Chapter 3

Mix Generation System

3.1 Introduction

Power generation comprises of thermal, nuclear, hydro, and gas plants. Among all these, hydro plants pose no fuel cost and its coordination with thermal generation provides significant cost minimization subject to constraint of water availability in a given period of time. Hydro power plants are classified as pumped storage plant, peaking plant and base plants. Some plants are coordinated with irrigation activities, that is plants are operated only when water for irrigatioin is released. Hence, provided water release time and its duration is known apriori and during the same period demand is known, thermal plant can be coordinated with hydro-plants and cost of fuel can be minimized. Similarly, for base plants, provided complete details of head, water inflow and total water to be utilised are known apriori, generation scheduling can be estimated. Hydrothermal scheduling attempted by many techniques and their usefulness is already established. Prominent among these are gradient, dynamic programming, Lagrangian relaxation etc[8,129]. Broadly, hydrothermal scheduling is performed in two ways.

(1) Long term scheduling

(2) Short term scheduling

Long term scheduling is a part of planning activities and its period may be a season or a full year. Short term scheduling is a part of operation planning and may have a period of twenty four hours or a week. In this Chapter, hydrotermal scheduling is attempted as short term problem of twenty four hours duration during scheduling horizon, it is assumed that demand variation is deterministic and remains constant over a sub interval of one hour duration. Second important assumption is that of fixed head. El-Hawary, Zaghool and Rasid [33,34,36] have developed the technique of hydrothermal scheduling for fixed head using Newtonian method. L.P. Singh [35] has also attempted the hydrothermal scheduling problem with fixed head using dynamic programming. Power generation scenario is sizably influenced by introduction of gas plants. Main advantages of gas plants are as follows:

(1) They occupy less space.

(2) Synchronizing time is very short (up to thirty minutes).

(3) Generator can be used as synchronous condenser for power factor improvement.

(4) They can be used as co-generation plant giving additional output through waste heat utilization.

Normally fuel-gas is supplied by supply companies to these plants on contractual basis. The contract is of the form 'take or pay'. Gas is supplied by the supply company as per commitment for twenty four hours or so. This volume of gas is a fixed amount and naturally its cost is also fixed. Hence, optimum utilization of gas is sought such that overall cost of power generation is minimum. Since volume of gas is fixed, thermal-gas co-ordination is similar to hydrothermal scheduling. Because of this similarity, mix-generation scheduling is attempted in this Chapter considering following points.

(1) Co-ordination of Hydro and thermal systems,

(2) Co-ordination of Thermal and Gas systems, and

(3) Co-ordination of Thermal, Hydro and Gas systems.

The technique is based on the equivalent cost function of thermal system. During scheduling horizon, it is assumed that thermal strategy is fixed and hence, its cost function is also fixed. The problem of hydrothermal, thermal-gas or otherwise a mix-generation scheduling is solved by first transforming consumption function into an equivalent cost function by applying weighting factors. Once this is achieved, the problem is solved like a thermal problem.

3.2 Hydrothermal Scheduling

For hydrothermal scheduling, the following assumptions are made:

(1) Fixed head,

(2) Discharge function is quadratic, and

(3) Fixed amount of water to be utilized in scheduling horizon.

The usual method adopted for coordination is to convert discharge function into a cost function by applying a weighting factor or water value. Since, in twenty four hours quantity of water to be used is known apriori, a unique water value or weighting factor is to be estimated. Weighting factors can be estimated by interpolation . Entire scheduling procedure is iterative. For a particular water value in an iteration, scheduling is calculated using dynamic programming and water volume being discharged is also calculated. The calculated volume of water is compared with the volume of water to be utilized. If calculated volume of water is sufficiently close to the goal value, the procedure is terminated; otherwise, by interpolation, new water value is assessed and the procedure is repeated until convergence is attained.

3.3 Formulation

A thermal subsystem is represented as

$$f_j(p_j) = a_j(p_j^2) + b_j p_j + c_j \qquad Rs/MW/hr \qquad ; \qquad j = 1, N_t \tag{3.1}$$

and hydro subsystem as

$$q_{jh}(ph_{jh}) = \alpha_{jh}(ph_{jh})^2 + \beta_{jh} ph_{jh} + \gamma_{jh} \qquad cum/MW/hr \qquad ; \qquad j = 1, N_t \tag{3.2}$$

where
N_t is number of thermal plants,
N_h is a number of hydro plants,
j is index for thermal plants,
j_h is index for hydro plants.

Then, as established earlier, the thermal subsystem can be represented by its equivalent cost function as

$$F_{N_t}(P_t) = A_{N_t}(P_t)^2 + B_{N_t}(P_t) + C_{N_t} \qquad Rs/MW/hr \tag{3.3}$$

where

$$P_t = \sum_{j=1}^{N_t} p_j \tag{3.4}$$

$$F_{N_t}(P_t) = \sum_{i=1}^{N_T} f_i(p_j) \tag{3.5}$$

Similarly, all hydro units at a plant can be represented as

$$Q(P_{h_j}) = \alpha(P_{h_j})^2 + \beta(p_{h_j}) + \gamma \qquad Cu.M/MW/hr \tag{3.6}$$

Where

$$P_h = \sum_{j=1}^{N_h} p_{h_j} \tag{3.7}$$

subject to

$Q_T \leq Q_{P_h}$

$P_{j_{min}} \leq P_j \leq P_{j_{max}}$

$P_{jh_{min}} \leq P_{jh} \leq P_{jh_{max}}$

and

$$\sum_{j=1}^{N_h} P_{jh} + \sum_{j=1}^{N_t} P_j = D + P_L \tag{3.8}$$

where, D is demand and P_L is transmission losses.

3.4 Method of Solution

Assume 'h' as water value to be used to convert water discharge function into an equivalent cost function. Hence, equation (3.6) can be converted into a cost function as

$$h[F(u)] = h\alpha(u)^2 + h\beta(u) + h\gamma \tag{3.9}$$

and augmented cost function is

$$[F(D)] = Min[(h\alpha(u)^2 + h\beta(u) + h\gamma + A_N(D-u)^2 + B_N(D-u) + C_N] \tag{3.10}$$

where,
D is demand at first hour.
u is unique value of $Ph_{,h}$
For cost minimization
$\frac{dF(d)}{du} = 0$, that is $h(2\alpha u + \beta) - 2A_N(D-u) - B_N = 0.0$
Therefore,

$$h = \frac{2A_{N_t}(D-u) + B_{N_t}}{2\alpha u + \beta} \tag{3.11}$$

Hence, original equation (3.2) can be expressed as

$$F(P_h) = A_h(P_h)^2 + B_h(P_h) + C_h \tag{3.12}$$

where,
$A_h = h * \alpha$; $B_h = h * \beta$ and $C_h = h * \gamma$ Once this set of equations is formed then for all subintervals of scheduling horizon, generation allocation can be estimated.

3.5 Decision of Hydro Plants as Peaking Plants

Eventhough, water to be utilized is known in a scheduling horizon, it is not necessary that hydro plants be operated for all the hours. For thermal cost minimization, optimum strategy of water to be utilized can be decided for different hours of the scheduling period. Decision will definitely depend on demand and the volume of water available. The hydro plants may be operated in two ways:

(1) As base plants, that is, operating along with thermal plants throughout the scheduling horizon, Or

(2) As peaking plants.

Both these situations can be handled by the proposed algorithm. Since, throughout the work, cost functions as well as discharge/consumption functions are quadratic, it is easy to take decision of time or stage at which hydro plants can be switched off or on. Now, assume that there are N_T units in thermal subsystem which can be represented by equations (3.3 & 3.9)

$$F_{N_t}(P_t) = A_{N_t}(P_t)^2 + B_{N_t}(P_t) + C_{N_t} \tag{3.13}$$

$$F(P_h) = A_h(P_h)^2 + B_h(P_h) + C_h \tag{3.14}$$

As per convention, these equations are representing two equivalent thermal subsystems. These two subsystems can now be jointly represented as

$$F(D) = A(D)^2 + BD + C \tag{3.15}$$

where,
$D = P_t + P_h$
Now, at a particular value of MW, the above, cost function (3.10) may yield a cost lesser than the cost given by only a thermal subsystem. This particular policy can be decided by equating equations (3.12) and (3.14), that is

$$A_{N_t}(D^2) + B_{N_t}(D) + C_{N_t} = AD^2 + BD + C \tag{3.16}$$

or

$$(A_{N_t} - A)D^2 + (B_{N_t} - B)D + C_{N_t} - C = 0 \tag{3.17}$$

Solving this equation, D can be estimated as a load level, above which joint hydrothermal cost function will provide lesser cost.

The above procedure can be generalized to coordinate any number of hydro plants with any number of thermal plants. The main requirement for this generalization is to decide a base subsystem and then assigning priority order to coordinate the plants. For example, assume that priority 1 is assigned to the thermal subsystem and 2 and 3 are assigned to the remaining two coordinating hydro plants. Under this condition, two critical policies can be framed, that is, D_{12} for thermal plus first hydro plant and D_{123} for thermal, first hydro and second hydro. Clearly, below D_{12} MW thermal is to be scheduled; then, when load crosses D_{12}, thermal and first hydro plant together are to be scheduled; and above D_{123}, all subsystems are to be scheduled. This idea can be further generalized to include gas plants.

3.6 Corrections of Weighting Factors

The important step at the end of each iteration is to find the total water utilized. The goal is to utilize given water volume, which depends upon energy generation which in turn depends upon the weighting factor. Hence, at the end of iteration water utilized is compared with the given volume and if necessary, weighting factor is corrected by interpolation using the following expression [6].

$$h_j^r = h^{r-1} + \frac{[(Q_j - Q_j^{r-1}) * (h_j^{r-1} - h_j^{r-2})]}{Q_j^{r-1} - Q_j^{r-2}} \qquad j = 1, N_h \tag{3.18}$$

where r is iteration count. On correcting this weighting factors, hydro functions are again converted into cost function and scheduling is repeated from first hour to the last hour of the scheduling horizon.

3.7 Thermal Gas Co-ordination

Gas plants with particular reference to Indian context are operated on contractual basis. Gas is supplied to these plants on 'Take or pay 'basis. In such contracts, it is mandatory for power company to consume gas for power generation in stipulated period, otherwise company has to pay penalty for not consuming gas. Now, in scheduling horizon, gas to be utilized is known in terms of volume units, say million cubic meters. The rate of charge of gas may or may not vary. However, during scheduling period if charge assumed is fixed, then cost of power generation by the gas plants is also fixed. Therefore, while co-ordinating with thermal plants, optimum utilization of gas in scheduling period is to be estimated. Following assumptions are made for thermal gas co-ordination:

(1) Rate of change of gas is fixed during scheduling period,

(2) Gas is available during scheduling period as per contract, that is, the volume of gas is deterministically known, and

(3) Consumption function is quadratic.

The consumption function representing gas consumed provides volume of gas in cubic meters /MW/hr. The same is to be converted in Rs/MW/hr using pseudo gas value or weighting factor. That is, if

$$V(P_g) = A_{gk}P_k^2 + b_{gk}P_k + C_gk \qquad CuM/MW/hr \tag{3.19}$$

the same may be converted as

$$F_g(P_g) = h_g * [V(P_g)] \tag{3.20}$$

That is,

$$F_g(P_g) = h_g * [a_{gk}P_k^2 + b_{gk}P_k + C_{gk}] \qquad Rs/MW/Hr. \tag{3.21}$$

Above expression are quadratic and at the end of scheduling period, gas volume is calculated and compared with net gas available for use. To utilize the gas optimally naturally, weighting factor has to be corrected and this is corrected by interpolation. Hence, the methodlogy of co-ordination of gas plants with thermal plants is exactly the same as hydro-thermal co-ordination.

3.8 Mix-Generation Scheduling

Having established co-ordination of hydro-thermal and thermal-gas plants, the final stage is to attempt the problem of Mix-generation scheduling. Mix generation system for this purpose is defined as 'a system comprising different energy sources'. The co-ordination can be attempted for (1) overall economy and (2) peaking purpose.

3.9 Problem Formulation

For formal definition of the problem, it is necessary to decide priority order of different subsystems. Since in present power scenario, major share is born by thermal system, it is natural to declare thermal as first priority. Also for simplicity, it is assumed that gas and hydro are given second and third priority. Hence, thermal system is represented as

$$F_T(P_T) = A_N P_T^2 + B_N P_T + C_N \qquad Rs/MW/Hr. \tag{3.22}$$

The gas consumption function is converted to cost function as

$$F_g(p_g) = A_g(p^2)_g + B_g p_g + C_g \qquad Rs/MW/hr \tag{3.23}$$

and lastly, the hydro function is expressed as

$$F_h(P_h) = A_h P_h^2 + B_h P_h + C_h \qquad Rs/MW/Hr \tag{3.24}$$

where

$$P_T = \sum_{i=1}^{N_t} P_i \tag{3.25}$$

$$P_g = \sum_{j=1}^{N_g} P_{gj} \tag{3.26}$$

$$P_h = \sum_{k=1}^{N_k} P_{hk} \tag{3.27}$$

The net generation requirement is

$P_g + P_T + +P_h \quad = D + P_l$

where D is net demand and P_l is Transmission losses with the following constraints

$Pmin_i \leq P_i \leq Pmax_i$	Thermal subsystem
$Pmin_j \leq P_j \leq Pmax_j$	Gas subsystem
$Pmin_k \leq P_k \leq Pmax_k$	Hydro subsystem
$\sum_{t=1}^{T} v = V_g$	Net available gas volume
$\sum_{t=1}^{T} q_h = Q_h$	Net available water volume

Since weighting factors are required to convert consumption function into cost function and exact value of the same cannot be guessed apriori, the procedure is iterative. After every iteration, new value of weighting factors are calculated by interpolation method as discussed in section (3.23), and the procedure is repeated till convergence is obtained.

3.10 Solution Procedure

The problem can be solved with and without transmission losses. The same procedure as established for hydro-thermal and thermal-gas co-ordination, will be used. The entire procedure is summarized in the form of following algorithm.

(1) Assign priority to each subsystem.

(2) Form cost function of thermal subsystem and equivalent consumption function for each remaining co-ordinating subsystems.

(3) Set iteration count to 1 and assign arbitrarily generation on each subsystem from the demand of first hour of scheduling horizon and using equation (3.8), find weighting factors and transform consumption function into cost function.

(4) Set $t = 1$ for scheduling period and form this period onwards, calculate generation scheduling with or without transmission losses up to last period.

(5) Calculate consumption of gas or water volume, as the case may be and compare the same with the given net volume of each subsystem.

(6) If calculated values of volumes are sufficiently near the goal value, go to step 7; otherwise, correct the respective coefficients and go to step 4.

(7) Calculate total cost of generation.

3.11 System Studies and Results

Methodology developed in Chapter 3 is applied for mix-generation system. Problems for hydrothermal and thermal-gas plants are attempted separately and then problem of mix generation system is solved without and with transmission losses. First, a generalized problem is formed consisting of three thermal plants and two hydro plants. Table 3.1 is data for thermal plant and Table 3.2 is data for hydro plants. Loss coefficients are shown in Table 3.3. Table 3.4 and 3.5 are the result of hydro thermal coordination. Next four problems are solved to establish the fact that the hydro plant may not necessarily be run along with thermal plants for all hours of scheduling horizon and a critical load can be obtained above which hydrothermal coordination proves to be economical or the same plant may then be treated as peaking plant. Decision of peak demand to include hydro plants for power generation can be deterministically computed. Table 3.6 is the input data for thermal plants when one hydro plant is considered. Data for hydro plant is first row of Table 3.2. The study is carried out both with and without transmission losses. Table 3.7 is the result of hydro-thermal coordination which shows the cost and water volume used. Table 3 8 is the result of hydro-thermal scheduling in which hydro plant is run for

Table 3.1: (a) Thermal Subsystem

Plant No	Cost Coefficients				
	a_i	b_i	c_i	$P_{i_{min}}$	$P_{i_{max}}$
1	.010000	.100000	100.000000	50.0000	250.0000
2	.020000	.100000	120.000000	60.0000	200.0000
3	.010000	.200000	150.000000	50.0000	250.0000

Table 3.2: Hydro Subsystem

Plant No	Discharge Coefficients			P_{min}	P_{max}
1	.060000	20.000000	140.000000	15.0000	65.0000
2	.050000	21.000000	130.000000	20.0000	100.0000

Water available for Generation
Plant No 1 18600 Cu ft
Plant No 2 26000 Cu ft

all hours of the scheduling horizon. On similar lines, two such problems are attempted including transmission losses. However, volume of water available for generationn is taken slightly different than the earlier one. Table 3.9 shows B-coefficient matrix. Table 3.10 and 3.11 are the results of hydro-thermal coordination with transmission losses for these two aspects. Next, to prove the validity of the technique for hydro-thermal scheduling data from IEEE [36] is taken and scheduling program is run. Table 3.12 is cost coefficients of thermal plants and 3.13 is discharge function of the hydro plants. Table 3.14 is B-coefficient matrix. Table 3.15 shows the detailed result. The result almost matches with the result given in [36]. Then, thermal-gas coordination is attempted. Table 3.16 [8] gives input data for thermal-gas plants. Table 3.17 gives result of thermal-gas coordination at the end of first iteration and Table 3.18 is the result at the end of 6^th iteration. The result of this coordination exactly matches with the result in [8]. Finally two problems are solved for mix generation. Table 3.19 shows input data of the sample system. The problem is solved excluding transmission losses. Table 3.20 is the result of this coordination. Next, a sample problem is solved for mix generation system including transmission losses using the same input data and B-coefficients as given in Table 3.3. Table 3.21 is the result of this coordination.

Table 3.3: B-Coefficients Matrix

.0000300	.0000150	.0000200	.0000100	.0000200
.0000150	.0000400	.0000900	.0000100	.0000150
.0000200	.0000900	.0000500	.0000200	.0000220
.0000100	.0000100	.0000200	.0000100	.0000110
.0000200	.0000150	.0000220	.0000110	.0000400

Table 3.4: Hydro-Thermal Dispatch

Demand MW	P_1 MW	P_2 MW	P_3 MW	Ph_1 MW	Ph_2 MW	Transmission Loss MW
400.00	151.9389	74.4388	144.1961	15.0000	20.0000	5.5740
690.00	250.0000	122.3179	240.4259	38.1539	55.2547	16.1528
540.00	211.4939	102.7754	201.2450	15.0000	20.0000	10.5147
650.00	242.5201	117.3796	230.5408	29.6552	44.4817	14.5777
755.00	250.0000	134.3257	250.0000	58.4208	80.9876	18.7348
560.00	219.6383	106.6151	208.9832	15.0000	21.0948	11.3317

Table 3.5: Water Available and Used

Plant No	Total Water used	Water Available for Generation
1	18599.94000 Cu. ft.	18600.0000 Cu. ft.
2	25999.93000 Cu. ft.	26000.0000 Cu. ft.

Total cost of Generation Rs 39765.66

No of iterations 15

Final cost Multiplier Plant No 1 0.2126595

Final cost Multiplier Plant No 2 0.1949477

Table 3.6: Input data For Hydro-Thermal Dispatch

Thermal	Cost Coefficients			Bounds	
Unit No	a_i	b_i	c_i	$P_{i_{min}}$	$P_{i_{max}}$
1	.0100000	.100	100.000	50.00	200.00
2	.0200000	.100	120.000	60.00	170.00
3	.0100000	.200	150.00	50.00	215.00

Table 3.7: Scheduling Result Without Transmission Losses with Hydro as A Peaking Plant

Hour NO	Demand MW	Thermal Generation P_1 MW	P_2 MW	P_3 MW	Hydro Generation Ph MW
01	175.00	60.000	60.000	55.000	.00
02	190.00	67.500	60.000	62.500	.00
03	220.00	82.500	60.000	77.500	.00
04	280.00	112.50	60.000	107.500	.00
05	320.00	130.00	65.000	125.000	.00
06	360.00	138.21	69.109	133.218	19.46
07	390.00	146.11	73.057	141.113	29.72
08	410.00	151.37	75.688	146.377	36.56
09	440.00	159.27	79.636	154.272	46.82
10	475.00	168.48	84.242	163.484	58.79
11	525.00	186.000	93.000	181.000	65.00
12	550.00	196.007	98.000	191.00	65.00
13	565.00	200.000	101.667	198.333	65.00
14	540.00	192.000	96.000	187.000	65.00
15	500.00	176.000	88.000	171.000	65.00
16	450.00	161.904	80.952	156.904	50.24
17	425.00	155.325	77.662	150.325	41.69
18	400.00	148.745	74.372	143.745	33.14
19	375.00	142.165	71.083	137.165	24.59
20	340.00	138.000	69.000	133.000	.00
21	300.00	122.000	61.000	117.000	.00
22	250.00	97.500	60.000	92.500	.00
23	200.00	72.500	60.000	67.500	.00
24	180.00	62.500	60.000	57.500	.00

Total cost of generation = Rs 22180.25

Number of iterations = 7

Total water consumed = 17400 cu ft

Available water for power generation 17400 cu ft

Table 3.8: Hydro-Thermal Scheduling using Hydro Plant at all Hours

Hour NO	Demand MW	Cost Rs.	Thermal Generation			Hydro Generation
			P_1 MW	P_2 MW	P_3 MW	Ph MW
01	175.00	513.00	50.0000	60.0000	50.0000	15.0000
02	190.00	531.25	60.0000	60.0000	55.0000	15.0000
03	220.00	574.75	75.0000	60.0000	70.0000	15.0000
04	280.00	688.75	105.0000	60.0000	100.0000	15.0000
05	320.00	784.65	124.0000	62.0000	119.0000	15.0000
06	360.00	894.25	140.0000	70.0000	135.0000	15.0000
07	390.00	984.85	152.0000	76.0000	147.0000	15.0000
08	410.00	1039.35	158.7959	79.3980	153.7959	18.0102
09	440.00	1108.79	167.0661	83.5331	162.0661	27.3347
10	475.00	1194.13	176.7147	88.3573	171.7147	38.2132
11	525.00	1324.12	190.4984	95.2492	185.4984	53.7541
12	550.00	1392.67	197.3902	98.6951	192.3902	61.5245
13	565.00	1439.85	202.0000	101.0000	197.0000	65.0000
14	540.00	1364.96	194.6335	97.3167	189.6335	58.4163
15	500.00	1257.94	183.6065	91.8033	178.6066	45.9837
16	450.00	1132.70	169.8228	84.9114	164.8229	30.4428
17	425.00	1073.65	162.9310	81.4655	157.9310	22.6724
18	400.00	1016.65	156.0000	78.0000	151.0000	15.0000
19	375.00	938.65	146.0000	73.0000	141.0000	15.0000
20	340.00	837.85	132.0000	66.0000	127.0000	15.0000
21	300.00	734.75	115.0000	60.0000	110.0000	15.0000
22	250.00	627.25	90.0000	60.0000	85.0000	15.0000
23	200.00	544.75	65.0000	60.0000	60.0000	15.0000
24	180.00	518.75	55.0000	60.0000	50.0000	15.0000

Total cost of generation = Rs 22518.31

Total water used = 17400 cu ft

Total water available for generation = 17400 cu ft

Number of iterations = 9

Table 3.9: Loss Coefficients - B

.0005000	.0000500	.0002000	.0000300
.0000500	.0000400	.0001800	-.0001100
.0002000	.0001800	.0005000	-.0001200
.0000300	-.0001100	-.0001200	-.0002300

Table 3.10: Scheduling Including Losses with Hydro as Peaking Unit

Hour NO	Demand MW	Cost Rs.	Thermal Generation P_1 MW	P_2 MW	P_3 MW	Hydro Generation Ph MW	transmission Loss MW	Total Generation MW
1	175.00	540.59	63.9560	60.0000	58.0397	.0000	6.9957	181.996
2	190.00	564.96	72.3958	60.0000	66.3600	.0000	8.7558	198.756
3	220.00	623.40	89.6214	60.0000	83.3364	.0000	12.9578	232.958
4	280.00	780.93	120.5647	68.9675	113.4872	.0000	23.0201	303.020
5	320.00	913.28	138.7011	81.1646	130.7686	.0000	30.6345	350.635
6	360.00	1004.72	149.3996	89.0843	141.6415	15.0000	35.1254	395.125
7	390.00	1105.32	160.4565	97.3487	152.3406	20.7759	40.4307	430.431
8	410.00	1161.75	167.0279	101.3088	157.8295	27.7268	43.2407	453.241
9	440.00	1244.07	175.0860	107.9869	165.2104	42.2847	46.6768	486.677
10	475.00	1344.94	184.3276	115.9998	173.5818	60.0433	50.5784	525.578
11	525.00	1542.29	199.3598	129.7187	191.5947	65.0000	60.6732	585.673
12	550.00	1692.83	210.0000	140.3232	203.0684	65.0000	68.3916	618.392
13	565.00	1790.31	210.0000	149.3786	213.1806	65.0000	72.5593	637.559
14	540.00	1631.14	206.4181	135.7654	198.1330	65.0000	65.3164	605.316
15	500.00	1403.58	187.6719	120.0075	180.6753	65.0000	53.3547	553.355
16	450.00	1272.36	177.7448	110.2517	167.6296	47.2719	47.8056	497.806
17	425.00	1202.43	171.0717	104.6263	161.5425	34.9309	44.9668	469.967
18	400.00	1129.41	162.8330	99.3084	154.8655	25.0763	41.5045	441.504
19	375.00	1065.51	156.3108	94.0640	148.1700	15.0000	38.5448	413.545
20	340.00	987.97	147.8847	87.5720	139.4476	.0000	34.9047	374.905
21	300.00	844.34	129.5941	74.9665	122.1136	.0000	26.6752	326.675
22	250.00	695.70	107.1651	60.3184	100.6085	.0000	18.0925	268.092
23	200.00	582.97	78.0853	60.0000	71.9680	.0000	10.0532	210.053
24	180.00	548.37	66.7569	60.0000	60.8011	.0000	7.5580	187.558

Total cost of generation 25673.18
No of iterations 9
Total water used 17557.33 cu. ft.
Total water available for generation 17557.33 Cu.ft.

Table 3.11: Scheduling Including Losses

Hour NO	Demand MW	Cost Rs.	Thermal Generation P_1 MW	P_2 MW	P_3 MW	Hydro Generation Ph MW	transmission Loss MW	Total Generation MW
1	175.00	518.80	55.04	60.00	50.00	15.00	5.04	180.04
2	190.00	539.98	63.57	60.00	57.98	15.00	6.55	196.55
3	220.00	591.65	80.49	60.00	74.75	15.00	10.23	230.23
4	280.00	735.32	113.26	64.52	107.05	15.00	19.83	299.83
5	320.00	858.92	131.18	76.40	124.29	15.00	26.87	346.87
6	360.00	1004.72	149.40	89.08	141.64	15.00	35.13	395.13
7	390.00	1129.79	163.26	99.17	154.71	15.00	42.14	432.15
8	410.00	1221.14	172.60	106.20	163.43	15.00	47.23	457.23
9	440.00	1325.48	182.48	113.97	172.77	23.66	52.43	492.43
10	475.00	1428.26	190.94	121.61	181.74	38.49	56.89	531.89
11	525.00	1601.39	205.94	132.95	195.15	58.01	64.64	589.64
12	550.00	1692.83	210.00	140.32	203.07	65.00	68.39	618.39
13	565.00	1790.31	210.00	149.38	213.18	65.00	72.56	637.56
14	540.00	1631.14	206.42	135.77	198.13	65.00	65.32	605.32
15	500.00	1503.78	196.76	127.10	188.03	49.35	60.00	560.00
16	450.00	1354.47	184.93	116.15	175.35	27.85	53.714	503.71
17	425.00	1280.84	178.30	110.69	168.88	17.57	50.3710	475.37
18	400.00	1174.64	167.92	102.66	159.07	15.00	44.6466	444.65
19	375.00	1065.51	156.31	94.06	148.17	15.00	38.5448	413.55
20	340.00	928.93	140.25	82.64	132.95	15.00	30.8428	370.84
21	300.00	794.45	122.18	70.37	115.65	15.00	23.2011	323.20
22	250.00	656.56	97.88	60.00	91.97	15.00	14.8446	264 85
23	200.00	555.80	69.16	60.00	63.52	15.00	7.6811	207.68
24	180.00	525.53	58.03	60.00	52.49	15.00	5.5192	185.52

Total cost of generation Rs. 25910.24
Total water used for generation 17557.333 Cu. ft.
Total water available for generation 17557.333 Cu. ft.
Number of itearions 9

Table 3.12: Thermal Data

Plant No	Cost Coefficients				
	a_i	b_i	c_i	$Pmin_i$	$Pmax_i$
1	.002500	3.200000	25.000000	.0000	300.0000
2	.000800	3.400000	30.000000	.0000	700.0000

Table 3.13: Hydro Data

Plant No	Discharge Coefficients			Discharge Coefficients	
	α_i	β_i	γ_i	$P_{i_{min}}$	$P_{i_{max}}$
1	.000216	.306000	1.980000	.0000	400.0000
2	.000360	.612000	0.936000	.0000	300.0000

Table 3.14: Loss Coefficients - B

.0001400	.0000100	.0000150	.0000150
.0000100	.0000600	.0000100	.0000130
.0000150	.0000100	.0000680	.0000650
.0000150	.0000130	.0000650	.0000700

Water to be used for Hydro Plant No 1 = 2500 cu mt
Water to be used for Hydro Plant No 2 = 2100 cu mt

Table 3.15: Hydrothermal Scheduling Including Transmission Losses

Hour NO	Demand MW	Cost Rs.	Thermal Generation p_1 MW	P_2 MW	Hydro Generation Ph_1 MW	Ph_2 MW	transmission Loss MW	Total Generation MW
1	400.0	797.37	77.51	136.59	168.54	23.00	5.632	405.632
2	300.0	573.44	61.19	90.22	148.49	3.41	3.244	303.244
3	250.0	445.49	52.30	62.69	137.44	.00	2.357	252.357
4	250.0	445.49	52.30	62.69	137.44	.00	2.357	252.357
5	250.0	445.49	52.30	62.69	137.44	.00	2.357	252.357
6	300.0	573.44	61.19	90.22	148.49	3.41	3.244	303.244
7	450.0	914.73	85.42	161.00	178.21	32.46	7.087	457.087
8	900.0	2048.85	158.02	384.55	266.98	119.08	28.630	928.630
9	1230.0	2975.17	212.98	553.09	334.21	184.40	54.711	1284.711
10	1250.0	3034.04	216.36	563.44	338.35	188.41	56.589	1306.589
11	1350.0	3333.24	233.35	615.41	359.14	208.55	66.504	1416.504
12	1400.0	3485.90	241.91	641.54	369.61	218.68	71.795	1471.795
13	1200.0	2887.46	207.92	537.60	328.02	178.40	51.960	1251.960
14	1250.0	3034.04	216.36	563.44	338.35	188.41	56.589	1306.589
15	1250.0	3034.04	216.36	563.44	338.35	188.41	56.589	1306.589
16	1270.0	3093.23	219.75	573.80	342.49	192.43	58.501	1328.501
17	1350.0	3333.24	233.35	615.41	359.14	208.55	66.504	1416.504
18	1470.0	3703.13	253.94	678.30	384.34	232.93	79.584	1549.584
19	1330.0	3272.75	229.94	604.98	354.97	204.51	64.450	1394.450
20	1250.0	3034.04	216.36	563.44	338.35	188.41	56.589	1306.589
21	1170.0	2800.47	202.87	522.14	321.85	172 41	49.286	1219.286
22	1050.0	2459.53	182.81	460.65	297.31	148.58	39.357	1089.358
23	900.0	2048.85	158.02	384.55	266.98	119.08	28.630	928.630
24	600.0	1276.97	109.33	234.75	207.44	61.03	12.553	612.553

total cost of generationm 53050.39
Total water to be available for plant 1 2500.0
total water used for Generation by plant 1 2500.0
Total water to be available for plant 2 2100.0
total water used for Generation by plant 2 2100.031
No of iteations 18

Table 3.16: Thermal Gas Coordination - Input Data

Plant Type	Cost Coefficients			Bounds	
Thermal	a	b	c	Pmin	Pmax
	1.2E-3	5.1	120.0	50.0	500.0
	Consumption Coefficients			Bounds	
Gas	e	f	g	pmin	pmax
	0.0025	6	300.0	50.0	400.0

Fuel Cost for Gas = Rs 2/ccf(where 1 ccf=$10^3 ft^3$)
The Gas is rated at 1100 Btu/ft^3
Total Gas to Be Used = $40x10^6$ Cu ft

Table 3.17: Result at the End of First Iteration

Sr.No.	Demand MW.	$P_{thermal}$ MW	P_{gas} MW	Remark
1	400.0	224.13	175.87	Duration of each demand is 4 hrs.
2	650.0	381.7873	268.2127	
3	800.0	476.384	323.616	
4	500.0	287.2	212.8	
5	200.0	98.0	102.0	
6	300.0	161.07	138.93	

Cost Multiplier σ = 0.821538461
Total Gas to Be Used = 40 x 10^6 Cu ft
Total Gas Consumed = 21 x 10^6 Cu ft
Cost of Generation by Thermal Plant = Rs 38699.32
Cost of Generation by Gas Plant = Rs 80000
Total Cost Of Generation = Rs 118699.32

Table 3.18: Result at The End of 6^{th} Iteration

Sr.No.	Demand MW.	$P_{thermal}$ MW	P_{gas} MW	Remark
1	400.0	197.348	202.652	
2	650.0	353.21	296.79	duratio of
3	800.0	446.727	353.273	each demand
4	500.0	259.693	240.307	is 4 hrs.
5	200.0	72.658	127.342	
6	300.0	131.003	168.997	

At the end of 6^{th} Iteration, the converged values are as follows.
Cost Multiplier $\sigma = 0.794727$
Total Gas consumed = 40 x 10^6 Cu ft
Cost of Generation of thermal Plant = Rs 34938.60
Cost of generation of gas plant = Rs 80000.00
Total cost of generation = Rs 114938.60

Table 3.19: Mix Generation System Scheduling Input Data

Plant Type	Cost Coefficients			Bounds	
Thermal	a	b	c	P_{min}	P_{max}
1	0.01	0.01	100.0	50.0	200.0
2	0.02	0.1	120.0	25.0	150.0
3	0.01	0.2	150.0	40.0	200.0
	Consumption Coefficients			Bounds	
Gas	e_g	f_g	g_g	$pmin_g$	$pmax_g$
1	0.025	6.0	300.0	50.0	400.0
	Discharge Coefficients			Bounds	
Hydro	e_h	f_h	g_h	$pmin_h$	$pmax_h$
1	0.06	20.0	140.0	25.0	100.0

Gas is Rated at 1100 Btu/cu ft
Fuel Cost for Gas = Rs. 2/ccf(where 1 ccf $=10^3 ft^3$)
Available Volume of Gas = 50 x 10^6 cu ft
Water Available = 40,000 cu ft

Table 3.20: Mix Generation System Scheduling

Sr.No.	Demand	Thermal Gen			Gen Gas	Hydro Gen	Remark
		P_1	P_2	P_3	P_g	P_h	
e	MW	MW	MW	MW	MW	MW	
1	400.0	102.65	51.32	97.65	117.31	31.06	duration of each demand is 4 hours.
2	600.0	114.72	57.36	109.72	264.97	53.23	
3	750.0	123.77	61.88	118.77	375.72	69.84	
4	900.0	162.00	81.00	157.00	400.00	100.00	
5	800.0	129.70	64.85	124.70	400.00	80.74	
6	500.0	108.68	54.34	103.68	191.14	42.14	

Cost Multiplying Factors: $\alpha_g = 0.32668$; $\alpha_h = 0.0907414$
Total Gas Consumed = 49.996 x 10^6 cu ft
Total water Used = 39994 Cu ft
Total Cost Of Generation = Rs 18991.41

Table 3.21: Mix Generation System Scheduling Including Trans Losses

Hour	Demand MW	Trans Losses MW	Thermal Gen.			Hydro Gen	Gen(gas)
			P_1 MW	P_2 MW	P_3 MW	P_h MW	P_g MW
1	600.00	10.77	173.91	85.06	165.16	28.62	158.01
2	650.00	12.42	178.71	87.38	169.71	34.03	192.57
3	700.00	14.22	183.54	89.71	174.27	39.49	227.19
4	750.00	16.19	188.39	92.06	178.85	44.98	261.89
5	800.00	18.30	193.27	94.41	183.44	50.51	296.66
6	850.00	20.58	198.17	96.77	188.05	56.08	331.49
7	880.00	22.02	201.12	98.19	190.82	59.44	352.43
8	900.00	23.02	203.09	99.14	192.67	61.69	366.40
9	910.00	23.52	204.08	99.62	193.59	62.81	373.39
10	955.00	25.99	211.80	103.30	200.87	65.00	400.00
11	980.00	27.50	222.76	108.48	211.24	65.00	400.00
12	1090.00	35.47	250.00	160.46	250.00	65.00	400.00
13	980.00	27.50	222.76	108.48	211.24	65.00	400.00
14	900.00	23.02	203.09	99.14	192.67	61.69	366.40
15	870.00	21.54	200.13	97.72	189.89	58.32	345.45
16	840.00	20.11	197.19	96.30	187.12	54.96	324.52
17	800.00	18.30	193.27	94.41	183.44	50.51	296.66
18	780.00	17.44	191.31	93.47	181.60	48.30	282.74
19	700.00	14.22	183.54	89.71	174.27	39.49	227.19
20	750.00	16.19	188.39	92.06	178.85	44.98	261.89
21	700.00	14.22	183.54	89.71	174.27	39.49	227.19
22	660.00	12.77	179.67	87.85	170.62	35.12	199.49
23	650.00	12.42	178.71	87.38	169.71	34.03	192.57
24	600.00	10.77	173.91	85.06	165.16	28.62	158.01

Input Data Is Same as Earlier Sample Example of Mix Generation System
Water utilised 31000.000 cu. ft
Water avilable 31000.000 cu ft.
Gas Consumed 50x10^6
Gas Avialable 50x10^6 cu. ft.
No. Of Iterations 8
σ_h= .1543621
σ_g .5250523
Thermal cost of generation Rs 32857.32
Gas cost Rs 100000.00
Total cost of generation Rs 132857.32

3.12 Conclusion

In this Chapter, an attempt is made to estimate generation scheduling of a mix-generation system. First, a simple technique is developed for hydro-thermal scheduling using dispatch algorithm developed in Chapter 2. Further, using equivalent cost function criteria, a critical load level is calculated above which hydrothermal coordination will be economical. The same technique is then extended for thermal gas coordination and lastly the problem is generalized as a scheduling problem of mix-generation system. These exercises lead to following observations.

(1) For fixed head hydro plants having quadratic discharge function, hydrothermal dispatch can be estimated using scheduling method developed in Chapter 2 (Tables 3.4 and 3.15).

(2) Comparing results from Tables 3.7 and 3.8, the cost of hydrothermal scheduling using hydro plants at appropriate hours is less than its counterpart.

(3) This procedure is also useful for thermal-gas coordination. The example attempted here is the same as given by Wood et al.[8] who solved the problem by gradient technique. However, our results by DP match very closely with those of Wood et al.

(4) Lastly, a successful attempt is made to obtain a solution of scheduling of mix generation system.