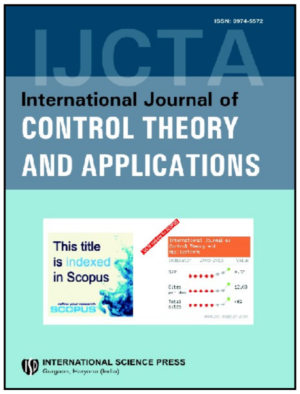

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Optimal Short Term Hydrothermal Scheduling Using Differential Evolution Algorithm

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Abstract: In this paper, short term hydro thermal scheduling problem has been carried out with the help of Differential Evolution (DE) algorithm. The hydrothermal system considered is a test case consisting of four hydro units and three thermal units. The fuel cost function espoused here is non-smooth function with valve point loading effect has been taken into account. The constraints considered in this problem are power balance constraint, generation limits of both hydro and thermal units and also the hydraulic constraints such as discharge limits, initial and end reservoir volume constraint and water dynamic balance constraint. The results obtained provide a conclusive proof that the proposed algorithm provides better solutions in terms of a reduced operational cost and minimum computation time as compared to other evolutionary algorithms such as Evolutionary Algorithms such as Evolutionary Programming (EP), Simulated Annealing (SA) and Constriction factor based PSO (CFPSO).

Index Terms: Hydrothermal generation scheduling, Differential Evolution, DE control parameters

I. INTRODUCTION

The primary purpose to have additional units of thermal plants connected up to the same grid as done by units of hydro power plants is to make sure that the average demand per hour is being satisfied. The major problem encountered with hydro power plants is the lack of gravitational head in the reservoir tank and also the lower discharge rate. Due to insufficient amount of water in the reservoir, the power generated is being affected and the demand could not be satisfied with a big margin. Therefore, the thermal units generate the additional power which is required to satisfy the demand. There is no fuel cost associated with the hydro power units and hence their operational cost is very minimal. But the fuel cost required to operate the thermal units is quite high which contributes extensively to the net operational cost. Therefore the net operational cost of the hydrothermal system can be minimized by minimising the net fuel cost required to run the thermal units under the various hydraulic and power balance constraints. For the system considered here, the rate of inflows for each reservoir for each hour and initial and final reservoir volume is assumed to be known for 24 hours. In this problem the water transport time delay is also considered and the total power demand is assumed to be known for 24 hours. In this paper, Differential Evolution (DE) is applied to solve the short term hydrothermal scheduling problem. Instead of directly deriving the daughters chromosome from the parents chromosome, mutation process was carried out on the parent so as to get a new variant of the parent and then both these versions were combined by means of binomial crossover option to create the new daughter offspring which provides the validity of the proposed method with the already existing methods. Thus this DE algorithm with its mutation parameters provides a better solution with lesser computational time.

II. PROBLEM FORMULATION

The short term hydrothermal scheduling is formulated as an optimisation problem with the fuel cost function as the objective or fitness function. The fitness function can be described as follows:

$$\sum_{t=1}^{T}\sum_{i=1}^{N} Fit(Pgit) \tag{1}$$

Fuel cost function for thermal unit *i* is defined as:

$$F_{it} = \left[\sum_{t=1}^{t}\sum_{i=1}^{n}[a_i + b_i Pg_{it} + c_i P^2 g_{it}] + |\, d_i \sin\left(Pg_{it}^{\min} - Pg_{it}\right)\}\,|\right] \tag{2}$$

where t is the time interval, Pg_{it} is the thermal power generated (MW) in the unit i, $F(Pg_{it})$ is the fuel cost of unit i in ($/hour), FT is the total fuel cost in ($). N is the number of thermal plants. The other constraints are as follows:

2.1 Power Balance Constraint

$$\sum_{i=1}^{N} Pgit + \sum_{j=1}^{M} Phjt = PDt \tag{3}$$

2.2 Generation Limit constraint

$$Pg_i^{\min} \le Pg_i \le Pg_i^{\max} \tag{4}$$

$$Ph_j^{\min} \le Ph_j \le Ph_j^{\max} \tag{5}$$

2.3 Water Discharge Constraint

$$q_j^{\min} \le q_j \le q_j^{\max} \tag{6}$$

2.4 Reservoir Volume constraints

$$Vh_j^{\min} \le Vh_j \le Vh_j^{\max} \tag{7}$$

2.5 Water Dynamic Balance Constraint

$$.V_{hjt} = V_{hjt-1} + \Sigma_{l=1}^{R_u}[q_{u(t-\tau)} + S_{u(t-\tau)}] - q_j(t) - s_j(t) + r_{ij} \tag{8}$$

6) Hydro Power Generation

The hydro power generated by unit *j* can be represented as

$$P_{hjt} = C_{1i} V_{hjt}^2 + C_{2i} q_{jt}^2 + C_{3i}(V_{hjt} q_{jt}) + C_{4i} V_{hjt} + C_{5i} q_{jt} + C_{6i} \tag{9}$$

where

C_{1i}, C_{2i}, C_{3i}, C_{4i}, C_{5i} *and* C_{6i} are the hydro power generation coefficients.

III. DIFFERENTIAL EVOLUTION ALGORITHM

Differential Evolution (DE) is a stochastic search algorithm devised by Storn and Price [11,12] in the year 1995. It is quite similar to Genetic Algorithm (GA) and Evolutionary Programming (EP) [1-3]. It is a population based algorithm whereby an initial population is created which has *NP* particles and has *D* dimensions. This initial population is called as the target vector *X*. It is being randomly initialised between the random limits of x_j^{min} and x_j^{max} as shown in Equation (10).

$$X_{j(0)} = X_j^{\min} + rand(0-1).\left(x_j^{\max} \le x_j^{\min}\right) \tag{10}$$

From this initial start, the iterative process proceeds with the following step of events:

The first part is the formation of mutant vector V which is formed by the mutation of X vector. There are basically five mutation operations possible in DE out of which DE/rand/2 has been chosen since it offers best solution among the other operators as in Equation 11.

$$V_{ij(t+1)} = X_{r1(t)} + F(X_{r2(t)} - X_{r3(t)}) + F(X_{r4(t)} - X_{r5(t)}) \tag{11}$$

where *r1, r2, r3, r4* and *r5* are mutually exclusive integers which lie between [*1,NP*]. *F* is called as the scaling factor which lies between [*0,1*]..

The second part is formation of the trial vector U, obtained from the crossover of X vector and V vector. In DE there are two types of crossover options; binomial and exponential crossover. In this paper binomial crossover option has been chosen. It is defined as follows:

$$U_{ij(t+1)} = V_{ij(t+1)} \ \ if \ \ rand_j \ [0,1] > CR \tag{12}$$

$$U_{ij(t+1)} = X_{ij(t+1)} \ \ if \ \ rand_j \ [0,1] < CR \tag{13}$$

where CR is the crossover constant. The third part is the construction of X(t+1) vector by comparing the fitness values produced by X(t) vector and U(t+1) vector which is given by

$$X_{ij(t+1)} = U_{ij(t+1)} \ \ if \ \ fitness \ (X_{ij(t)} > U_{ij(t+1)}) \tag{14}$$

By trial and error method, the control parameters *F* and *CR* were fine tuned to distinct values so as to improve the quality of results obtained. The value of scaling factor (*F*) was found out to be 0.63 and the value of crossover constant (CR) is 0.30.

IV. IMPLEMENTATION OF DE ALGORITHM FOR SHORT TERM HYDROTHERMAL SCHEDULING

The following steps have been carried out for applying DE algorithm for short term hydrothermal problem:

Step 1) Read the hydrothermal system data which includes all the power constraints for *M* hydro plants and *N* thermal plants along with the data about the reservoir volume, inflow and discharge rate. Read the demand for first hour.

Step 2) Initialise the number of particles NP and the number of iterations.

Step 3) Create the target vector X of size [*NP,7*] using the equation (10) ; where the seven dimensions are the discharges *q1,q2,q3,q4* and the thermal power output *Pg1,Pg2 and Pg3*.

Step 4) Calculate the volume of the reservoir using equation (8) from which the hydropower generated *ph1,ph2,ph3,ph4* will be obtained. Using the power balance criterion in Equation (3), thermal power required is found out.

Step 5) Calculate the difference between actual thermal power required (as obtained in step 4) and then evaluate the cost of each unit and the total fuel cost per hour using Equations (1) and (2) respectively.

Step 6) Evaluate mutant vector V using (13) and if the coordinates exceed the limits, then the coordinates are reset to the minimum or maximum bounds.

Step 7) Using binomial crossover option, trial vector U is determined. Follow steps 4 and 5 and determine the fitness values for U vector.

Step 8) Compare the fitness of X vector and U vector, if the cost provided by the particle in U vector is lesser than the cost obtained from the particle in X vector then replace the corresponding particle in X vector with the particle from U vector.

Step 9) If the number of iterations has reached the desired value, then go to Step 10; otherwise go to step 6.

Step 10) The obtained result includes the power output of each hydro plant and each thermal plant.

Step 11) Proceed to step 1 for accomplishing the demand for next hour. This iterative process is repeated until the demand for all 24 hours. Then proceed to step 12.

Step 12) Finally sum up the entire net fuel cost per hour to get the value of net operational cost for 24 hours.

V. EXPERIMENT AND RESULTS

The hydrothermal system considered in this problem consists of four hydro plants and three thermal plants. The system data required for this problem are demand for 24 hours, hydro and thermal power plant constraints, volume and discharge constraints, water transport delays between each reservoir of the multi chain cascade hydro system, coefficients of fuel cost equation for each thermal plant and coefficients for hydro power generation. These test datas were taken from [4],[5] and [6]. The coding was implemented in C++ platform with the help of Dev-cpp software. It was executed on a Intel Core I5 processor, 3.0 GHz and 4 GB RAM. After 30 trial runs, the following results were obtained. Table I shows the optimal control parameters carried out for the test case considered. It was observed that for the following combination of scaling factor (F) and the crossover constant (CR) happened to give better optimised results.

Table I
Optimal Control parameters of DE Algorithm for Short Term Hydrothermal problem

DE parameters	*Value*
Number of particles(NP)	50
Iterations	15000
Dimensions	7
Scaling factor(F)	0.63
Crossover Constant(CR)	0.30
DE Variant	DE/best/2

The scheduling for each hour for both hydro and thermal plants has been shown in table II. The optimised fuel cost for each unit per hour is given in table III. Tables IV rate of discharge and the volume of water in the reservoir during every hour.

Table II
Optimal hydrothermal scheduling for the test-case

HOUR	*Thermal Generations (MW)*			*Hydro Generations (MW)*			
	Pg1	*Pg2*	*Pg3*	*Ph1*	*Ph2*	*Ph3*	*Ph4*
1	102.6730	124.9070	50.0000	83.2740	86.8456	48.1349	253.7240
2	27.1990	40.0000	229.5200	95.2888	83.3290	60.7547	243.9090
3	102.6730	40.0000	139.7600	76.6596	78.2811	58.4223	204.2040
4	45.0566	40.0000	139.7600	90.3713	73.6300	61.5823	199.6000
5	102.6730	40.0000	139.7600	55.1597	72.5000	60.6830	199.2230
6	20.6915	209.8160	139.7600	86.6200	72.5000	61.6573	208.9560
7	185.3420	209.8160	139.7600	85.1573	62.9988	58.7674	208.1580
8	185.3230	294.7230	139.7600	86.4446	66.3318	24.3909	212.9620
9	112.6160	209.8400	319.2800	82.6267	72.5000	61.6531	224.4040
10	102.6730	294.7240	229.5200	86.6395	71.7648	59.9290	233.9290
11	113.3680	209.8350	319.2760	86.8200	72.5000	62.0240	233.3510
12	185.3150	294.7230	229.5200	76.8113	67.2133	58.9903	236.4410
13	185.5230	225.9220	229.5750	86.6415	72.5000	62.8439	244.2000
14	113.7450	209.8280	229.5280	86.6235	72.5000	63.3332	251.5270
15	102.6730	209.8150	229.5190	77.6154	68.3712	62.4807	259.5480
16	185.3430	209.8160	229.5160	49.2359	72.2998	59.1817	254.6388
17	118.6610	209.8500	229.5250	86.7655	72.5000	62.3428	267.3960
18	102.6740	294.7220	229.5190	86.6200	70.8252	62.5574	272.4610
19	185.3310	294.7240	139.7600	86.5773	64.8905	59.5975	239.1200
20	103.6390	209.8190	229.5130	86.6391	72.5000	62.9673	280.9050
21	102.6730	124.9080	229.5190	70.2171	72.5000	33.3958	276.7870
22	19.9998	209.8160	139.7590	68.9297	62.7301	60.2241	299.0910
23	20.0000	124.9080	229.5200	85.9917	37.0840	54.7446	298.0110
24	20.0000	209.8160	50.0000	104.6390	69.1400	42.9499	303.4550

Table III
Hourly Optimised fuel cost for the test-case

HOUR	*F1 ($/hr)*	*F2 ($/hr)*	*F3 ($/hr)*	*FT ($/hr)*
1	364.2030	425.3900	258.7500	1048.3400
2	210.7520	214.4000	711.0100	1136.1600
3	364.2000	214.4000	472.7950	1051.4000
4	343.1710	214.4000	472.7950	1030.3700
5	364.2000	214.4000	472.7950	1051.4000
6	155.4120	650.7950	472.7950	1279.0000
7	595.3400	650.7960	472.8000	1718.9400
8	595.4000	890.6220	472.7960	1958.8200
9	450.1510	651.1550	973.4030	2074.7100
10	364.2030	890.6210	711.0100	1965.8300

contd. table III

HOUR	*F1 ($/hr)*	*F2 ($/hr)*	*F3 ($/hr)*	*FT ($/hr)*
11	456.4180	650.9780	973.4110	2080.8100
12	595.4260	890.6250	711.0100	2197.0600
13	596.9040	796.2120	711.5520	2104.6700
14	459.5480	650.9070	711.0920	1821.5500
15	364.2000	650.7980	711.0100	1726.0100
16	595.3360	650.7970	711.0240	1957.1600
17	498.9520	651.1130	11.0630	1861.1300
18	364.2010	890.6280	711.0130	1965.8400
19	595.3760	890.6240	472.7950	1958.7900
20	372.6760	650.8300	711.0360	1734.5400
21	364.2020	425.3890	711.0100	1500.6000
22	149.4810	650.7950	472.7960	1273.0700
23	149.4800	425.3890	711.0100	1285.8800
24	149.4800	650.7950	258.7500	1059.0300

Table IV
Rate of discharge from each reservoir per hour (×10^4 m^3/hour)

HOUR	*q1*	*q2*	*q3*	*q4*
1	9.4618	14.2508	19.1529	18.7249
2	15.0000	15.0000	13.1068	24.4106
3	8.6394	14.7157	10.4189	19.8350
4	14.4165	15.0000	13.2576	25.0000
5	5.7915	15.0000	14.0033	24.3608
6	15.0000	15.0000	13.2722	23.3236
7	12.8806	11.2411	10.1353	21.7452
8	14.1483	12.2338	24.5309	18.7679
9	14.9576	15.0000	13.1860	23.8179
10	14.9603	14.5235	15.9134	24.5422
11	14.9998	15.0000	13.4165	24.2277
12	9.9121	12.6975	10.3088	25.0000
13	14.8353	15.0000	13.9370	24.6007
14	14.9194	15.0000	13.6869	24.6302
15	9.9919	12.9507	15.2008	24.6388
16	5.0619	14.8538	16.5579	22.4124
17	14.7646	15.0000	13.4242	24.9630
18	15.0000	14.0126	12.6728	22.9743
19	14.3640	11.7827	16.9058	15.2277
20	14.8677	15.0000	13.5187	24.9692
21	8.5080	15.0000	23.0946	20.2119
22	8.2676	11.1142	11.3679	25.0000
23	13.5158	6.0000	17.8355	23.2993
24	13.5284	10.7980	20.4489	24.9588

Table V shows the comparison between the results obtained using DE and other evolutionary techniques such as CFPSO, SA, EP etc. The total operational cost and the time taken to execute were taken as the major criteria to compare the outcomes of the proposed DE algorithm in comparison with other evolutionary algorithms. It clearly goes on to show the feasibility and effectiveness of DE algorithm in obtained lesser operational cost and lesser execution time.

Table V
Comparison of total operational fuel cost and computation time between DE and other evolutionary algorithms

Method	*Total fuel cost ($)*	*Computation Time (s)*
Proposed DE	38841.10	52.3
CFPSO [4]	44925.62	183.64
SA [7]	45466.00	246.19
EP[7]	47806.00	9879.45

VI. CONCLUSION

In this paper, short term hydrothermal scheduling problem has been solved with the help of Differential Evolution (DE) algorithm. It has been tested with the help of a sample system consisting of four hydro plants and three thermal plants. To include the practical aspect of the problem, valve point loading effect has also been taken into account since hence the fuel cost function is non-smooth. The water transport delay of the multi chain hydro sub system was considered. The results obtained from the algorithm establishes a conclusive proof that the proposed DE algorithm with the optimised control parameters provide much lesser total operating cost and takes lesser computation time as compared to other evolutionary techniques such as Evolutionary Programming (EP), Simulated Annealing (SA) and Constriction Factor based PSO (CFPSO). Thus from the obtained results furnished proves the superiority and effectiveness of the proposed DE algorithm suitability for solving hydrothermal optimization problem.

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