

Power Systems Operation and Control

Lecture 7

Hydrothermal-Renewable Energy (RE) Generations Scheduling

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Lecture learning outcomes:

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

- i. Understand the importance of Hydrothermal-RE operations.
- ii. Knows the importance of RE-mix with the traditional hydrothermal units
- iii. Develop the mathematical modeling of hydrothermal-RE mixes for optimal operations
- iv. Knows the optimization methods to solve the hydrothermal-RE mixes.

Content

1. Introduction
2. Contribution of RE sources to the traditional hydrothermal scheduling
3. Economic Operation of Hydrothermal, Wind & Solar power Plants
4. Mathematical modeling of Hydro-thermal, wind and Solar
5. Solution Techniques for Hydrothermal-RE scheduling

Summary

References

1. Introduction

- Hydrothermal-renewable energy generation scheduling is one of the modern energy combination that comprises the natural energy resources and man-made engineering approach's[1].
- It involves the optimization of hydrothermal and RE systems, where water, RE and geothermal energy come together to create a sustainable power solution
- The aim is to have reliable and sustainable energy solutions while optimizing the resources like the fuel cost of thermal units, ensuring water availability for hydro, utilizing the wind speed efficiently for wind-power, optimizing solar power generation and etc.
- Generally, it enhances the availability of power supply with variety options while mitigating the seasonality problems

Introduction

Cont....

- Furthermore, the flexibility and efficiency of the system as a whole is improved by combining hydrothermal energy with the renewable resources like solar or wind.
- This integration is analogous to gathering a super soccer-team of heroes, each with special abilities to win always, means to fight the evil forces of fossil fuel dependence through RE resources.
- However, scheduling hydrothermal-renewable energy generation seeks special attentions since mixing energy resources[2] , which needs strategic operational planning, technological innovation, and natural resources managements.
- Choices needs, special attention of economic operation for better satisfaction of the demands while maintaining overall system reliability.

2. Contribution of RE to Traditional Hydrothermal Scheduling

- Mixing the renewable energy (RE) sources into traditional hydrothermal scheduling significantly enhance the efficiency and sustainability of energy generation as given by[3]:

a. Diversification of Energy Mix: the energy mix-refers to the integration of various energy sources to create a balanced and sustainable energy set.

- It helps to reduce dependence on a single energy source, enhances energy security, and minimizes environmental impact.
- The energy mix includes the operation of different power plants having different input or resources to generate electrical energy as given by:

Contribution of RE sources

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1. Renewable Energy: Solar, wind, hydro, geothermal, and biomass.
2. Non-Renewable Energy: Natural gas, coal, oil, and nuclear power.
2. Emerging Technologies: Hydrogen, energy storage solutions, and advanced nuclear.

The general benefits of mixing these diverse energy resources are:

- Ensures energy security while reducing the vulnerability of supply shortage and price volatility.
- Enhances positive environmental and societal impact by reducing greenhouse gas emissions and pollution.
- Maintains economic stability by encouraging the job creation in various sectors and lead to lower energy costs.

Contribution of RE sources

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- Enhances operational flexibility, by supplying electricity during periods of high demand, renewables can lessen the requirement for costly peak-load thermal power.
- Maintains the load balancing, energy resources like hydroelectric facilities are able to quickly modify their production in order to balance the intermittent RE resources like solar and wind power.
- Provides improved grid stability like: hydro and modern RE resources easily works together to supply essential grid services, maintaining the voltage and frequency stability.
- Ensures better energy Storage, power plants like hydroelectric power has the ability to store excess renewable energy and use it during periods of high demand, which means the seasonality problem can be easily mitigated.

Contribution of RE sources

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- However, the economic operation of hydrothermal-RE is essential as there are a number of difficulties while integrating renewable energy into the grid such as:
 - Maintaining the demand-driven power or maintaining energy conservation
 - Reducing the overall operational costs.
 - lowering emissions is a component of this issue.
- Thus, the integration of RE into the grid has made it more challenging to meet demand at the lowest possible cost, and power consumption has increased significantly in recent decades.
- Therefore, Hydro, thermal, and renewable energy source (RES) mix is one of the often employed tactics, which needs economic operation.

3. Economic Operation of Hydrothermal, Wind & Solar power Plants(EOHTWS)

- The grid mix from hydrothermal, solar and wind is the most common energy mix in recent world.
- The economic operation of these plants, (hydro, thermal, wind, and solar) involves optimizing the operation of these power generation sources to meet demand while minimizing costs.
- The simple economic operation of grid mix from these energy resources is presented in Fig.1.
- Hydro provides flexibility and respond quickly to demand changes, which can provide auxiliary services like frequency regulation.
- The scheduling requires: water availability, reservoir levels, seasonal flow variations, and ecological impacts.
- Different optimization techniques can be adopted by operators to determine how much water to release for generation.

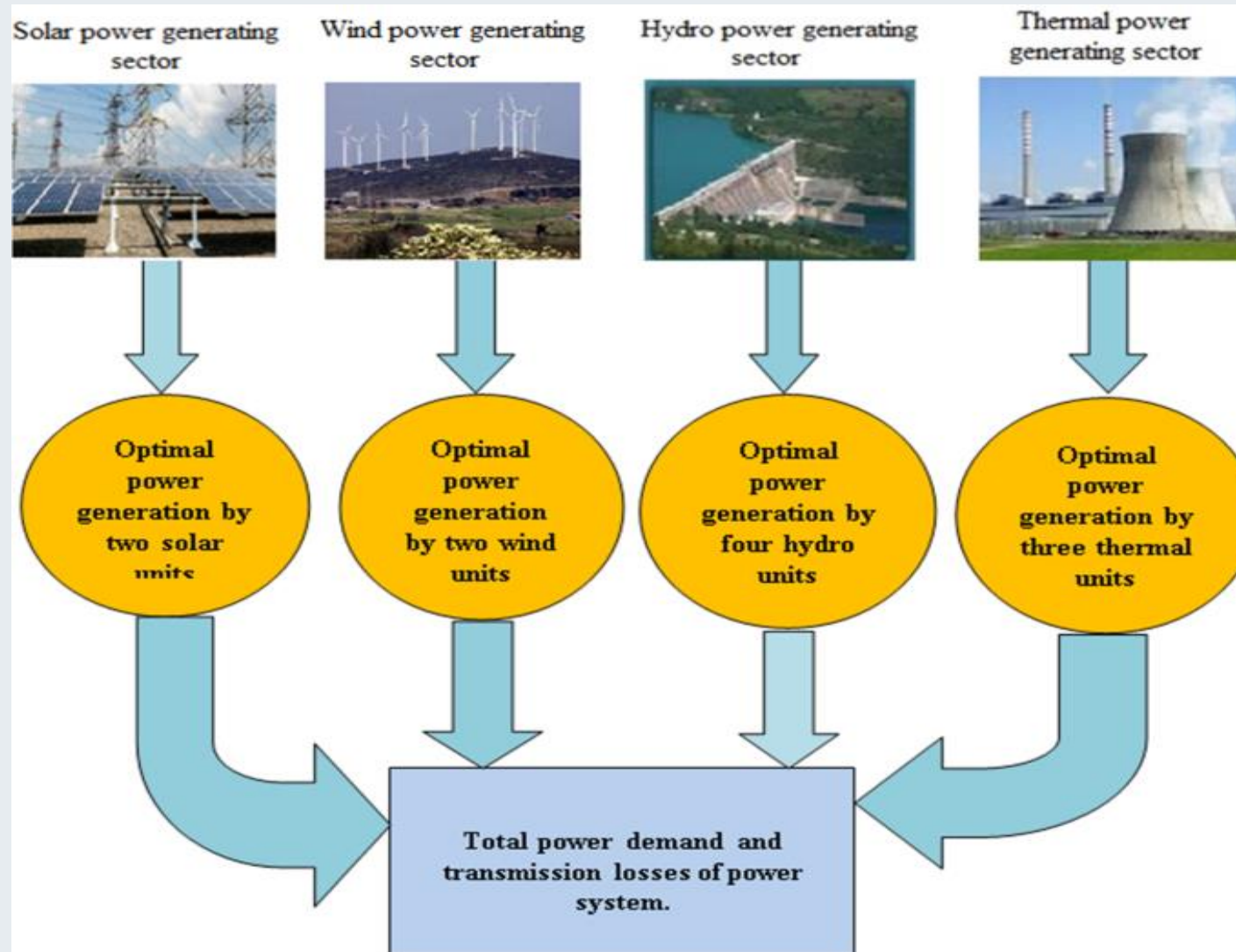


Figure 1. Hydrothermal, solar and Wind energy Mix

url: https://media.springernature.com/lw685/springer-static/image/art%3A10.1007%2Fs00500-023-09315-1/MediaObjects/500_2023_9315_Fig1_HTML.png

- On other hands, the thermal Power plant provides reliable power for base load.
- The thermal power plants ramps (ramps up or down), but not as quickly as hydro.
- Its scheduling needs the reduction of fuel cost, timing maintenance, and startup/shutdown costs.
- ED, UC or OPF are used to minimize these overall costs by determining which plants to run and at what output.
- Besides this, the mixing of wind power to the grid provides further reduction in operational costs as it's RE though it's highly variable and depends on weather conditions.
- Its scheduling needs better wind forecasts, knowledge of grid capacity, and the impact of wind speed volatility while integrating with other energy sources through stochastic approaches.

- The solar power is also enhances the comparative advantage of increasingly cost-competitive, specifically during day time while peak generation occurs.
- The scheduling needs an insightful knowledge in solar forecasts, grid demand, and storage options.
- Economic scheduling for solar often involves time-of-use pricing and demand response strategies to align generation with demand.
- For the grid mix in Fig.1, the strategies like UC, ED, OPF and others can be adopted
- Finally, enhanced modeling and optimization is needed for using energy storage, better demand responses, and grid enhancements to balance variable renewable energy sources with load .

4. Mathematical Modeling of Hydro-thermal, wind and Solar

- Mathematical modeling for the economic operation of hydro-thermal, wind, and solar power needs for formulating optimization problems that account for the unique characteristics of each generation source.

Objective Function:

- **Cost Minimization:** The primary objective often involves minimizing the total generation cost, which includes the costs of thermal, hydro, wind and solar, maintenance costs, and emission costs as given by:

$$\text{Min}(C) = \sum_{i=1}^N C_i(P_i) + C_{startup} + C_{fuel} + C_{Penalty} \quad \text{eqn.(1)}$$

- Where, $C_i(P_i)$, $C_{start-up}$, C_{Fuel} and $C_{penalty}$ are the cost of each plant, starting up, fuel cost and the penalty cost for not meeting the demand and emissions, respectively

- The decision variables are crucial for optimizing the operational performance of each plant and cost reduction as given by:

1. Hydro-Thermal Systems:

- Power Generation Levels (P_H , P_T): The output power from hydro and thermal plants.
- Water Storage Levels (S): The amount of water available in reservoirs for hydro generation.
- Dispatch Order: The scheduling of which plants to operate and when.
- Fuel Consumption (F): The amount of fuel used in thermal generation.
- Cost Variables: Operational and maintenance costs for both hydro and thermal plants.

2. Wind Energy Systems:

- Power Output (P_w): The generated power from wind turbines based on wind speed as given in eqn.2.

$$P_w = \frac{1}{2} \rho A C_p V^3 \quad \text{eqn.(2)}$$

- Turbine operation status: Whether each turbine is ON or OFF.
- Decision variables related to the location of wind farms, site selection.
- The efficiency of wind turbines, affected by wind speed and design, capacity factor should be known .
- Maintenance scheduling, timing for routine maintenance to minimize downtime.

3. Solar Energy Systems:

- Power Output (P_S), the energy produced by solar panels based on solar irradiance is as a function of:

$$P_S = \eta_{sol} * A_{sol} * S_{irradiance} \quad \text{eqn.(3)}$$

- Decision on panel orientation and tilt angle, the angle of solar panels to maximize sunlight capture.
- The amount of energy stored in batteries for later use.
- Grid Interaction, decisions on energy fed into or drawn from the grid.
- Operation and Maintenance (O&M) Costs, costs associated with the upkeep of solar facilities.

4. The common decision Variables

- Market Pricing, pricing decisions based on supply and demand.
- Emissions Levels, If applicable, to meet regulatory requirement.
- Investment Decisions, costs related to new installations or upgrades.

The overall optimization target is:

- Minimize costs (fuel, maintenance, etc.), maximize reliability and availability of power supply.
- Balance renewable and non-renewable generation.
- Reduce carbon emissions and comply with regulations.

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 plant limits**, restrictions on minimum and maximum generation capacities for thermal units.
- **Environmental regulations**, compliance with environmental standards, including flow requirements for aquatic ecosystems.
- **Wind and solar generation**, these are typically modeled as functions of forecasted output , which is;

$$P_W = f(W_{forecast}), \quad P_S = g(S_{forecast}) \quad \text{eqn.(4)}$$

- **Time Periods**, the planning horizon can be divided into time periods to account for seasonal variations in water availability and demand patterns.

- **Specific Considerations for each source are:**

Hydro-Thermal Systems:

- **Seasonal Variations:** Model water inflows and thermal generation capacity over different seasons to account for hydro reservoir levels and fuel availability.
- **Daily Operations:** Schedule hourly dispatch to balance load and manage reservoir levels.

Wind Power Plants:

- Intermittency: capture hourly variations in wind speed and generation capacity, as wind resources can be highly variable.
- Seasonal trends: Analyze monthly wind patterns to optimize turbine operation and maintenance.

Solar power plants:

- Daily Solar Cycles: Focus on hourly generation profiles based on sunlight availability, considering seasonal shifts in solar irradiance.
- Long-Term Trends: Evaluate annual data to assess performance and degradation of solar panels over time.

4.1 Modeling of wind power

- In general, wind speed is the dominant factor that can affect how much power is generated and needs to be carefully modeled .
- Since, wind does not always move at the same speed, the wind energy produced might not always be enough to meet demand that needs careful attention
- Because of this, the cost function used to determine the cost of wind power generation has taken into account both overestimation and underestimation components of wind power.
- when the wind energy produced is less than electricity needed, buying power from other generating sources makes up for the power lag.

Modeling of wind power

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- This kind of expense is known as the wind power generating over-estimated cost ($W_{COVE,j,Z}$).
- Under-estimated cost ($W_{CUNE,j,Z}$) is the term used to describe the occasional overproduction of wind power.
- The overestimated and underestimated cost functions are shown in eqns.5 and 6, respectively[4].

$$W_{Cove,j,Z} = w_{j,Z} * C_{Ove,j} [1 + \exp(-(\frac{V_{lout,j}}{K_{fj}})^{K_{hj}}) - \exp(-(\frac{V_{lin,j}}{K_{fj}})^{K_{hj}})] \quad \text{eqn.(5)}$$

$$+ (\frac{w_{r,j} V_{lin,j}}{V_{elrj} - V_{elin,j}} + w_{j,Z}) [\exp(-(\frac{V_{lin,j}}{K_{fj}})^{K_{hj}}) - \exp(-(\frac{(V_{lin,j} * w_{r,j} - w_{j,Z} (V_{lr,j} - V_{lin,j}))}{K_{fj} * w_{r,j}})^{K_{hj}})]$$

$$+ \frac{w_{r,j} * S_{fj}}{V_{lr,j} - V_{lin,j}} \{ \Gamma[1 + \frac{1}{K_{hj}} ((\frac{V_{lin,j} * w_{r,j} - w_{j,Z} (V_{lr,j} - V_{lin,j}))}{K_{fj} * w_{r,j}})^{K_{hj}}] - \Gamma[1 + \frac{1}{K_{hj}} (\frac{V_{lin,j}}{K_{fj}})^{K_{hj}}] \}$$

$$W_{Cune,j,Z} = (w_{r,j} - w_{j,Z}) * C_{Une,j} [\exp(-(\frac{V_{lr,j}}{K_{fj}})^{K_{hj}}) - \exp(-(\frac{V_{lot,j}}{S_{fj}})^{K_{hj}})] \quad \text{eqn.(6)}$$

$$+ (\frac{w_{r,j} V_{lin,j}}{V_{r,j} - V_{in,j}} + w_{j,Z}) [\exp(-(\frac{V_{lr,j}}{K_{fj}})^{K_{hj}}) - \exp(-(\frac{(V_{lin,j} * w_{r,j} - w_{j,Z} (V_{lr,j} - V_{lin,j}))}{K_{fj} * w_{r,j}})^{K_{hj}})]$$

$$+ \frac{w_{r,j} * S_{fj}}{V_{lr,j} - V_{lin,j}} \{ \Gamma[1 + \frac{1}{K_{hj}} ((\frac{V_{lin,j} * w_{r,j} - w_{j,Z} (V_{lr,j} - V_{lin,j}))}{K_{fj} * w_{r,j}})^{S_{hj}}] - \Gamma[1 + \frac{1}{K_{hj}} (\frac{V_{lr,j}}{K_{fj}})^{K_{hj}}] \}$$

Modeling of wind power

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- Where, $V_{lin,j}$, $V_{lout,j}$ and $V_{lr,j}$ represents the cut-in, cut-off and rated speeds of wind, $w_{r,j}$ and $w_{j,Z}$ are rated and generated power of wind, and K_{fj} & K_{hj} are the scale factor and shape factor, respectively.
- Since the generated power should feed the demand, the power feed or purchased from the wind the satisfy the demand is given by ;

$$W_{Cdir,j,Z} = W_{j,Z} * g_i \quad \text{eqn.(7)}$$

- Where , $W_{Cdir j,Z}$ and g_j are the direct cost and cost coefficient of j^{th} wind generators
- Then, the total cost function of Wind generator is given by:

$$C(P_W) = \sum_{Z=1}^h \sum_{j=1}^{G_W} (W_{Cove j,Z} + W_{Cune j,Z} + W_{Cdir j,Z}) \quad \text{eqn.(8)}$$

4.2 Mathematical Formulation for PV-System

- Solar power is created by converting the solar radiation, directly or diffusely, through the atmosphere to electrical energy[5].

- The power generated from solar plants is determined using ;

$$P_s = \frac{S_i * P_{rated}}{1000} [1 + \alpha(T_{ref} - T_{amb})] \quad \text{eqn.(9)}$$

- Where, P_{rated} , S_i , α , T_{ref} and T_{amb} are the rated power, solar radiation incident, temperature coefficient, rated temperature and ambient temperature, respectively
- Generation limit constraint is considered for solar power generating units, which is 30% of demand power (PD) may be generated using solar units.

- Generating limit of solar power is shown in;

$$\sum_{i=1}^{G_s} P_{Si} * D_{Si} \leq 0.3 * P_D$$

eqn.(10)

- D_{Sj} denotes the validity of solar power Plant at ON or OFF state

- Then, the generation cost of solar panel is given by;

$$C(P_S) = \sum_{i=1}^{GS} (P_{uCosti} * P_{Si} * D_{Si})$$

eqn.(11)

- Where, $P_{uCost,i}$ is the per unit cost of i^{th} solar power plant
- Then, the overall mathematical cost can be represented as their summation.

4.3 Mathematical modeling of thermal Power Plant

Objective Function:

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

$$\text{Min } F(P) = \sum_{i=1}^N C_i(P_i) \quad \text{eqn.(12)}$$

- 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 include:

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

4.4 Mathematical modeling Hydropower

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 & RE generations.

• Objective function is:
$$\text{Min } C_T = \int_{i=1}^t C(P_{Gi}) \partial t \quad \text{eqn.(13)}$$

s.t:

a. The real power balance equation: eqn.(14)

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

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

Mathematical modeling hydropower

Water availability equation: $X'(t) - X'(0) - \int_0^T J(t) \partial t + \int_0^T q(t) \partial t = 0$ eqn.(15)

- 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:

$$P_{GH}(t) = f(X'(t), q(t)) \quad \text{eqn.(16)}$$

Mathematical modeling

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- The discretization concept makes it simple to answer the issues in equations (15) and (16).
- 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 and RE plants, the same formula may thus be recast as follows for N intervals:

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

eqn.(17)

Subject to the constraints:

- Power balance constraints:

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

eqn.(18)

- Water availability equation:

$$X'^K - X'^{(K-1)} - j^K * \Delta t + q^K * \Delta t = 0 \quad \text{eqn.(19)}$$

- 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 19, by the change in "t" yields

$$X^K - X^{(K-1)} - j^K + q^K = 0 \quad \text{eqn.(20)}$$

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

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

$$P_{GH}^K = h_0 \{1 + 0.5e(X^K + X^{K-1})\} * (q^k - \rho) \quad \text{eqn.(21)}$$

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:

$$P_{GH}^K = 9.81 * 10^{-3} h_{av}^K (q^K - \rho) MW \quad \text{eqn.(22)}$$

- Where, $(q^K - \rho)$ is the effective discharge in m^3/s at interval K and h_{av}^K is the average head in k^{th} interval as given by:

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

$$h_{av}^K = h_0' + \frac{\Delta t(X^K + X^{K-1})}{2A} \quad \text{eqn.(23)}$$

$$h_{av}^K = h_0' (1 + 0.5e(X^K + X^{K-1})) \quad \text{eqn.(24)}$$

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

$$P_{GH}^K = h_0 \{1 + 0.5e(X^K + X^{K-1})\} (q^K - \rho) \quad \text{eqn.(25)}$$

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

- The optimization problem is mathematically stated for any sub-interval 'K' by the objective function g given which is subjected to constraints .
- 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 $K = 2, 3, \dots, N$ and for $K \neq 1$.
- Dependent variables are represented by P_{GH}^K , P_{GT}^K , X^K , and q^1 , for $K = 1, 2, \dots, N$.

- Then, for $K=1, 2, \dots, N$, eqn.(20), water availability can be rewritten as:

$$X^1 - X^0 - j^1 + q^1 = 0, \text{ for } K = 1$$

$$X^2 - X^1 - j^2 + q^2 = 0, \text{ for } K = 2$$

.

$$X^N - X^{N-1} - j^N + q^N = 0, \text{ for } K = N^{\text{th}} \text{ interval}$$

eqn.(26)

By adding them, we can get:

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

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

eqn.(27)

- It is observed that for $K = 2, 3, \dots, N$, 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.28 as:

$$q^1 = X^0 - X^N + \sum_{K=1}^N j^K - \sum_{K=2}^N q^K \quad \text{eqn.(28)}$$

Which, the discharge of water for the 1st interval

5. Solution Techniques for Hydrothermal-RE scheduling

- In order to solve the optimization problem in a hydro-thermal -RE system, the first-order gradient method is combined with a non-linear programming technique.
- By defining the Lagrangian function by supplementing the objective function, 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

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- Thus, considering the operation time to be T, let us divide into intervals 1,2,...N to suit the load curve s

o that

$$\sum_{j=1}^N n_j = T \quad \text{eqn.(29)}$$

- The equality constraint for the total volume of water available for discharge over this period is:

$$\sum_{j=1}^N n_j w_j - W = 0 \quad \text{eqn.(30)}$$

where w_j is the water rate for interval j

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

$$\sum_{j=1}^N n_j C(P_{TGj}) = C_T \quad \text{eqn.(31)}$$

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

Solution Technique

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

$$L(P_{TG}, P_{HG}, P_{WG}, P_{SG}, \lambda, \gamma, \gamma', \gamma'') = \underbrace{\sum_{j=1}^N n_j C(P_{SGj})}_{\text{Objective function}} - \underbrace{\sum_{j=1}^N \lambda_j ((P_{TGj} + P_{HGj} + P_{Wj} + P_{Sj}) - P_{Dj})}_{\text{Power balance constraint}} - \underbrace{\gamma \left(\sum_{j=1}^N n_j w_j (P_{HGj}) - W \right)}_{\text{Water balance constraint}} - \underbrace{\gamma' \left(\sum_{j=1}^N n_j V_j (P_{Wj}) - P_{W,r} \right)}_{\text{Wind balance constraint}} + \underbrace{\gamma'' \left(\sum_{j=1}^N n_j S_{in,j} (P_{Sj}) - P_{S,r} \right)}_{\text{Irradiance balance constraint}} \quad \text{eqn.(32)}$$

For any specific value of j , the necessary conditions are

$$\begin{aligned} \frac{\partial L(.)}{\partial P_{TGj}} = 0 & \qquad \qquad \qquad n_j \frac{\partial C_{Sj}}{\partial P_{TGj}} = \lambda_j \\ \frac{\partial L(.)}{\partial P_{HGj}} = 0 & \qquad \qquad \qquad \gamma n_j \frac{\partial w_j}{\partial P_{HGj}} = \lambda_j \\ \frac{\partial L(.)}{\partial P_{WGj}} = 0 & \qquad \qquad \qquad \gamma' n_j \frac{\partial w_j}{\partial P_{WGj}} = \lambda_j \\ \frac{\partial L(.)}{\partial P_{SGj}} = 0 & \qquad \qquad \qquad \gamma'' n_j \frac{\partial w_j}{\partial P_{SGj}} = \lambda_j \end{aligned} \quad \text{eqn.(33)}$$

- Solution to the above equations gives the economic generations at Thermal, hydro , wind and solar plants over any time interval.

Summary

- It is observed that mixing of hydrothermal power plant with RE enhances, the overall system reliability and maintain power continuity.
- The presented lecture note also reveals that there are several advantage of mixing different energy resources like operational cost reduction, providing grid stability and hence reduces the dependence on fossil fuel that results in environmental pollutions.
- Accordingly, mixing energy resources has positive environmental and societal impacts
- It is also noted that effective and efficient mathematical modeling of each power plant is needed while integrating them into a single unit.
- Thus, the decision, state and control variables for each power unit needs to be identified for proper operation of the grid mix.
- Finally, the overall objective function (multi-objective function) is developed for the grid mix while considering different equality and inequality constraints

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Thank you !