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Augmented Lagrangian Algorithm for Hydrothermal Scheduling

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Abstract

This paper mainly deals with a new algorithm for solving hydrothermal scheduling problem with transmission and environmental constraints using Augmented Lagrangian(AL) method. Hydrothermal scheduling is a most important task in power management system. Transmission capacity and environmental constraints are relaxed by using Lagrangian multipliers. The existing methods are provided suboptimal solutions from the computational burden due to the large number of variables involved in the problem. This paper ensures efficient technique that involves a reduced number of decision variables for hydrothermal scheduling to reduce the total operating cost through AL method. The ultimate aim of hydrothermal scheduling is to ensure the optimal generation in both hydro and thermal units in order to fulfill the demands over a scheduled horizon. In this paper optimal hourly schedule for power generation in hydrothermal scheduling system applying Augmented Lagrangian Relaxation (ALR) technique.

Keywords: *Augmented Lagrangian, Scheduling, Power demand, Hydro electric sources, Thermal generation cost.*

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1. Introduction

In day to day life hydro-thermal scheduling is an important activity for electric utilities to meet the future demand. In overall energy utility of India, more than 70% of the electricity requirements are contributed from thermal sources. Hydro electric sources contributes a major share than any other sources whereas in India utilize below 24% of hydropower sources. In spite of this low share of the hydroelectric sources the overall generation of country is reduced due to more demand on peak hours of the customers. Studies on Hydro-thermal scheduling are carried out by many researchers. Some of the studies are mentioned here: The general structure of a unit commitment problem for power generation operation and management was discussed by Allen [1]. A fuel constrained based unit commitment problem was designed by Lee [2], Viramani [3] implemented a Lagrangian Relaxation based and based on genetic algorithm Rudolf et al [4] designed a unit commitment problem for hydro thermal power system. Researchers have developed methods to solve hydro subproblems like Dynamic Programming (DP), network flow, and standard Mixed Integer Programming (MIP) methods. Lagrangian framework is a successful method discussed by Cohen et al [5], Shaw et al [6]. Xiaohong et al [7] proposed a nonlinear. approximation method for hydrothermal scheduling using Lagrangian Relaxation.

Baslis et al [8] proposed a MIP approach to the yearly scheduling problem of a mixed hydro thermal system. Rodrigues et al [9] solved the short-term scheduling problem of hydrothermal systems via Lagrangian Relaxation and augmented Lagrangian Methods. Borghett et al [10] proposed a MILP approach for short-term hydro scheduling and unit commitment with head-dependent reservoir. Cheng et al [11] analyzed the Comparison of Particle Swarm Optimization and Dynamic

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Programming for Large Scale Hydro Unit Load Dispatch. Pousinho et al [12] discussed the Scheduling of Hydro Producer Considering Head-De pendency, Price Scenarios and RiskAversion. Pérez-Díaz et al [13] conducted an Assessment of the Economic Impact of Environmental Constraints on Short Term Hydro power Plant Operation. PerézDíaz et al [14] analyzed a study on the Contribution of Regulation Reservoirs Considering Pumping Capability to Environmentally Friendly Hydro power Operation. The above mentioned studies helped the present study on arriving minimum production cost and maximum power utility period for the generating units.

Subramani et al [15-17] proposed Lagrangian Decomposition algorithms for power management systems. These algorithms are formulated based on generation, storage and distribution systems in various power plants. Thillainathan et al [18] combines LR simultaneously Evolutionary Algorithm (EA) to provide a hybrid algorithm for the real time energy environments. Hari et al [19] proposes a Ant Line Optimization algorithm whose inspiration from the hunting behaviour of ant lions, six step hunting behaviour is modelled using six easier operations for solution procedure with a variety of difficult constraints.

2. Mathematical Model Formulation

In the present study, the optimization model that have been designed for power generation by using thermal and hydro units with respect to various parameters and generating conditions of the power system. The objective of Hydro-thermal scheduling is to generate the number of units that would satisfy the expected demand and to give the minimum power production cost in the planning time interval. Thesecalculation includes a set of energy constraints such as range of thermal and hydro units, water discharge rate, demand and energy consumption constraints, transmission loss constraints etc.

2.1. Parameters

N_a – Set of all thermal units
N_b – Set of all hydro units
N_t – Total Study intervals (in hrs)
k – Set of all time slots
N – Total number of (Thermal and Hydro) units
$C_iP_i(k)$ – Thermal generation cost
FC_i – Fuel cost for thermal unit i
$C_{s\,i}(k)$ – Startup cost for unit i at k
$C_{sd\,i}(k)$ – Shut down cost for unit i at k
$C_{m\,i}(k)$ – Maintenance cost for unit i k
$P_i(k)$ – Power output of thermal unit i at k (MW)
$P_j(k)$ – Power output of hydro unit j at k (MW)
$P_i^{max}(k)$ –Upper limits of thermal units i in time slot k (MW)
$P_i^{min}(k)$ –Lower limits of thermal units i in time slot k (MW)
$P_j^{max}(k)$ – Upper limits of hydro units j in time slot k (MW)
$P_j^{min}(k)$ – Lower limits of hydro units j in time slot k (MW)
$P_R(k)$ –Spinning reserved requirement of unit i at time slot k (MW)
$P_D(k)$ – Load demand for whole System (MW)
$P_L(k)$ – System loss at time slot k (MW)
$W_{D\,j}(k)$ – Discharged water for hydro generation in unit j at k (MW)
$W_{v\,j}$ – Available volume of water in hydro unit j (MW)
$W_{F\,j}(k)$ – Rate of water flow in hydro unit j at k
$P_t(k)$ – Power flow in transmission line t at k (MW)
$P_t^{max}(k)$ – Upper limit of power flow unit i at time slot k (MW)
$P_t^{min}(k)$ – Lower limits of power flow unit i at time slot k (MW)
$N_{a\,i}^{on/off}$ – On/Off time duration for unit i at k
$T_i^{on/off}$ – Minimum on/off time for unit i
ER_i – Emission rate
H_i – Heat function for the thermal unit i (lb/Mbtu)
EM – Maximum emission rate for the whole system over Nt
$I_i(k)$ – Commitment unit i at time slot k
λ_i ,μ_j – Lagrangian Multipliers

2.2. Optimization Model Formulation

Hydrothermal generation scheduling can be formulated as a Non Linear Programming Problem (NLPP) based on the energy constraints and various system parameters. The objective of these scheduling is to minimize the cost of power produced by generation units Given a power station that contains Na thermal units and Nb hydro units the best generation commitment at each time k over a time horizon Nt are calculated. Cost optimization consists of startup cost, normal operational cost maintenance cost and shutdown costs. Since the marginal costs are so small for the hydro electric generation therefore they are negligible. Hence the objective function is defined by f: $\wp \times I \rightarrow \Re$ ($\wp \subset \Re^{m\times n}$, I = {0 or 1}$^{m\times na}$ where n and n_a are denoted by the number of generated units in Na and $N = N_a \cup N_b$ respectively).

$$f(\wp, I)=\sum_{k=1}^{Nt}\left[\sum_{i=1}^{Na} C_i\left(P_i(k)\right)I_i(k)+I_i(k)(1-I_i(k))\times C_{s\,i}(k)+C_{sd\,i}(k)+C_{m\,i}(k)\right]+\sum_{j=1}^{Nb} C_{m\,j}(k) \tag{1}$$

where $\wp$ is a m×n matrix each row of $\wp$ represents the power loading units (both thermal and hydro) at each time hour in N_t and I is m×n_t each row of this represents the status of thermal units at each hour in Nt. It is a nonconvex mixed integer non linear programming problem. Fuel cost for thermal unit is calculated by array equation numbers.

$$C_i P_i(k) = x_1 + y_1 F_i + z_1 F_i^2 \qquad i \in Na \tag{2}$$

Subject to the Constraints

System Power Balance Constraints:

$$\sum_{i,j \in N} I_i(k) P_i(k) = P_D(k) \tag{3}$$

(System Demand constraint)

$$\sum_{i=1}^{Na} P_i^{\max}(k) I_i(k) + \sum_{j=1}^{Nb} P_j^{\max}(k) I_j(k) - P_D(k) - P_L(k) = 0 \tag{4}$$

(Spinning Reserved constraint)

Transmission loss can be calculated by

$$P_L(k) = \sum_{i=1}^{Na+Nb} \sum_{j=1}^{Na+Nb} P_i(k) L_{ij} P_j(k) + \sum_{i=1}^{Na+Nb} L_{0i} P_i(k) + L_{00} \tag{5}$$

Where L_{ij} , L_{0i} , L_{00} are the loss formula coefficients of the transmission lines.

Spinning reserved requirement:

$$\sum_{i=1}^{Na} P_i^{\max}(k) I_i(k) + \sum_{j=1}^{Nb} P_j^{\max}(k) I_j(k) \geq P_D(k) + P_R(k) \tag{6}$$

Unit Generation limit:

$P_i^{min} \leq P_i(k) \leq P_i^{max}$ i=1,2,3,…,Na (7)

(Thermal unit bounds)

$P_j^{min} \leq P_j(k) \leq P_j^{max}$ j=1,2,3,…,N_b (8)

(Hydro unit bounds)

Relationship between water discharge and Power flow:

Water availability is

$$\sum_{k=1}^{Nt} \sum_{j=1}^{Nb} W_{Dj}(k).1hr = W_{vj} \tag{9}$$

(Water conservation constraint)

The rate of water flow is calculated by

$$W_{Fj}(k) = x_2 + y_2 F_j + z_2 F_j^2 \tag{10}$$

where x_2, y_2, z_2 are water discharge coefficients for hydro unit j.

Startup and Shut down time for Thermal units:

$(N_{a\,i}^{on}(k-1) - T_i^{on}).(I_i(k-1) - I_i(k)) \geq 0$ (11)

$(N_{a\,i}^{off}(k-1) - T_i^{off}).(I_i(k) - I_i(k-1)) \geq 0$ (12)

Transmission line capacity limit:

$P_t^{min}(k) \leq P_t(k) \leq P_t^{max}(k)$ (13)

Emission Constraints:

$$\sum_{k=1}^{Nt} \sum_{i=1}^{Na} ER_i H_i(p_i(k)) I_i(k) \leq EM \tag{14}$$

$$\sum_{k=1}^{Nt} q_i C_i(P_i(k)) \leq EM(k) \tag{15}$$

The NOx, SO_2, CO_2 emission objective can be defined as:

$$F_{1i}(k) = \theta_1 + \tau_1 F_i + \delta_1 F_i^2 \ (Kg/hr)$$
$$F_{2i}(k) = \theta_2 + \tau_2 F_i + \delta_2 F_i^2 \ (Kg/hr)$$
$$F_{3i}(k) = \theta_3 + \tau_3 F_i + \delta_3 F_i^2 \ (Kg/hr)$$

where θ_1, τ_1, δ_1 are the coefficients for NOx emission; θ_2, τ_2, δ_2 are the coefficients for SO_2 emission and θ_3, τ_3, δ_3 are CO_2 emission coefficients.

3. Augmented Lagrangian (AL) Method

An AL method is implemented to solve this problem. Therefore the primal problem becomes, From the proposed problem both thermal and hydro units are independent but together must met the overall system demand. The total operating cost to be minimized hence this attains Lagrangian Relaxation technique to exploit the decomposability of the proposed problem. The solution of the subproblems are piecewise linear cost functions which attains the optimal solution only in bounds and it may oscillates the small changes of the multipliers. To overcome this difficulty Lagrangian a quadratic penalty function is added associated with demand constraint is known as Augmented Lagrangian Relaxation technique. The Augmented Lagrangian function for the proposed problem is denoted by,

$$\begin{aligned} L(U,\lambda,\mu,c) = & \sum_{k=1}^{Nt} \sum_{i=1}^{Na} C_i P_i(k) + \sum_{k=1}^{Nt} \lambda_i \left[P_D(k) + P_L(k) - \sum_{i=1}^{Na} P_i^{\max}(k) - \sum_{j=1}^{Nb} P_j^{\max}(k) \right] \\ & + \sum_{j=1}^{Nb} \mu_j \left[\sum_{k=1}^{Nt} k(W_{Fj} + \alpha_1 - W_{vj}) \right] + \frac{C_k}{2} \sum_{k=1}^{Nt} \left[P_D(k) + P_L(k) - \sum_{i=1}^{Na} P_i^{\max}(k) - \sum_{j=1}^{Nb} P_j^{\max}(k) \right]^2 \\ & + \frac{C_j}{2} \sum_{j=1}^{Nb} \left[\sum_{k=1}^{Nt} (W_{Fj} + \alpha_2 - W_{vj}) \right]^2 \end{aligned} \tag{16}$$

Here C_k, C_j are positive penalty coefficients and α_1, α_2 are the slack variables. The quadratic penalty terms in are relaxed by Lagrangian decomposition.

4. Numerical Calculations and Graphical Representations

The proposed ALR method is solved in MATLAB2010a, the computations were done in HP Laptop. Computational results enforces from best among 50 runs of the ALR algorithm. Minimum, maximum limits and fuel cost for the generation of thermal units calculated by using ALR method over hourly planning horizon and it is depicted in Table 1.

Table 1. Generation cost for thermal units

Plant	x_1 (\$/MW hr)	y_1 (\$/MW hr)	z_1 (\$/MW hr)	$P_i^{min}(k)$ (MW)	$P_i^{max}(k)$ (MW)
1	0.01	0.1	100	50	200
2	0.02	0.1	120	40	170
3	0.01	0.2	150	30	215

For optimal hydrothermal generation schedule in both plants met the load demand and transmission losses are calculated using ALR algorithm is shown in Table 2.and Table 3. over one day hourly planning horizon.

Table 2. Load demand

Hour	P_D (MW)	Hour	P_D (MW)	Hour	P_D (MW)
1	175	9	440	17	425
2	190	10	475	18	400
3	220	11	525	19	375
4	280	12	550	20	340
5	320	13	565	21	300
6	360	14	540	22	250
7	390	15	500	23	200
8	410	16	450	24	180

Table 3. Generation cost for hydro units

Pl ant	P_j^{min} (k)	P_j^{max} (k)	Water Volume (m^3)	x_j	y_j	z_j
1	50	200	25000	0.01	0.10	100

Figure1. reflects that the system demand over one day scheduling period and it attains maximum in 13th hour. For hydro units the corresponding power generation limits and water availability and its discharge rate coefficients are calculated in table -3

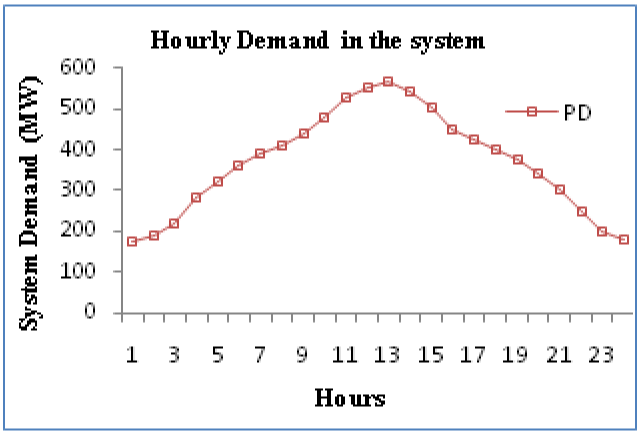

Figure 1. Hourly demand of the system

The efficiency of the Augmented Lagrangian Relaxation Technique is tested for a hydrothermal plant. The purpose of applying Augmented Lagrangian method is minimize the loss of the system as well as maximize the generation utility over a planning horizon. In order to fulfill the demand (load) of the system generation scheduling offers to schedule the units for generation by satisfying all the system constraints. In spite of achieving maximum profit for the power generating utility supply and demand are utilized in a reliable manner.

Fig 2 classifides that the unitwise generation of both thermal and hydro units; the maximum load is utilized by using ALR technique over one day planning horizon.

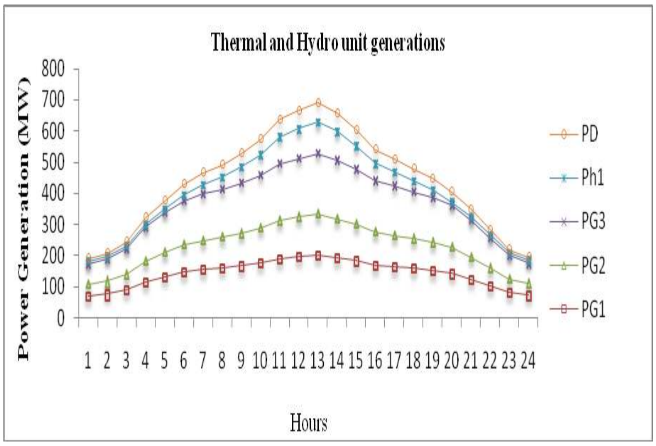

Figure 2. Unit wise Generation

The energy losses are calculated in quadratic nature over hourly planning horizon and it is depicted in Table 4.

Table 4. Power loss obtained from AL Technique

Ho ur	Thermal Generation			Hydro Generati on	Loss (MW)
	P_{G1} (MW)	P_{G2} (MW)	P_{G3} (MW)	P_{h1} (MW)	
1	68.1356	40.0000	64.0655	10.0000	7.2007
2	77.1462	41.6310	70.0654	10.0000	8.8426
3	88.9214	50.2145	83.0333	10.0000	12.1691
4	114.2141	67.3381	109.2003	10.0000	20.7527
5	131.7539	78.4389	127.8284	10.0741	28.0956
6	145142	88.5791	141.4943	17.8482	34.4359
7	154.6471	94.8724	148.4014	29.9173	37.8385
8	160.5308	98.7054	153.0133	38.0547	40.3041
9	165.1055	102091	162.3226	50.2454	43.8825

10	175.8352	113.1778	169.6516	64.9265	48.5912
11	188.4399	123.3503	183.0102	81154	55.9155
12	194.9369	129.0775	189.3461	92.4565	59.9155
13	200.0000	134.1211	193.8283	100.00	62.9491
14	191.6835	127.1509	184970	92.6519	57.9831
15	182.4302	118.2798	173102	75.2374	52.2576
16	167.5452	108.4111	164.5151	54.6059	45.0773
17	162.1553	102.7916	158.2515	43.8912	42.0896
18	157.9871	96312	150.7118	33.8157	39.9440
19	149.6308	92.4476	144.9175	23.9481	35.9440
20	141.1155	85.3907	135.2588	10.2154	31.9807
21	123.4245	72.6379	118.2341	10.0000	24.2965
22	101.6896	57.8784	96686	10.0000	12363
23	80.5810	44.9917	74.2655	10.0000	9.8386
24	71.7041	40.0000	60655	10.0000	7.7696

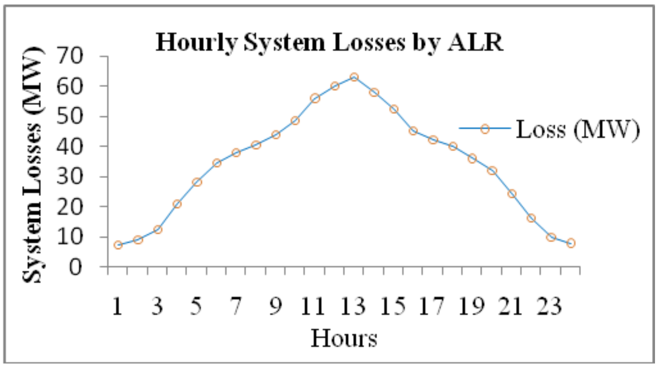

Figure 1. Hourly system loss

Figure.3 reveals that the calculated overall system losses (MW) over one day planning horizon. From this maximum loss are obtained in 13th hour which leads up to 62.9491MW energy losses due to peak demand of the consumers.

Figure. 4 ensures that the water discharge rate for a single hydro generation unit based on ALR technique over one day planning horizon.

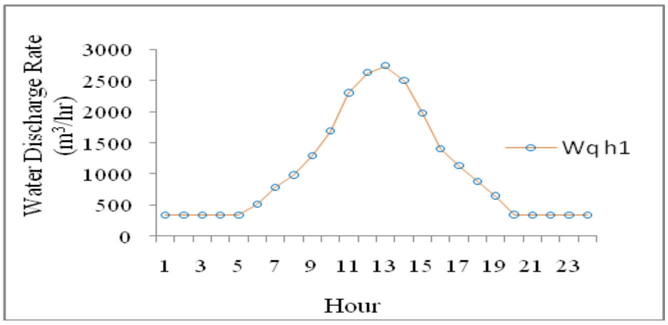

Figure 4. Hourly water discharge rate

Table 5. ensures that the generation cost for one hydro unit and three thermal units obtained by ALR technique. From the below table it is clear that generation cost is increased from 1 – 13th hours based on the peak demand and it is decreased from 13 – 24 due to off peak demand.

Table 5. Generation cost for thermal and hydro plants over hourly planning horizon

Hours	F_1 (\$ / hr)	F_2 (\$ / hr)	F_3 (\$ / hr)	F_t (\$ / hr)	Wq_{h1} (m^3 / hr)
1	153.2382	150000	203.8570	513.0952	340000
2	167.2299	158.8259	213.1048	539.1606	340000
3	187.9623	175.4514	235.5519	598.9656	340000
4	241.8700	217.4222	291.0872	750.3794	340000
5	287662	250.8972	338.9666	876.300	347.5712
6	329.3155	285.7832	378.5053	993.604	510775
7	354.6219	309.5029	399.9101	1064.0349	792.0487
8	373.7544	324.7256	414.7333	1113.2133	987.9836
9	389.1088	352285	445.9508	1191.2881	129384
10	427638	387.5019	471.7471	1280128	1691.457
11	473.9399	436409	521.5294	1432.1102	2307.260
12	499.4977	461279	543887	1512.0143	2627.361
13	520.0000	493.1817	564.4598	1577.6415	2740.000
14	485941	450622	535.1106	1477.7669	2508.101
15	451.0509	411.6302	491148	1358.7959	1984.388

16	397.4685	365.9007	453.5553	1219245	1411.026
17	379.1589	341.6012	432.0856	1152.8457	1133.410
18	365.3979	314148	407.2829	1089.0956	884.9241
19	338.8569	300.1758	388.9942	1028.0269	653.3727
20	313.2474	274.3705	360.0013	947.6192	350.5693
21	264.6784	232.7892	313.4398	810.9074	340000
22	213.5766	192.7861	262.7819	669.1446	340000
23	172.9911	164.9841	229.0067	569819	340000
24	158.5851	150000	298596	611.4447	340000

Table – 6 Comparative study results

Method	Total Fuel Cost ($)	Computational Time (Sec)
PSO	24378.7028	15.32
GA	24378.0589	18.14
ALR	24337.7032	10.23

The proposed results are compared with other heuristic algorithms such as Particle Swam Optimization (PSO) and Genetic Algorithm (GA). Based on the numerical calculations and graphical representations proposed Augmented Lagrangian Relaxation techniques leads to the acceptable solutions. Particle Swarm Optimization and Genetic Algorithm are the populations based soft computing techniques, attains convergence limit at 15.32 seconds and 18.14 seconds whereas proposed ALR technique attains convergence limit in 10.23 seconds with 50 iterations.

5. Conclusion

In order to solve hydrothermal generation and scheduling problem a new ALR algorithms has been proposed as a Nonlinear Integer Programming Problem. With the help of Lagrangian multipliers the complicating constraints such as demand and reserve requirements are decomposed. These Lagrangian multipliers act as a price resources to concentrate the generation limits and reserve contribution in both individual and hybrid configurations. The algorithm has been modified to reduce the number of variables and hence problem minimizes the computational burden. The reservoir level and the maintenance scheduling are optimized, simultaneously, to minimize the thermal generation complement and to maximize the future water value. Test results shows that this algorithm is fast efficient and provides reasonable results in practical size systems.

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