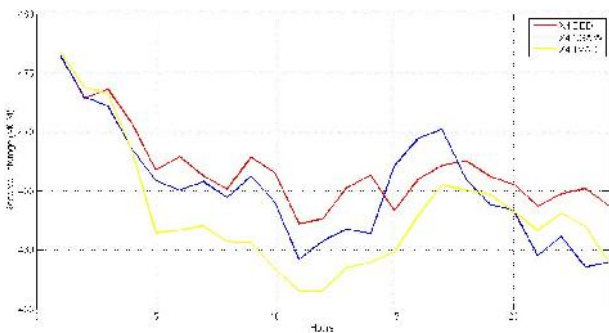


Figure 7(d): Reservoir storage trajectories: Maheshwar.

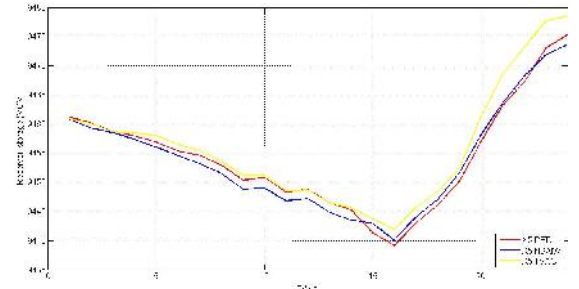


Figure 7(e): Reservoir storage trajectories: Sardar Sarovar.

Figures 7(a) - (e): Hourly reservoir storage trajectories of RBPHs using DED_PSO, NSAIW_PSO & TVAC_PSO for case 3.

The average reservoir storage of BPHs has been mentioned in Table 8.

Table 8: Average reservoir storage of RBPHs.

Name of RBPH	Average reservoir storage for scheduled horizon (MCM)		
	DED_PSO	TVAC_PSO	NSAIW_PSO
RABS	3913.436	3913.523	3914.176
ISP	12170.92	12172.2	12178.13
OSP	982.2463	984.9171	982.5979
MSP	470.6988	468.9958	471.2388
SSP	9445.918	9445.973	9448.363

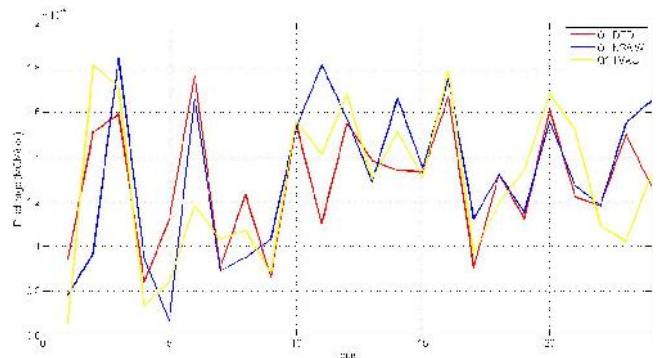


Figure 8(a): Discharge trajectories: Rani Avanti Bai Sagar.

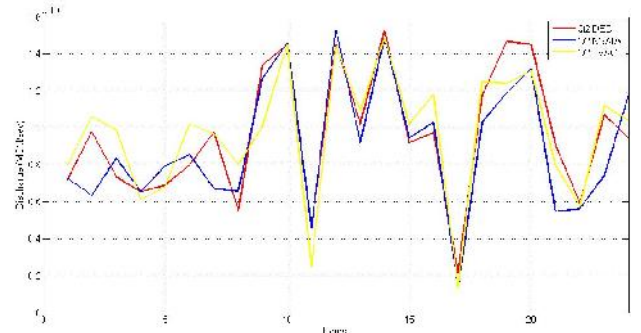


Figure 8(b): Discharge trajectories: Indira Sagar.

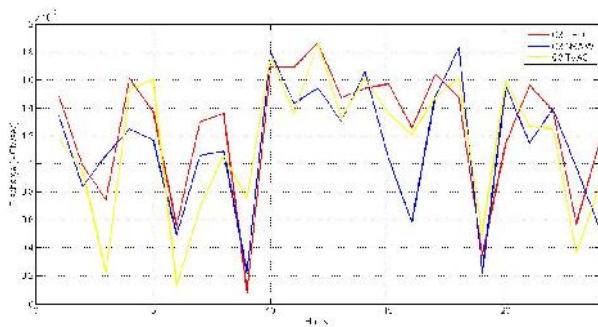


Figure 8(c): Discharge trajectories: Omkareshwar.

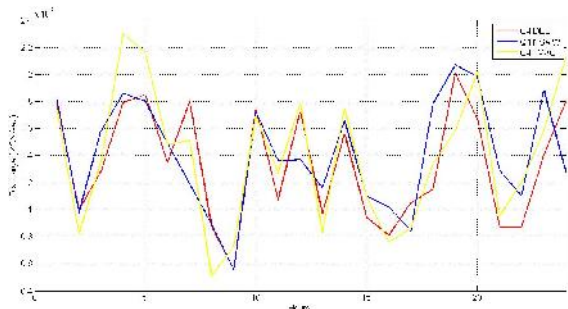


Figure 8(d): Discharge trajectories: Maheshwar.

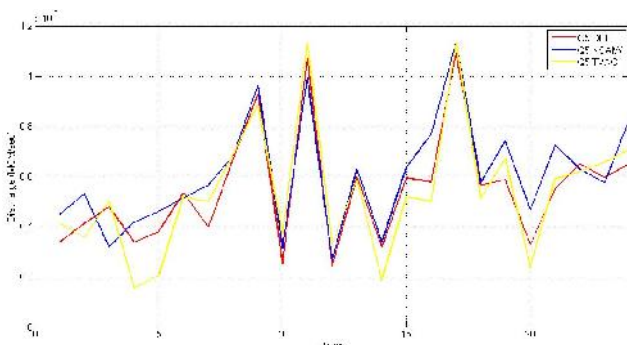


Figure 8(e): Discharge trajectories: Sardar Sarovar.

Figures 8(a)-(e) : Hourly discharge trajectories of RBPHs using DED_PSO, NSAIW_PSO & TVAC_PSO for case 3.

Thus obtained average discharge in the schedule horizon through each RBPHs from all three variants has been summarized below in Table 9.

Table 9: Average discharge through RBPHs.

Name of RBPH	Average discharge during 24hours scheduled horizon (MCM)		
	DED_PSO	TVAC_PSO	NSAIW_PSO
RABS	12.5946	12.78324	12.303
ISP	91.9584	91.0836	89.0064
OSP	83.3292	75.1068	79.28316
MSP	92.6676	88.5096	100.4544
SSP	48.2868	46.9908	46.6056
Total	328.8366	314.474	327.6526

V. Conclusion

In this research new meta-heuristics PSO technique has been applied for generation scheduling of NCHES problem. It is found that, DED_PSO is giving better value of

objective function in comparison to other PSO variants. Amongst all population sizes, population size of 10 is giving the best value, i.e., 4.38E-16, 3.64E-16 and 7.24E-16 for case 1, case 2 and case 3 respectively. Results of objective function indicate the effectiveness of PSO algorithm in terms of precision.

Optimal power generation schedule of hydro power plants of NCHES for all three cases using all variants of PSO clearly shows that plant factor of OSP-RBPH, MSP-RBPH and RABS-RBPH is more in comparison to ISP-RBPH and SSP-RBPH. Hence for optimal operation of hydropower plants of small reservoirs are contributing more power in fulfilment of load demand in comparison to big reservoirs. Total average discharge in scheduled horizon from hydro power plants of NCHES is 328.84 MCM for DED_PSO, 314.47 MCM for TVAC_PSO, 327.65MCM for NSAIW_PSO respectively.

From results it has been observed that a = 0.4 and b = 0.5 the probability to get minimum value of E^t is more in case of DED_PSO. Out of 30 trails minimum value of E^t obtained by PSO variants are also presented in Table 5. It clearly shows that solution quality is also good with a = 0.4 and b = 0.5.

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APPENDIX:

Table X: Nomenclature.

Symbol	Name (Stands for)
P_D^t	Total load demand at time t
P_L^t	Transmission losses at time t
P_j^t	Electrical power generated from j th plant at time t
P_{chj}^t	Electrical Power generated through canal head power plants
X_j^t	Reservoir storage of the j th plant at time t
X_j^{\min}	Minimum storage in j th reservoir
X_j^{\max}	Maximum storage in j th reservoir
H_j^t	Head for the j th river bed hydro power plant at time t
H_{chj}^t	Head for the j th canal head power plant at time t
HF_j^t	Reservoir elevation of j th plant at time t
HT_j^t	Tailrace elevation of j th plant at time t considering the total discharge
Y_j^t	Natural inflow in the j th plant at time t
U_j^t	Discharge through turbine of j th plant at time t
C_{chj}	Hydro turbine model constant for canal head power houses
U_{chj}^t	Discharge through turbine of j th canal head power plant at time t

S_{chj}^t	Spillage from j th canal head hydro power plant.
U_j^{\min}	Minimum discharge through turbine of j th plant
U_j^{\max}	Maximum discharge through turbine of j th plant
S_j^t	Spillage from the j th river bed hydro power plant at time t
Q_j^t	Total discharge through the plant at time t including spillway and turbines discharge
IR_j^t	Irrigation requirement from j th hydroelectric power plant at time t
EL_j^t	Evaporation loss in j th hydroelectric power plant at time t
u	Time delay for water flows from upstream plant to downstream plant
A_i	Hydro turbine model constants of river bed hydroelectric power plants
B_i	Reservoir elevation model constants of river bed and canal head power plants
C_i	Tail race elevation model constants of river bed and canal head hydroelectric power plants
up	Index for immediate upstream plant
t, T	Time index, total scheduled horizon
n	Total number of river bed & canal head hydroelectric power plants
j	Index of hydroelectric power plants
$A_1, A_2, A_3, A_4, A_5, A_6$	Hydro turbine model constant
B_1, B_2, B_3, B_4, B_5	Reservoir storage model constant
C_1, C_2, C_3	Tail race elevation model



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