Scheduling of Pumped Storage Hydrothermal System with Evolutionary Programming

S. K. Khandualo, A. K. Barisal, and P. K. Hota

Abstract—**This paper presents the ever proved evolutionary programming techniques for solving the generation/ pumping scheduling problem of hydro thermal system with pumped storage plants. Pumped storage hydro plant is used to save fuel cost by serving the peak load with hydro energy and then pumping the water back up into the reservoir at light load periods. Therefore, a pumped storage unit can be operated any one mode out of three states such as generation, pumping and idle states. It can smooth peak loads and provide reserves and plays a vital role in reducing the total generation cost in a hybrid power system.**

Index Terms—**Short term hydro scheduling, pumped storage plant, evolutionary programming, and Gradient search.**

I. Nomenclature

$P_{si(t)}$: power generation of thermal unit i in hour t

$P_{hj(t)}$ power generating or pumping of P/S plant j in hour t positive: generating; negative: pumping

$F_{i(t)}P_{si(t)}$: production cost for $P_{si(t)}$

T : Number of scheduling hours

N_h : Number of P/S plants

N_s : Number of thermal units

$P_{d(t)}$: System load demand in hour t

$P_{loss(t)}$: System transmission network losses in hour t

$V_{j(t)}$: Water volume of the upper reservoir of plant j at the ending of hour t

$V_{jl(t)}$:Water volume of the lower reservoir of plant j at the ending of hour t

$I_{j(t)}$: Natural inflow into reservoir j in hour t

$Q_{j(t)}$: Water discharge of P/S plant j in hour t

Q_{jtP} : Water pumping of P/S plant j in hour t

S_{jt} : water spillage of P/S plant j in hour t

II. Introduction

The efficient and optimum economic operation and planning of electric power generation are always vital to the electric power industry. The Short term hydro thermal scheduling problem with a pumped hydro plant is concerned with optimization over a time span of a day or a week. The pumped hydro plant can be used as a spinning reserve unit to safeguard the system against forced generation outages if the reserve availability is very marginal. The solution to this problem, if the time span is a day gives a plan for the optimal quantity of water to be discharged from or pumped to the pumped hydro plant and the corresponding thermal generation such that the total fuel cost of the thermal plants over the day is minimized subject to the operating constraints of the hydro, pumped hydro and thermal plants.

The Pumped storage hydro plants are designed to save fuel cost i.e during peak load periods; it discharges water for generation at hours of high demand and high costs, displacing high cost fossil generation. During light load periods i.e period of low demand and low cost water is pumped from the lower to the upper reservoir utilizing the economical energy generated by base load units. A pumped storage unit can therefore smooth peak loads, provide reserve, and play an important role in reducing total generation cost.

The optimal scheduling of hydrothermal power system with pumped storage units is usually more complex than that for an all thermal system. It is basically a nonlinear programming problem involving non-linear objective function and a mixture of linear and non-linear constraints. Conventional methods based on Lagrangian multiplier and gradient search techniques require models of hydro as well as thermal plants to be represented as piecewise linear or polynomial approximations of monotonically increasing nature. But such an approximation may lead to suboptimal solution resulting in huge loss of revenue over the time. Methods based on Lagrangian multiplier and gradient search techniques [1] for finding the most economical hydrothermal with pumped storage generation schedule under practical constraints have been well documented. Kirchmayer [2] utilized calculus of variation for short range scheduling problem and proposed the well known coordination equations. In this respect stochastic search algorithms like particle swarm optimization (PSO) [3], simulated annealing (SA) [4], genetic algorithm (GA) [5], evolutionary strategy (ES) [6] and evolutionary programming (EP) [7] may prove to be very efficient in solving highly nonlinear HS problems since they do not place any restriction on the shape of the cost curves and other non-linearities in model representation.

Although these heuristic methods do not always guarantee the globally optimal solution, they will provide a reasonable solution (suboptimal near globally optimal) in a short CPU time. These evolutionary algorithms (EAs) are search algorithms based on the simulated evolutionary process of natural selection and genetics. EAs are more flexible and robust than conventional methods. EP differs from GA in two aspects. Firstly, EP uses the control parameters, but not their

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codings as in GAs. Secondly the generation and selection procedure in EP are mutation and competition but in GAs the procedures are reproduction, mutation and crossover. Hence considerable computation time may thus be saved in EP based on normally distributed mutations.

In recent years, a lot of developments have taken place in EP in terms of efficiency and quality. Here, mutation is the only operator used to generate new offspring. This mutation is implemented by adding to the parent a random number from a certain distribution, e.g. Gaussian distribution in the case of classical EP (CEP). An important parameter of the Gaussian mutation is its standard deviation which is also called strategy parameter. In self-adaptation scheme of EP, this parameter instead of being pre-fixed is evolved along with the objective variables.

III. Problem Statement

As hydrogenating units do not incur any fuel cost, the HS problem is aimed to minimize the total thermal cost while making use of the availability of hydro resource as much as possible.

A. Objective Function and Constraints

The objective function and associated constraints of the problem are formulated as follows. The scheduling of P/S units deals with the problem of obtaining the optimal generations both for P/S and thermal units. It aims to minimize the production costs of thermal units while satisfying various constraints. With discretization of the total scheduling time into a set of shorter time intervals (say, one hour as one time interval), the scheduling of P/S units can be mathematically formulated as a constrained nonlinear optimization problem as follows

$$\text{Minimize } \sum_{t=1}^{T} \sum_{1}^{Ns} F_i^t \left(P_{si}^t\right) \tag{1}$$

Subject to the following constraints:

System Power Balance equation:

$$\sum_{i=1}^{N_s} P_{si}^t + \sum_{j=1}^{N_h} P_{hj}^t - P_d^t - P_L^t = 0 \tag{2}$$

The Hydro Generation P_{hj} is assumed to be a function of discharge only

$$P_h = f(q) \tag{3}$$

Thermal Plant generation limit

$$P_{si}(\min) \le P_{si}(t) \le P_{si}(\max) \tag{4}$$

Hydro Plant generation limit

$$P_{hj}(\min) \le P_{hj}(t) \le P_{hj}(\max) \tag{5}$$

Water Dynamic. Balance

$$V_j^t = V_j^{t-1} + I_j^t - Q_j^t + Q_{j.p}^t - S_j^t \tag{6a}$$

$$V_{j.l}^t = V_{j.l}^{t-1} + Q_j^t - Q_{j.p}^t + S_j^t \tag{6b}$$

Water Discharge limits

$$Q_j(\min) \le Q_j(t) \le Q_j(\max) \tag{7}$$

Water pumping limits

$$Q_{jp}(\min) \le Q_{jp}(t) \le Q_{jp}(\max) \tag{8}$$

Reservoir limits

$$V_j(\min) \le V_j(t) \le V_j(\max) \tag{9a}$$

$$V_{j.l}(\min) \le V_{jl}(t) \le V_{j.l}(\max) \tag{9b}$$

IV. Evolutionary Programming Based Hydrothermal Scheduling for Pumped Storage Plant

Taking the population size to be I_p, each initial parent trial vector Q_i, for i= 1, 2, . . ., I_p is selected at random from feasible range of each element. To satisfy the constraints on the initial and the final reservoir storage states, a dependent hydro discharge rate q_d is randomly selected. The non-dependent hydro discharges q_j for j= 1, 2, 3, . . ., J, j≠ d are together taken as (J- 1)-dimensional trial vector. Let $Qi = [q_1, q_2, ..., q_{(d-1)}, q_{(d+1)}, ... q_j]$ be the trial vector designating the ith individual of a population to be evolved. The selection of each parent trial vector at random is done by setting the jth components of each parent as:

$q_j = rand[q_{\min}, q_{\max}]$ for $j = 1,2,...,(d-1),(d+1),...j$

where $rand[q_{\min,}, q_{\max}]$ denotes a uniform random variable ranging over $[q_{\min}, q_{\max}]$ The hydro discharge at dependent interval, q_d is calculated from equation (3) with zero spillage (for simplicity) by:

$$q_d = V^0 - V^T - \sum_{\substack{j=1 \\ j \ne d}}^{j} q_j + \sum_{j=1}^{j} I_j \tag{10}$$

Knowing hydro discharges, hydrogenations can be calculated from equation (3) by simple algebraic method as the discharge in the present case is a function of hydrogenation. From the calculated hydrogenations P_{hj} and the given load demand P_{dj}, for j= 1, 2, . . ., J, power generation of thermal unit in the jth interval P_{sj} can be calculated as:

$$P_{sj} = P_{dj} + P_{Lj} - P_{hj} \tag{11}$$

Now the thermal production cost and the fitness function which is the sum of production cost and penalty for constraint violation can be calculated for each individual of the parent population as

$$FIT_i = F + \sum_{z=1}^{Nc} PF_z \tag{12}$$

And $PF_z = \lambda_z \times [VIOL_z]^2$

FIT_i : Fitness value of the ith individual

I_p :No of individuals in the parent population

I_p' :No of individuals in the child population

j No of scheduling intervals

PF_z Penalty associated with the constraint z

$VIOL_z$: amount of violation of constraint z

A. Creation of Offspring

An offspring is created by mutation as follow:

By Gaussian mutation -An offspring vector Qi' is created from each parent Q_i by adding to each component of parent, q_j , a Gaussian random variable with a zero mean and a standard deviation proportional to the scaled cost value of the parent trial solution, i.e.

$$Q_i' \text{ for } i = 1,2...I_p \quad q_j' = q_j + \sigma N(0.1) \text{ for } j = 1,2,...j \tag{13}$$

where $N(0,1)$ represents a Normal Gaussian random variable with mean 0 and standard deviation $\sigma = 1$ The ρ indicates the range of the off springs created around the parent trial vector and their expressions in case of scaled cost are given by:

$$\sigma = \beta \times FIT_i / FIT_{\min}(q_{\max} - q_{\min}) \tag{14}$$

where $FIT_{\min}$ is the minimum value of fitness among the I_p trial solutions and β is scaling factor.

TABLE I: LOAD PATTERN OF THE TEST SYSTEM

Interval number	Interval	Demand (MW)
1	00:00_ 04:00 h	1600
2	04:00_ 08:00 h	1800
3	08:00_ 12:00 h	1600
4	12:00_ 16:00 h	500
5	16:00_ 20:00 h	500
6	20:00_ 24:00 h	500

TABLE-II : TUNED PARAMETER SETTINGS OF THE EPS

Control parameters	Value
Scaling factor (β)	0.01
Population size	10
Maximum Iteration	250

B. Competition and Selection

After generation of offspring population, competition and selection procedure is implemented to determine which solutions are to be retained into the next generation and which are to be removed from the competiting pool of trials. The parent trial vectors Q_i ,for $i = 1,2,...I_p$ and their corresponding off springs Q_i' contend with each other for survival within the competiting pool. In this process a competitor Q_r is selected at random from among the $2I_p$ trial solutions, where 'r' is an integer as given by: $r \approx [2I_p \times u_1 + 1]$ here r is taken to be the greatest integer less than or equal to the value of the expression in the right hand side.

A weight value w^r is assigned to each individual as follows

$$w_{Q_i} = \sum_{m=1}^{I_p} w_m \tag{15}$$

And a

$$w_m = 1, \text{ if } u_2 \le FIT\lambda / FIT_l + FIT\lambda \tag{16}$$

$w_m = 0$, otherwise

where u_1 and u_2 are uniform random numbers ranging over [0.1].

After the competition is over, the $2I_p$ trial solutions are sorted in descending order of the score obtained in equation (15). The first I_p trial solutions from the sorted pool are selected as the new parent vectors for the next generation.

V. IMPLEMENTATION OF EP IN HYDROTHERMAL SCHEDULING

Step 1: The problem variables to be determined are represented as a J-dimensional trial vector, where each vector is an individual of the population to be evolved.

Step 2: An initial population of parent vectors, Q_i , for i_ 1, 2, . . ., I_p , is selected at random from a feasible range in each dimension. The distribution of these initial parent vectors is uniform.

Step 3:An offspring (Q_i') is generated from each parent by Gaussian mutation (CEP), as depicted in Section 3 with adaptation of strategy parameter, s based on scaled cost.

Step 4: Fitness function, FIT_i is evaluated for each individual of both parent and child populations.

Step 5: A competitor is chosen randomly from the combined population of $2I_p$ trial solutions (I_p parent and I_p' offspring) and stochastic competition is performed based on the value of fitness function where each individual in the competing pool compete against other members for survival.

Step 6: After the competition is over, the $2I_p$ trial solutions in the competing pool are sorted according to their scores from the highest to the lowest. There after the first I_p trial solutions are selected as the new parent vectors for the next generation.

Step 7: If current generation is greater than or equal to the maximum generation, stop and print the result. Otherwise repeat the steps 3 to 6.

VI. TEST SYSTEM

The performance of the proposed EP algorithms is verified on a test system which has been adopted from [1]. It comprises a pumped storage hydro and an equivalent thermal plant. The schedule horizon is 1 day and there are six 4h intervals. The load pattern showing the load demands in the intervals are given in Table 1.

The fuel cost function of the equivalent thermal unit is:

$F(P_s) = 575 + 9.2P_s + 0.00184P_s^2$ (Rs/h)

$(200mw \le P_s \le 2500mw)$

The pumped storage plant has the following characteristics Generating

q Positive when generating, P_H is positive

$0 \le P_H \le +300MW$

$q(P_H) = 200 + 2P_H$ acreft / hr

Pumping: q negative when pumping, P_P is negative and $-300MW \prec P_P \le 0MW$, $q(P_P) = -600$ acreft/h with $P_P = -300MW$.

Operating restrictions: The pumped hydro plant will be allowed to operate only at $-300mw$ when pumping. Cycle efficiency is 0.6667 [The efficiency has already been built into the $q(P_H)$ equations].

The reservoir starts at $8000acre-ft$ and must be at $8000acre-ft$ at the end of the sixth period. The water inflow rate is assumed to be neglected and the spillage is not counted. Further, the electrical loss from the hydro plant to the load is taken to be negligibly small.

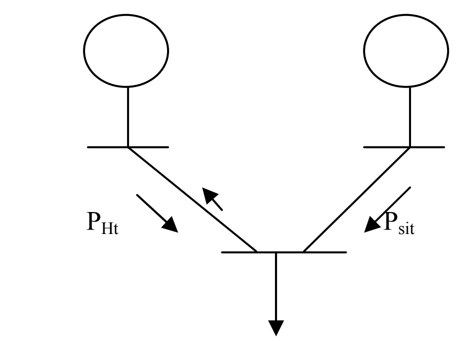

Fig. 1. Schematic diagram of test system

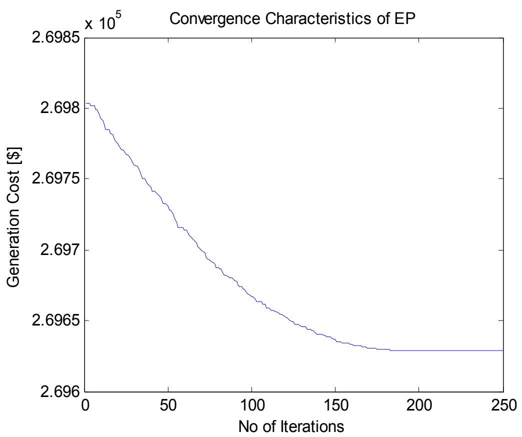

Fig. 2. Convergence characteristics of EP algorithm.

VII. Simulation Results

All the programs were implemented in MATLAB command line on a PC (Pentium-III, 4GB). The control parameters in the EP programs used for solving the test case were tuned and their tuned values are listed in Table II. The HS and the system costs obtained from proposed EP and the gradient search [1] are summarized in Table III.

The optimal system costs obtained from EP are given in the table. It can be seen from the table that the optimal cost obtained by the proposed EP is the lower than the Gradient Search technique.

TABLE III: The Scheduling of Pumped Storage Hydrothermal Plant

Methods	Int. No	Thermal Power	Hydro Power	Volume Acre ft	Q Acreft/hr	Cost
EP	1	1466.4211	133.5789	6131.37	467.16	269628.8
	2	1466.9846	333.0154	2667.25	866.03	
	3	1466.5943	133.4057	800	466.81	
	4	800	-150	3200	-600	
	5	800	-300	5600	-600	
	6	800	-300	8000	-600	
GS	1	1450	150	6000	500	269642.4
	2	1500	300	2800	800	
	3	1450	150	800	500	
	4	800	-300	3200	-600	
	5	800	-300	5600	-600	
	6	800	-300	8000	-600	

VIII. Conclusion

Evolutionary programs with Gaussian mutation was developed and demonstrated to solve the pumped storage Hydro scheduling problem. Results show that EP-based algorithms are more capable of finding highly near-global solutions than Gradient Search techniques. The optimal cost obtained by the Evolutionary Programming is quite cheaper than the Gradient Search technique for the system adopted. In future, attempts can be made to apply the Evolutionary programming technique to Pumped storage unit in conjunction with wind energy by incorporating emission, spinning reserve and reliability constraints.

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