Power Systems Operation and Control

Lecture 6

Hydrothermal Power Plant Scheduling

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Lecture learning outcomes:

At the end of this lecture, you will be able to:

i. Understand the principle of hydrothermal scheduling.

ii. Knows the short and long term hydrothermal scheduling

iii. Formulates the mathematical modeling for hydrothermal scheduling

iv. Knows solution techniques for hydrothermal scheduling

Content

1. **Introduction**
2. **Importance of Hydrothermal Unit**
3. **Short and Long-Term Hydrothermal scheduling**
4. **Mathematical modeling for Hydro-thermal**
5. **Solution Techniques for Hydrothermal scheduling**

Summary

References

1. Introduction

- Hydrothermal scheduling is the practice of optimizing hydroelectric power generation in conjunction with thermal power facilities.
- This scheduling is critical for guaranteeing an efficient and consistent energy supply, particularly in systems that use both hydro and thermal resources.
- The goal of hydrothermal scheduling is to calculate the ideal generation levels for both hydroelectric and thermal units over a specific time period, which might range from **hours to days**.
- **This entails balancing the variable availability of hydro resources**: dependent on water input and reservoir levels with the more stable but typically less flexible output of thermal facilities, which use fossil fuels or nuclear energy.

Introduction Cont.…

Key factors in hydro-thermal scheduling include:

- Efficiently utilizing available water while considering ecological and regulatory constraints.
- Reducing overall generation costs by optimizing the dispatch of generation units based on fuel prices and operational characteristics.
- Forecasting electricity demand to ensure that supply meets consumption requirements.
- Maintaining grid stability by considering contingencies and ensuring that generation meets load demand during normal operation, outages or peak periods.

Introduction Cont.…

- Accordingly, hydro-thermal coordination is critical for the proper operation of energy systems that generate both hydroelectric and thermal power by considering the following significant factors:
- **Cost Efficiency**, making better use of hydroelectric resources, utilities can minimize their reliance on more expensive thermal generating, cutting total operating costs. This is especially important during times of high demand, when fuel costs for thermal plants can increase.
- **Reliability and Stability**: Coordinating hydroelectric and thermal generation improves system reliability.
- By carefully deploying these resources, utilities may better adapt to swings in electricity demand and unanticipated outages, assuring a consistent supply.

Introduction Cont….

- **Sustainability**: Hydro-thermal coordination encourages the use of renewable energy sources while lowering greenhouse gas emissions and the environmental impact of fossil fuel consumption.
- **Water Resource Management**: Effective coordination enables better management of water resources, such as maximizing reservoir levels and ensuring that hydroelectric power is consistent with ecological concerns and regulatory limits.
- Peak Shaving: Hydro plants can swiftly increase generation during peak demand periods, allowing thermal units to operate more efficiently.
- This reduces the need for peaking thermal plants, which are typically less efficient and more expensive to operate.

2. Importance of Hydrothermal Unit

- The majority of the first electrical power plants were thermal ones. **The following reasons make the construction of hydroelectric plants necessary:**
- Because of the increase in power demand for the load from all sources, including as domestic, commercial, agricultural, and industrial.
- Because fuel (coal) is expensive.
- Because of the fuel's restricted range.
- The hydropower plants are simple to start and can be given a load in a relatively short period of time.
- In thermal plants, a number of hours are needed to make the ready-to-use boilers, super heaters, and turbine systems the weight.
- Thus, the hydro-plants are able to manage efficiently changing loads quickly.

Importance Cont……

- Therefore, the maximum advantage of **cheap hydro-power** should be taken so that the coal reserves can be conserved and environmental pollution can be minimized.
- In a hydrothermal system, the whole or a part of **the base load** can be supplied by the run-off river hydro-plants and the peak or the remaining load is then met by a proper coordination of reservoir-type hydro-plants and thermal plants.
- The operating cost of thermal plants is very high and at the same time its capital cost is low when compared with a hydro-electric plant.
- The operating cost of a hydro-electric plant is low and its capital cost is high such that it has become economical as well as convenient to run both thermal as well as hydro-plants in the same grid.
- The hydro-thermal scheduling is presented in Fig.1:

Importance Cont……

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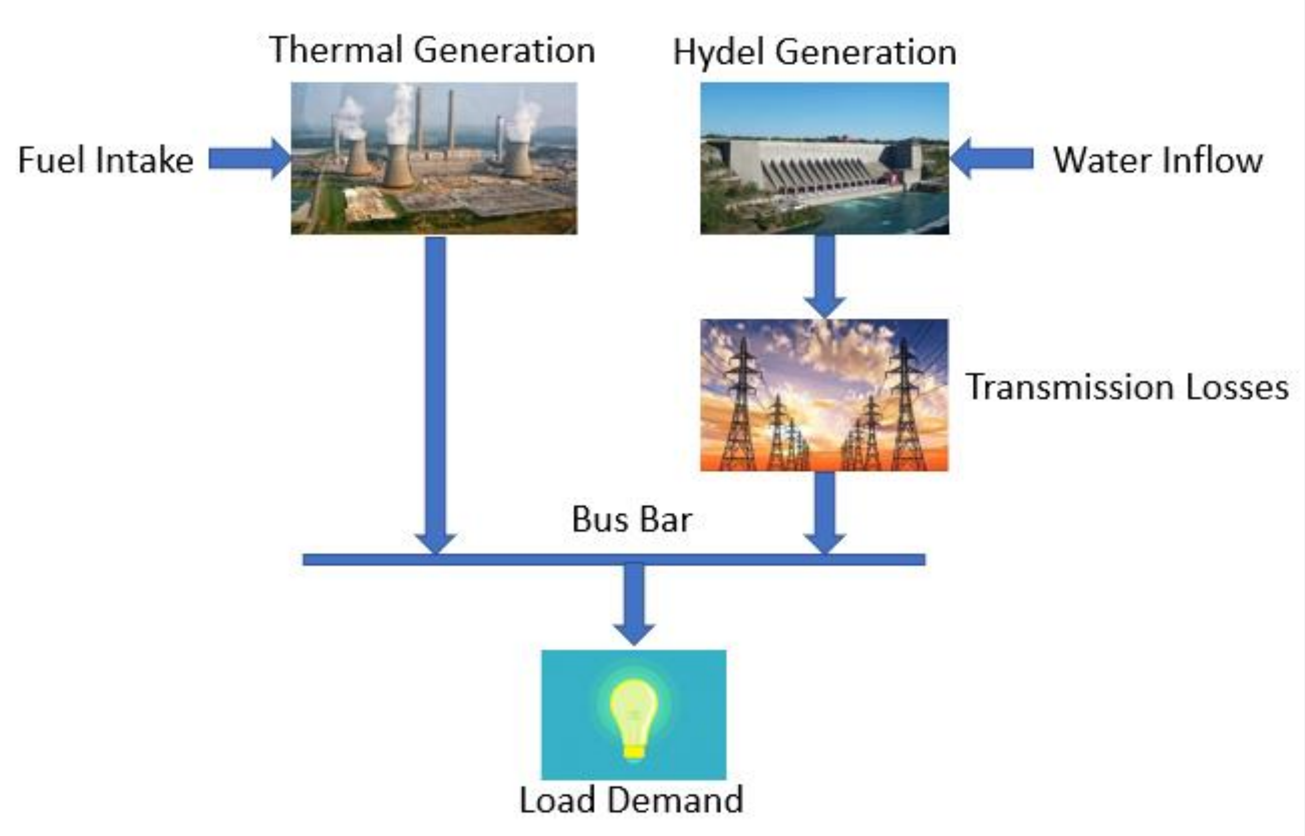

Figure 1: Hydrothermal Unit Operation

[Url: https://www.researchgate.net/profile/Akhtar-Rasool-5/publication/333795299/figure/fig1/AS:769877115670529@1560564416397/Generation-model-of-the-Short-Term-Hydrothermal-Scheduling-STHTS-problem-25.ppm](https://www.researchgate.net/profile/Akhtar-Rasool-5/publication/333795299/figure/fig1/AS:769877115670529@1560564416397/Generation-model-of-the-Short-Term-Hydrothermal-Scheduling-STHTS-problem-25.ppm)

Importance Cont……

- The optimal scheduling problem in a hydro-thermal system can be stated as to minimize the fuel cost of thermal plants under the constraint of water availability for hydro-generation over a given period of operation.
- Consider a simple hydro-thermal system, shown in Fig. 1, which consists of one hydro and one thermal plant supplying power to load connected at the center in between the plants and is referred to as the fundamental system.
- Which increases the overall reliability of the power and reduces the operation cost of thermal power plant

3. Short and Long-Term Hydrothermal scheduling

Short-term hydro-thermal Scheduling[1]:

- Real-time Dispatch: This involves making immediate decisions (usually on a daily or hourly basis) to determine which power plants should generate electricity based on current demand forecasts, fuel prices, and availability of water
- Unit Commitment: Deciding which specific generating units (both hydro and thermal) will be operational and at what levels within the next few hours or days. This decision considers factors such as production costs, operational constraints, and environmental regulations.
- Load Ensuing: Adjusting the output of power plants in real-time to match fluctuations in electricity demand throughout the day.
- Market Participation: In deregulated markets, energy scheduling also involves participating in energy markets to optimize revenues through selling excess generation or purchasing

additional power when needed.

Short and Long-Term Cont.….

Long-term Energy Scheduling[2]:

- Capacity Expansion Planning: Making decisions on adding new generation capacity (either hydro or thermal) based on long-term forecasts of energy demand growth, regulatory changes, and technological advancements.
- Fuel Procurement Strategy: Planning the procurement of fuels (like coal, natural gas, or biomass) for thermal plants over longer time horizons, considering factors such as price volatility, availability, and environmental regulations.
- Maintenance Scheduling: Planning scheduled maintenance and overhauls of power plants to ensure reliability and efficiency over their operational lifetimes.
- Investment Decisions: Evaluating investments in renewable energy sources or energy storage technologies to improve system flexibility and resilience.

Short and Long-Term Cont.….

Key Considerations:

- Hydrological Conditions: Availability of water for hydroelectric plants can vary seasonally and annually, impacting both short-term dispatch and long-term capacity planning.
- Fuel Costs: Fluctuations in fuel prices (e.g., natural gas prices) can significantly influence short-term dispatch decisions and long-term investment planning.
- Regulatory Environment: Compliance with environmental regulations, such as emissions limits and renewable energy targets, shapes both short-term operational decisions and long-term investment.
- Technological Advances: Advances in renewable energy technologies, energy storage systems, and grid management software can influence both short-term dispatch strategies and long-term investment decisions.

Short and Long-Term Cont.….

The economic operation of a combined hydro-thermal system, short or long depends on:

- Load cycle.
- Incremental fuel costs of thermal power stations.
- Expected water inflow in hydro-power stations.
- Water head that is a function of water storage in hydro-power stations.
- Hydro-power generation.
- Incremental transmission loss (ITL).

Short and Long-Term Cont.….

The following are the few important methods for short-term hydro-thermal co-ordination:

- Constant hydro-generation method.
- Constant thermal generation method.
- Maximum hydro-efficiency method.
- Kirchmayer’s method.

Constant hydro-generation: a scheduled amount of water at a constant head is used such that the hydro-power generation is kept constant throughout the operating period.

Short and Long-Term Cont.….

- Constant thermal generation: Thermal power generation is kept constant throughout the operating period in such a way that the hydro-power plants use a specified and scheduled amount of water and operate on varying power generation schedules during the operating period.
- Maximum hydro-efficiency: **during peak load periods**, the hydropower plants are operated at their maximum efficiency; during off-peak load periods they operate at an efficiency nearer to their maximum efficiency with the use of a specified amount of water for hydro-power generation.

4. Mathematical modeling for Hydro-thermal

- Mathematical modeling of long-term hydro-thermal coordination involves developing frameworks to optimize the operation and planning of hydro and thermal power resources over extended time horizons.
- This typically requires balancing multiple objectives, such as minimizing costs, maximizing reliability, and ensuring environmental sustainability[3].

Objective Function:

- **Cost Minimization**: The primary objective often involves minimizing the total generation cost, which includes operational costs of thermal plants, maintenance costs, and potentially environmental costs.

Decision Variables:

- Generation levels for hydroelectric and thermal units over the planning horizon.
- Water release from reservoirs for hydro plants.
- Operational status of thermal plants (on/off).

Mathematical modeling Cont.…

Constraints:

- Supply-Demand Balance: Ensuring that total generation meets forecasted electricity demand at all time
- Reservoir Management: Constraints related to water inflow, reservoir capacity, and minimum/maximum water levels.
- Thermal Unit Limits: Restrictions on minimum and maximum generation capacities for thermal units.
- Environmental Regulations: Compliance with environmental standards, including flow requirements for aquatic ecosystems.
- **Time Periods: The** planning horizon can be divided into time periods (e.g., hours, days, months) to account for seasonal variations in water availability and demand patterns.

Mathematical modeling Cont.…

Objective Function:

- The objective of OPF is usually to minimize the total generation cost, which can be expressed as:

$$Min \ \ F(P) = \sum_{i=1}^{N} C_i(P_i)$$

- Where, C_i (P_i) is the cost function of generator i, which is a quadratic function, $P_{(i)}$ is the power output of generator i and N is the total number of generators.

The costs typically minimized include:

- Generation Costs: The cost of electricity produced by power plants, which can be represented as a function of generation levels (usually quadratic functions).

Mathematical modeling Cont….

For mathematical formulation, the following assumptions must be made for a given time of operation T (a day, a week, or a year):

- Storage of a hydro-reservoir at the beginning and end of the duration of operation T is determined.
- After accounting for irrigation, water inflow to the reservoir and system load demand may be calculated deterministically as functions of time with certainties.
- The optimization goal here is to find the water discharge rate q(t) that minimizes the cost of thermal generating.
- Objective function is: $$Min\ C_T = \int_{i=1}^{t} C(P_{Gi}) \partial t$$ eqn.(1)

s.t:

a. The real power balance equation: eqn.(2)

$$P_{GH}(t) + P_{GT}(t) = P_D(t) + P_L(t)$$

$$\Leftrightarrow P_{GH}(t) + P_{GT}(t) - P_D(t) - P_L(t) = 0, t \in (0,T)$$

Mathematical modeling Cont.…

b. Water availability equation: $X^{'}(t)-X^{'}(0)-\int_{0}^{T}J(t)\partial t+\int_{0}^{T}q(t)\partial t=0$ eqn.(3)

- Where, the water storage at time t is denoted by X'(t), the water storage at the start of operation time T by X'(0), and the water storage at the end of operating time by X'(T), the water intake rate is J(t), and the water discharge rate is q(t)

c. Real power hydro-generation

- The real power generation P_{GH}(t) is a function of water storage X′(t) and water discharge rate q(t) as given by:

$$P_{GH}(t)=f(X'(t),q(t))$$ eqn.(4)

Mathematical modeling Cont.…

- The discretization concept makes it simple to answer the issues in equations (3) and (4).
- N equal sub-intervals of Δt time duration are created from the optimization interval T.
- It is assumed that the values of all variables stay the same during each sub-interval. For thermal power plants, the same formula may thus be recast as follows for N intervals:

$$Min \quad q^k = \sum_{k=1}^{N} C_{GT}{}^k(t)$$

eqn.(5)

Subject to the constraints:

- Power balance constraints:

$$P_{GT}^K + P_{GW}^K - P_D^K - P_L^K = 0$$

eqn.(6)

Mathematical modeling Cont.…

- Water availability equation:

$$X'^{K} - X'^{(K-1)} - j^{K} * \Delta t + q^{K} * \Delta t = 0 \qquad \text{eqn.(7)}$$

- where j is the water inflow rate during interval K, q is the water discharge rate during interval K, and X′ is the water storage at the conclusion of interval K.

- Then, dividing the equation 7, by the change in "t" yields

$$X^{K} - X^{(K-1)} - j^{K} + q^{K} = 0 \qquad \text{eqn.(8)}$$

Where, $X^{K} = \frac{X'^{K}}{\Delta t}$ the water storage in discharge unit.

Mathematical modeling Cont.…

d. The real power hydro-generation in any sub-interval can be written as:

$$P_{GH}^{K} = h_0\{1 + 0.5e(X^{K} + X^{K-1})\} * (q^{k} - \rho)$$ eqn.(9)

Where, $h_0 = 9.81 * 10^{-3} * h_0^{'}$

- Where, ρ is the non-effective discharge that is necessary for a hydro generator to operate at no-load conditions, e is the water head correction factor to account for the fluctuation in head with storage, and h'$_0$ ′ is the basic water head that corresponds to dead storage. Then, the above equation can be rewritten as: $$P_{GH}^{K} = 9.81 * 10^{-3} h_{av}^{K}(q^{K} - \rho)MW$$ eqn.(10)
- Where, $(q^{K} - \rho)$ is the effective discharge in m^3/s at interval K and h_{av}^{K} is the average head in kth interval as given by:

Mathematical modeling Cont.…

- Where, A is the reservoir cross-section at the given interval

$$h_{av}^{K} = h_0^{'} + \frac{\Delta t(X^{K} + X^{K-1})}{2A}$$ eqn.(11)

$$h_{av}^{K} = h_0^{'}(1 + 0.5e(X^{K} + X^{K-1})$$ eqn.(12)

- Where, $e = \frac{\Delta t}{Ah_0^{'}}$ then, the hydropower equation can be rewritten as:

$$P_{GH}^{K} = h_0\{1 + 0.5e(X^{K} + X^{K-1})\}(q^{K} - \rho)$$ eqn.(13)

- where $h_0 = 9.81 \times 10^{-3} h_0'$

Mathematical modeling Cont.…

- The optimization problem is mathematically stated for any sub-interval ‘K ’ by the objective function given by Equation (5), which is subjected to equation constraints given by Eqns. 6, 8 and 9.
- In the above optimization problem, it is convenient to choose water discharges in all sub-intervals except one sub-interval as independent variables and hydro-generations, thermal generations, water storages in all sub-intervals and except water discharge as dependent variables;
- Independent variables are represented by q^K , for $K = 2, 3, \ldots, N$ and for $K \neq 1$.
- Dependent variables are represented by P^K_{GH} , P^K_{GT} ,X^K , and q^1, for $K = 1, 2, \ldots, N$.

Mathematical modeling Cont.…

- Then, for K=1, 2…..N), eqn.(8), water availability can be rewritten as:

$$X^1 - X^0 - j^1 + q^1 = 0, \; for \;\; K = 1$$

$$X^2 - X^1 - j^2 + q^2 = 0, \; for \;\; K = 2$$

.

$$X^N - X^{N-1} - j^N + q^N = 0, \; for \;\; K = N^{th} \,\mathrm{int}\, erval$$

eqn.(14)

By adding them, we can get:

$$X^N - X^0 - (j^1 + j^2 + ... j^N) + (q^1 + q^2 + ...q^N) = 0$$

$$or, X^N - X^0 - \sum_{K=1}^{N} j^K + \sum_{K=1}^{N} q^K = 0$$

eqn.(15)

Mathematical modeling Cont.…

- It is observed that for K = 2, 3, …, N, there are (N – 1) number of water discharges (q’s), which can be specified as independent variables.
- The remaining one, i.e., q^1, is specified as a dependent variable and it can be determined from Eqn.15 as:

$$q^1 = X^0 - X^N + \sum_{K=1}^{N} j^K - \sum_{K=2}^{N} q^K \qquad \text{eqn.(16)}$$

Which, the discharge of water for the 1st interval

5. Solution Techniques for Hydrothermal scheduling

- In order to solve the optimization problem in a hydro-thermal system, the first-order gradient method is combined with a non-linear programming technique[4].
- By defining the Lagrangian function by supplementing the objective function presented in Eqn.(5), while satisfying the inequality constraints of hydropower, thermal power plants based on the above equation gives the optimal solution.
- In addition, the equality constraints of demand satisfaction should be also considered.
- Other constraints like transmission line losses should be also taken into account.

Solution Technique Cont.….

- Thus, considering the operation time to be T, let us divide into intervals 1,2,….N to suit the load curve so that $$\sum_{j=1}^{N} n_j = T$$ eqn.(17)
- The equality constraint for the total volume of water available for discharge over this period is:

eqn.(18)

$$\sum_{j=1}^{N} n_j w_j - W = 0$$

where w_j is the water rate for interval j

- The fuel cost required to be minimized over this period T is given as

$$\sum_{j=1}^{N} n_j C(P_{TGj}) = C_T$$ eqn.(19)

- For load balance assuming loads are constant during this interval and head of water is also remain constant, the equality constraint is

Solution Technique Cont…..

- The Lagrange function for minimization subject to the above constraints is

$$L(P_{TG},P_{HG},\lambda,\gamma)=\underbrace{\sum_{j=1}^{N} n_j C(P_{SGj})}_{\text{Objective function}}-\underbrace{\sum_{j=1}^{N}\lambda_j\left(P_{TGj}+P_{HGj}-P_{Dj}\right)}_{\text{Power balance constraint}}-\underbrace{\gamma\left(\sum_{j=1}^{N} n_j w_j(P_{HGj})-W\right)}_{\text{Water balance constraint}} \qquad \text{eqn.(20)}$$

- For any specific value of *j*, the necessary conditions are

$$\begin{aligned}\frac{\partial L(.)}{\partial P_{SGj}}&=0\\ \frac{\partial L(.)}{\partial P_{HGj}}&=0\end{aligned} \quad\Longrightarrow\quad \begin{aligned} n_j\frac{\partial C_{Sj}}{\partial P_{SGj}}&=\lambda_j\\ \gamma n_j\frac{\partial w_j}{\partial P_{HGj}}&=\lambda_j\end{aligned} \qquad \text{eqn.(21)}$$

- Solution to the above equations gives the economic generations at steam and hydro plants over any time interval.
- The incremental production cost at the steam plants must be the same as incremental production cost at the hydro plants.

Summary

- In this lecture, the hydroelectric and thermal generation, hydro-thermal scheduling is discussed well.
- Thus, the inflow and its discharge rate limitation with discretization process for economic operation of power system is discussed.
- In line with, the cost function of thermal power flow, specifically the quadratic form of fuel cost minimization while combining with reliable operation of power generation is discussed.
- In addition, the importance of hydropower in terms of meeting peak load demand is also mentioned
- The mixing of thermal power plant, specifically, to minimize the operation cost of thermal power plant and the investment cost of hydropower plant is discussed.
- Finally, the lagarangian equation is also discussed

References

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Thank you !