POWER SYSTEM OPERATION AND CONTROL

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UNIT-1

Economic Operation of Power Systems

Power System Economic Operation

- Different generation technologies vary in the:
  - capital costs necessary to build the generator
  - fuel costs to actually produce electric power

- For example:
  - nuclear and hydro have high capital costs and low operating costs.
  - Natural gas generators have low capital costs, and (with gas available from fracking) moderate operating costs.

Power System Economic Operation

- Fuel cost to generate a MWh can vary widely from technology to technology.

- For some types of units, such as hydro, “fuel” costs are zero but the limit on total available water gives it an implicit value.

- For thermal units it is much easier to characterize costs.

- We will focus on minimizing the variable operating costs (primarily fuel costs) to meet demand.

Power System Economic Operation

- Power system loads are cyclical.
- Therefore the installed generation capacity is usually much greater than the current load.
- This means that there are typically many ways we could meet the current load.
- Since different states have different mixes of generation, we will consider how generally to minimize the variable operating costs given an arbitrary, specified portfolio of generators.

Thermal versus Other Generation

- The main types of generating units are thermal and hydro, with wind and solar rapidly growing.

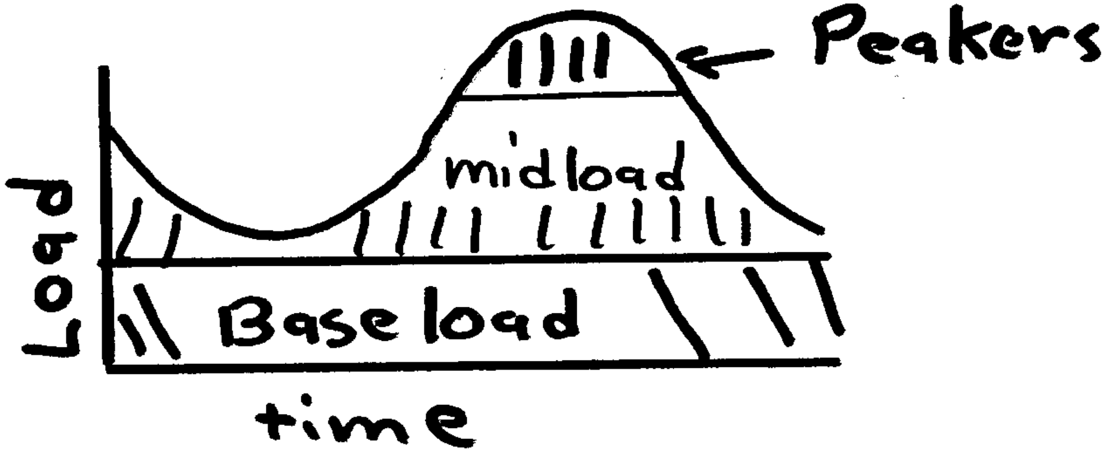
- For hydro the fuel (water) is free but there may be many constraints on operation:
  - fixed amounts of water available,
  - reservoir levels must be managed and coordinated,
  - downstream flow rates for fish and navigation.

- Hydro optimization is typically longer term (many months or years).

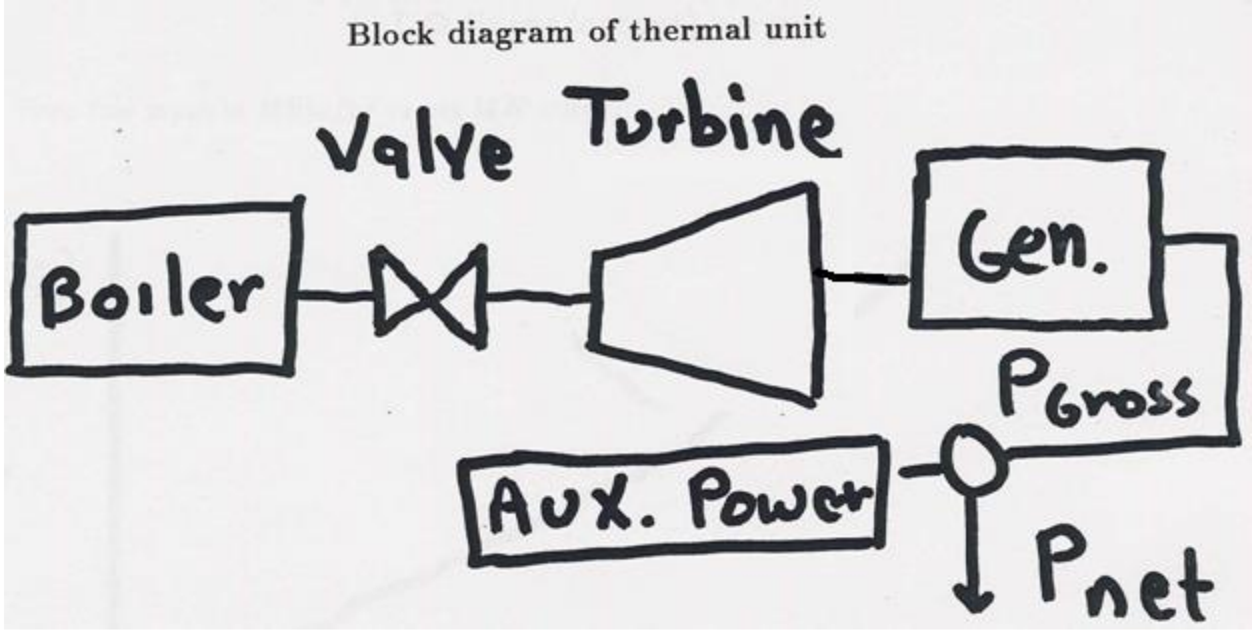
- We will concentrate on dispatchable thermal units, looking at short-term optimization:
  - Non-dispatchable wind and solar can be incorporated by subtracting from load.

Generator types

- Traditionally utilities have had three broad groups of generators:
  - “Baseload” units: large coal/nuclear; almost always on at max.
  - “Midload,” ‘intermediate,” or “cycling” units: smaller coal or gas that cycle on/off daily or weekly.
  - “Peaker” units: combustion turbines used only for several hours. during periods of high demand



Block Diagram of Thermal Unit



- To optimize generation costs we need to develop cost relationships between net power out and operating costs.

- Between 2-10% of power is used within the generating plant; this is known as the auxiliary power.

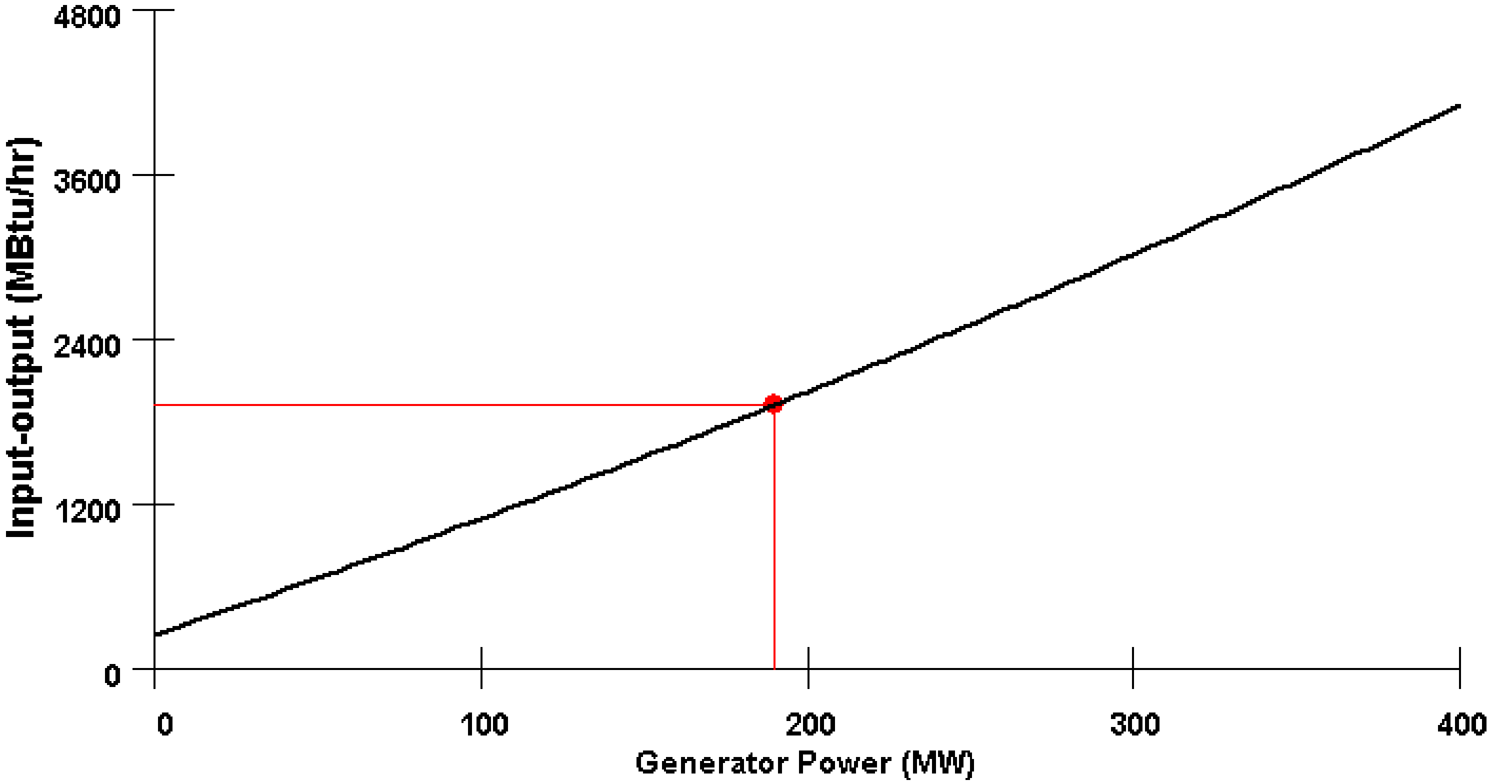
Thermal generator Cost Curves

- Thermal generator costs are typically represented by one or other of the following four curves
  - input/output (I/O) curve
  - fuel-cost curve
  - heat-rate curve
  - incremental cost curve

- For reference
  - 1 Btu (British thermal unit) = 1054 J
  - 1 MBtu = 1x10^6 Btu
  - 1 MBtu = 0.29 MWh

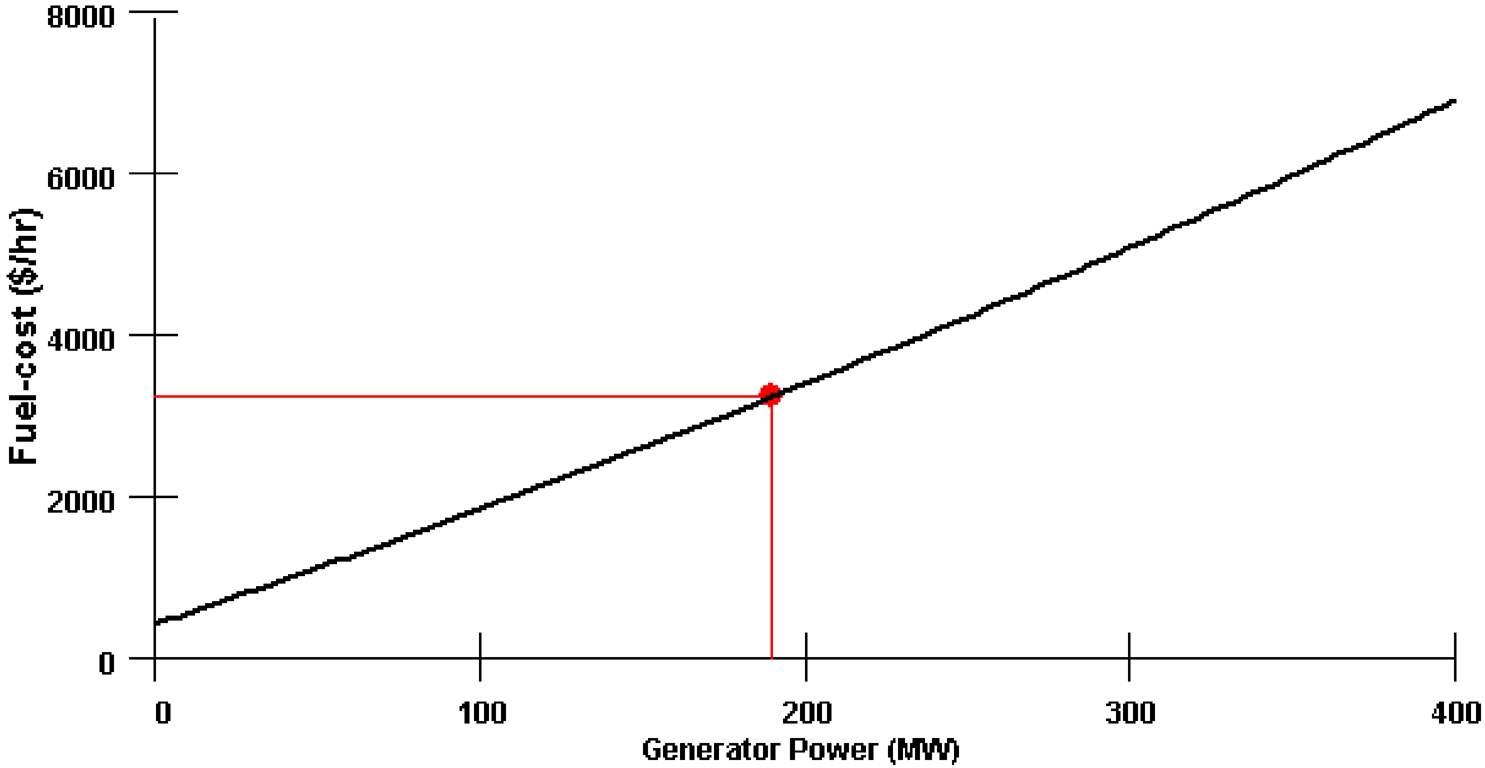
I/O Curve

- The IO curve plots fuel input (in MBtu/hr) versus net MW output.



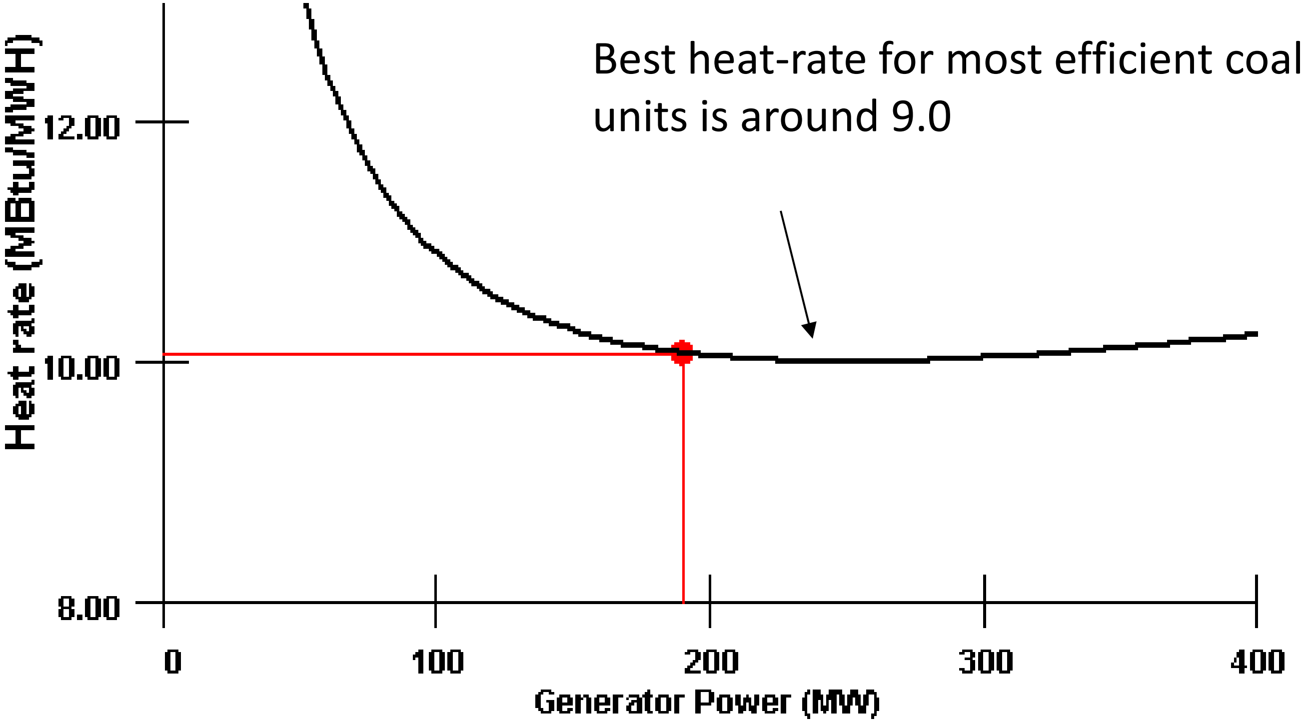
Fuel-cost Curve

- The fuel-cost curve is the I/O curve multiplied by fuel cost.
- A typical cost for coal is $ 1.70/MBtu.



Heat-rate Curve

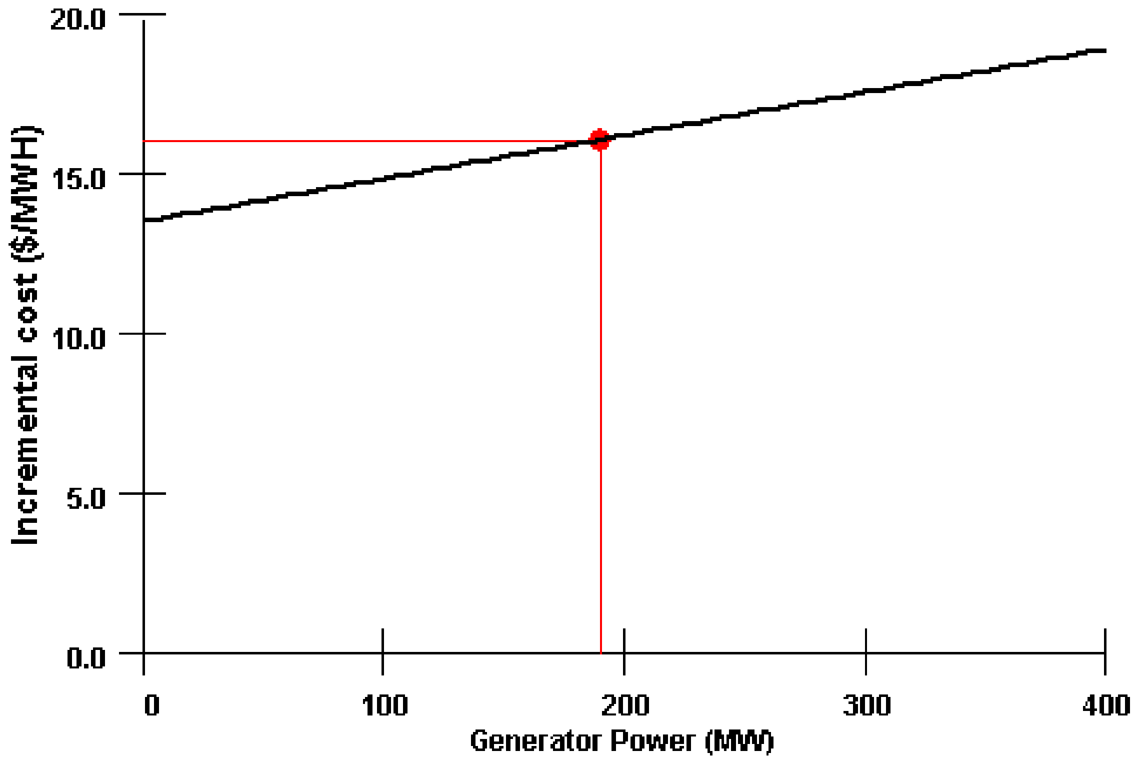
- Plots the average number of MBtu/hr of fuel input needed per MW of output.
- Heat-rate curve is the I/O curve divided by MW.



Best heat-rate for most efficient coal units is around 9.0

Incremental (Marginal) cost Curve

- Plots the incremental $/MWh as a function of MW.
- Found by differentiating the cost curve.



Mathematical Formulation of Costs

- Generator cost curves are usually not smooth. However the curves can usually be adequately approximated using piece-wise smooth, functions.

- Two approximations predominate:
  - quadratic or cubic functions
  - piecewise linear functions

- We'll assume a quadratic approximation:

$$C_i(P_{Gi}) \quad = \quad \alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2 \quad \text{\$/hr (fuel-cost)}$$

$$IC_i(P_{Gi}) \; = \; \frac{dC_i(P_{Gi})}{dP_{Gi}} = \beta_i + 2\gamma_i P_{Gi} \qquad \text{\$/MWh}$$

Coal Usage Example

- A 500 MW (net) generator is 35% efficient. It is being supplied with coal costing \$1.70 per MBtu and with heat content 9000 Btu per pound. What is the coal usage in lbs/hr? What is the cost?

At 35% efficiency required fuel input per hour is

$$\frac{500\text{ MWh}}{\text{hr}\times 0.35}=\frac{1428\text{ MWh}}{\text{hr}}\times\frac{1\text{ MBtu}}{0.29\text{ MWh}}=\frac{4924\text{ MBtu}}{\text{hr}}$$

$$\frac{4924\text{ MBtu}}{\text{hr}}\times\frac{1\text{ lb}}{0.009\text{MBtu}}=\frac{547{,}111\text{ lbs}}{\text{hr}}$$

$$\text{Cost}=\frac{4924\text{ MBtu}}{\text{hr}}\times\frac{\$1.70}{\text{MBtu}}=8370.8\text{ \$/hr or \$16.74/MWh}$$

Wasting Coal Example

- Assume a 100W lamp is left on by mistake for 8 hours, and that the electricity is supplied by the previous coal plant and that transmission/distribution losses are 20%. How much coal has he/she wasted?

With 20% losses, a 100W load on for 8 hrs requires 1 kWh of energy. With 35% gen. efficiency this requires

$$\frac{1\ \text{kWh}}{0.35} \times \frac{1\ \text{MWh}}{1000\ \text{kWh}} \times \frac{1\ \text{MBtu}}{0.29\ \text{MWh}} \times \frac{1\ \text{lb}}{0.009\text{MBtu}} = 1.09\ \text{lb}$$

Incremental Cost Example

For a two generator system assume

$$C_1(P_{G1}) = 1000 + 20P_{G1} + 0.01P_{G1}^2 \text{ \$/hr}$$

$$C_2(P_{G2}) = 400 + 15P_{G2} + 0.03P_{G2}^2 \text{ \$/hr}$$

Then

$$IC_1(P_{G1}) = \frac{dC_1(P_{G1})}{dP_{G1}} = 20 + 0.02P_{G1} \text{ \$/MWh}$$

$$IC_2(P_{G2}) = \frac{dC_2(P_{G2})}{dP_{G2}} = 15 + 0.06P_{G2} \text{ \$/MWh}$$

Incremental Cost Example, cont'd

If $P_{G1} = 250$ MW and $P_{G2} = 150$ MW Then

$$C_1(250) \;=\; 1000 + 20 \times 250 + 0.01 \times 250^2 \;= \$\,6625/\text{hr}$$

$$C_2(150) \;=\; 400 + 15 \times 150 + 0.03 \times 150^2 \;=\; \$6025/\text{hr}$$

Then

$$IC_1(250) = \;20 + 0.02 \times 250 \;= \$\,25/\text{MWh}$$

$$IC_2(150) = \;15 + 0.06 \times 150 \;= \$\,24/\text{MWh}$$

UNIT-2

Hydrothermal Scheduling

Introduction

From an overall systems view, the single most important attribute of hydroelectric plants is that there is no fuel cost, therefore production costs, relative to that of thermal plants, are very small.

There are three basic types of hydroelectric plants: run-of-river, pumped storage, and reservoir systems. We will just introduce the first two in this section, and then the remainder of these notes will be dedicated to understanding reservoir systems.

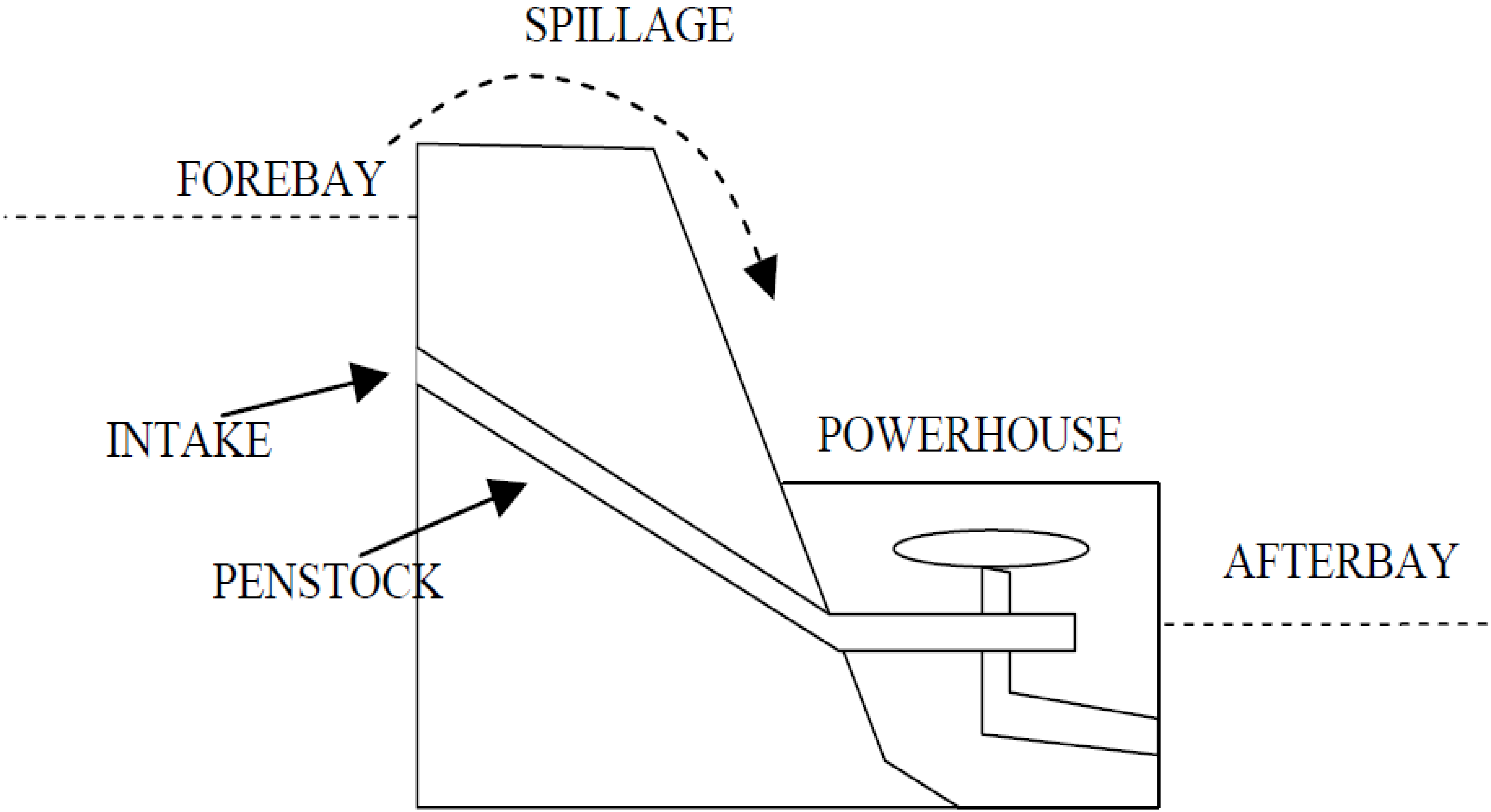
Hydro-Thermal Scheduling (HTS)

The goal of reservoir plant scheduling depends on the time frame of interest.

1. Long-range (weeks to year): Here we need the load forecast and expected water flow from a rainfall forecast. Then we can predict the energy availability from the hydro facilities and compute the necessary thermal energy.

2. Short-range (day to 1 week): Using results from (1) and more precise load and water information, we can formulate a problem where the solution yields the minimum cost of running the thermal plants on an hour-to-hour basis.

Hydro Station



Terminology

- Forebay: A lake or water impoundment (reservoir) before the entrance to the power plant.

- Afterbay: A lake or water impoundment downstream from the power plant that receives the water after it has passed through the turbines.

- Penstock: The pipe leading from the water intake to the turbine.

- Intake: The entrance from the forebay to the penstock.

- Spillage: releasing water over the dam rather than through the penstock. Some dams have spillways, as shown in Fig. 17, which allow smolts (adolescent salmon) to pass without transiting through the turbines.

UNIT-3

UNIT COMMITMENT

What is Unit Commitment:

- Unit commitment plans for best set of units to be available to supply the predicted or forecast load of the system over a future time period.
- "**Unit Commitment**" is therefore, one way to suggest, just sufficient number of generating units with sufficient amount of generating capacity to meet a given load economically with sufficient reserve capacity to meet any abnormal, operating condition.
- Here we consider the problem of scheduling fossil fired thermal units in which the aggregate costs(such as start up cost, operating fuel costs & shut down costs) are to be minimized over a daily load cycle.

Limitations of conventional unit commitment

- Some crew constraint are ignored.
- Exhausted combinations.
- Individual unit commitment is not considered.
- Unfeasible solutions.
- Ignoring physical feasibility of individual unit.

Difference between Economic Load Dispatch & Unit Commitment :

1. Economic Load Dispatch
    a) It’s a short term determination.
    b) Dispatch at lowest possible cost

1. Unit Commitment
    a) Unit commitment aims to make power system reliable

Dynamic Programming:

- We use “Dynamic programming” to solve Unit Commitment problem.

- Here we take an iterative relation embodying the principle that starting with given combination X_{i*} at stage k, the minimum unit commitment cost is found by minimizing the sum of the current single-stage cost $f_{ij}(k)$ plus the minimum cumulative cost $F_{ij}(k+1)$ over the later stages of study.

- This is one example of the *principle of optimality*, which states: if possible path from A to C passes through intermediate point B , then the best possible path from B to C must be corresponding part of the best path from A to C.

- Computationally, we evaluate one decision at a time beginning with the final stage N and carry the minimum cumulative cost function backward in time to stage k to find the minimum cumulative cost Fi*(k) for the feasible combination.

Contd.

- The minimum cumulative cost decisions are recovered as we sweep from stage 1 to stage N searching through the tables already calculated for each stage. This computational procedure is known as *Dynamic Programming*.[2]

- It involves *two* sweeps through each stage k.

- In the first sweep, which is computationally intensive, we work *backward* computing and recording for each candidate combination x_i of stage k the minimum $F_i(k)$ and its associated $x_j(k+1)$.

- The second sweep in the forward direction does not involve any processing since with $x_{i^*}(k)$ identified we merely enter the table of results already recorded to retrieve the value $F_{i^*}(k)$ and its associated combination $x_j(k+1)$, which becomes $x_{i^*}(k+1)$ as we move to next forward stage.

UNIT-4

LOAD FREQUENCY CONTROL

Introduction

- In an electric power system, **Load Frequency Control (LFC)** is a system to maintain reasonably uniform frequency, to divide the load between the generators, and to control the tie- line interchange schedules.

- The change in frequency is sensed when the rotor angle ∂ is changed.

- The error signals are transformed into real power command signal, which is sent to prime mover to call for an increment in the torque.

- The prime mover then brings change in the generator output by an amount which will change the values of within the specified tolerance.

Reasons for constant frequency

- The speed of the alternating current motors depends on the frequency of the power supply. There are situations where speed consistency is expected to be of high order.

- The accuracy of the electric clocks are dependent on the frequency of the supply.

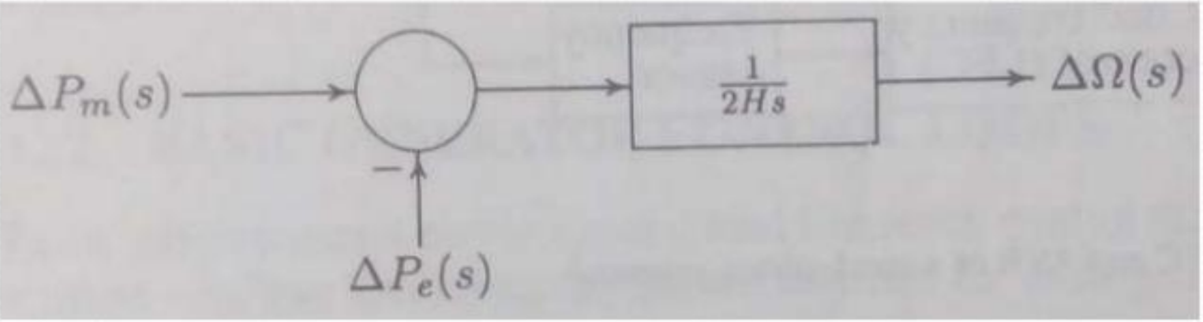
- If the normal frequency is 50 Hertz and the system frequency falls below 47.5 Hertz or goes up above 52.5 Hertz then the blades of the turbine are likely to get damaged so as to prevent the stalling of the generator .

- Due to the subnormal frequency operation the blast of the ID and FD fans in the power stations get reduced and thereby reduce the generation power in the thermal plants.

Various Modelings used in LFC

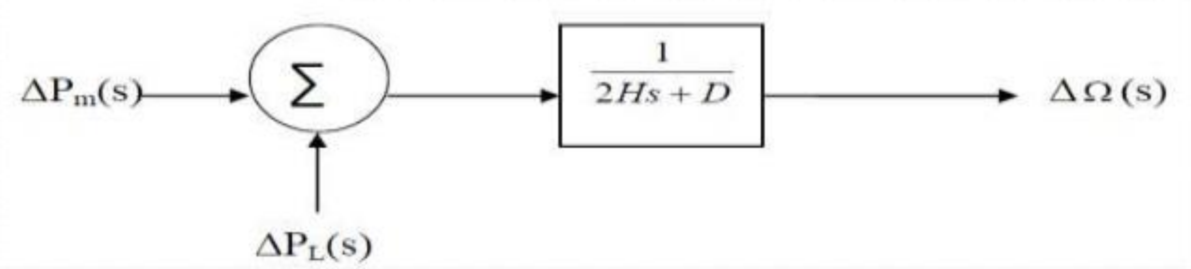
- **Generator Model:**

$$\Delta\Omega(s) = \frac{1}{2Hs}[\Delta Pm(s) - \Delta Pe(s)]$$



Load Model:

$$\Delta P_e = \Delta P_L + D\Delta\omega$$



- **Prime mover Model:**

$$G_T = \frac{\Delta P_m(s)}{\Delta P_V(s)} = \frac{1}{1+\tau_T s}$$

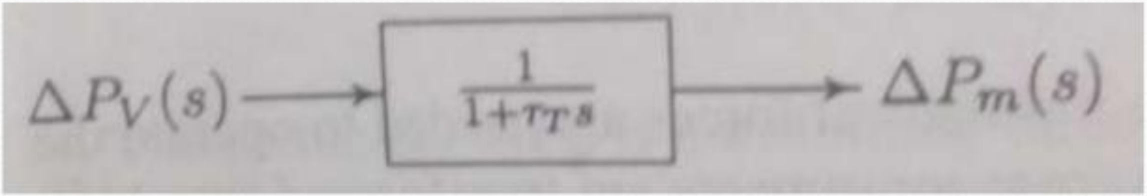
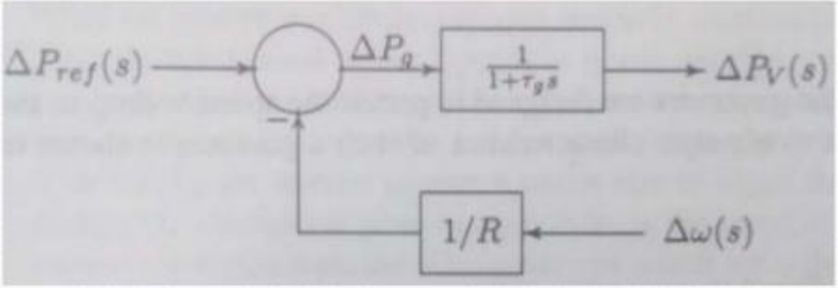


Fig: Block Diagram for a simple steam turbine

Governor Model:

$$\Delta \mathrm{P_V}(\mathrm{s}) = \frac{1}{1+\tau_g} \Delta P_g(s)$$



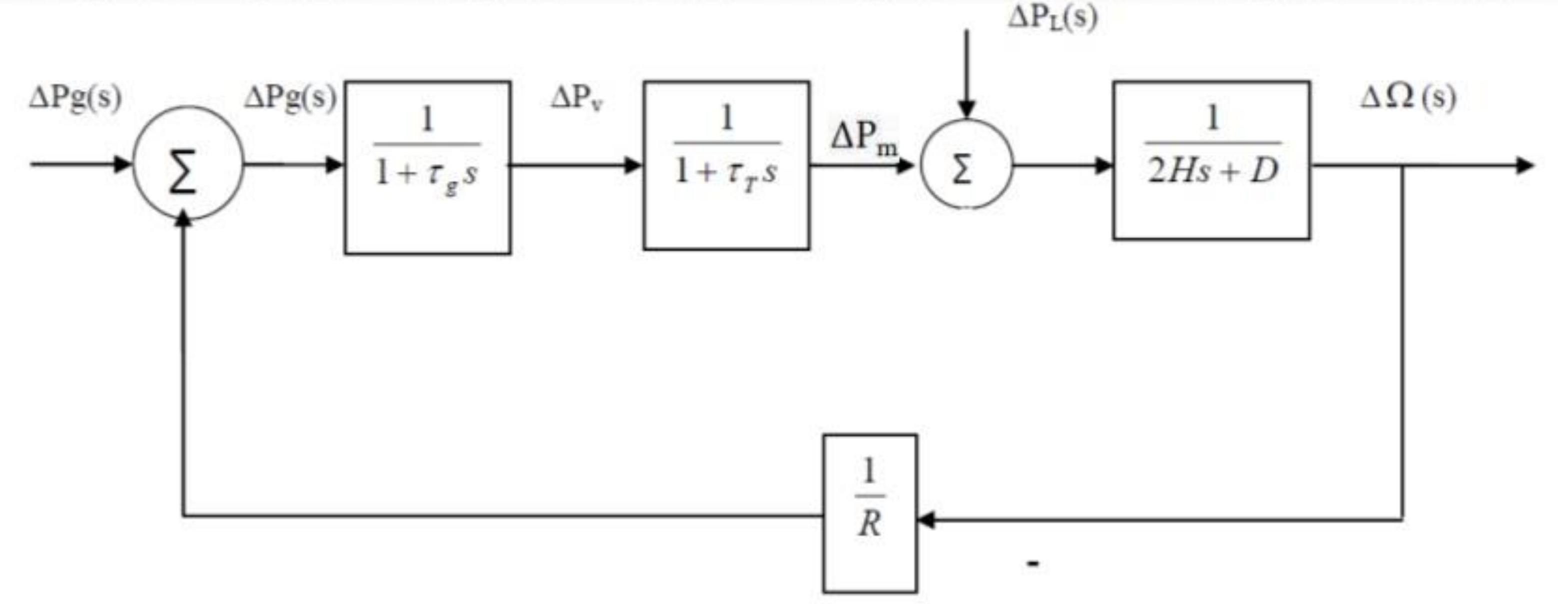


Fig: Load Frequency control block diagram of an isolated power system

Automatic Generation Control

- Sometimes, load on the system is increased suddenly then the turbine speed drops before the governor can adjust the input of the steam to the new load.

- As the change in the value of speed diminishes, the error signal becomes smaller and the position of the governor get closer to the point required to maintain the constant speed.

- One way to restore the speed or frequency to its nominal value is to add an integrator on the way.

- As the load of the system changes continuously the generation is adjusted automatically to restore the frequency to the nominal value. This scheme is known as automatic generation control.

- In an interconnected system consisting of several pools, the role of the AGC is to divide the load among the system, stations and generators so as to achieve maximum economy and reasonably uniform frequency.

AGC of Single Area System

- With the primary Load Frequency Control (LFC) loop a change in the system load will result in a steady state frequency deviation , depending on the governor speed regulation.

- In order to reduce the frequency deviation to zero an integral controller is connected to provide reset action on the load reference setting to change the speed set point.

- The integral controller gain must be adjusted for a satisfactory transient response.

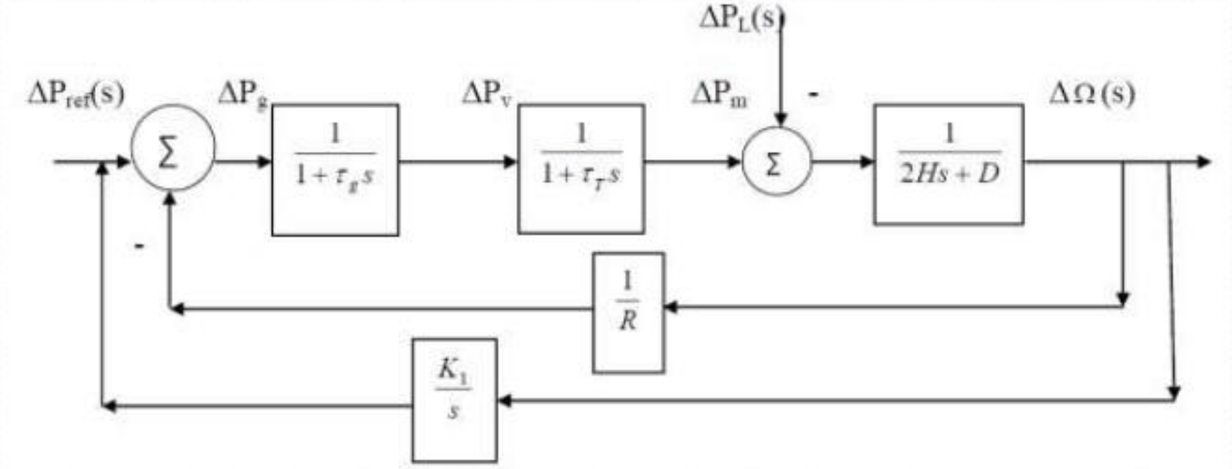


Fig: Mathematical Modeling of AGC for an isolated power system

AGC of a Multi- Area System

- Now a days in most of the cases, a group of generators are closely coupled internally and swing in unison.

- These generator turbines tend to have the same response characteristics and such a group of generators are said to be coherent.

- The LFC loop represent the whole system and the group is called the control group.

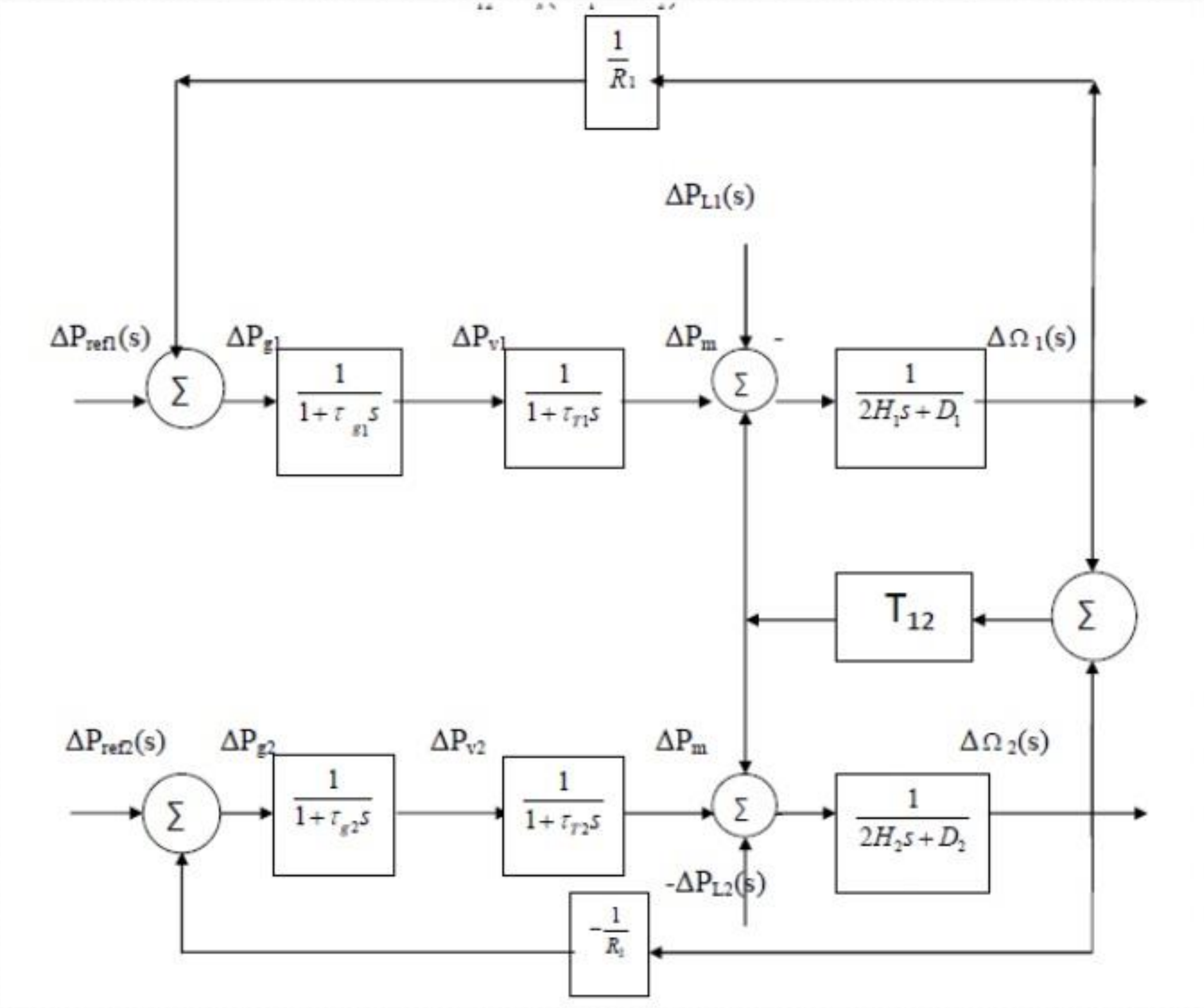
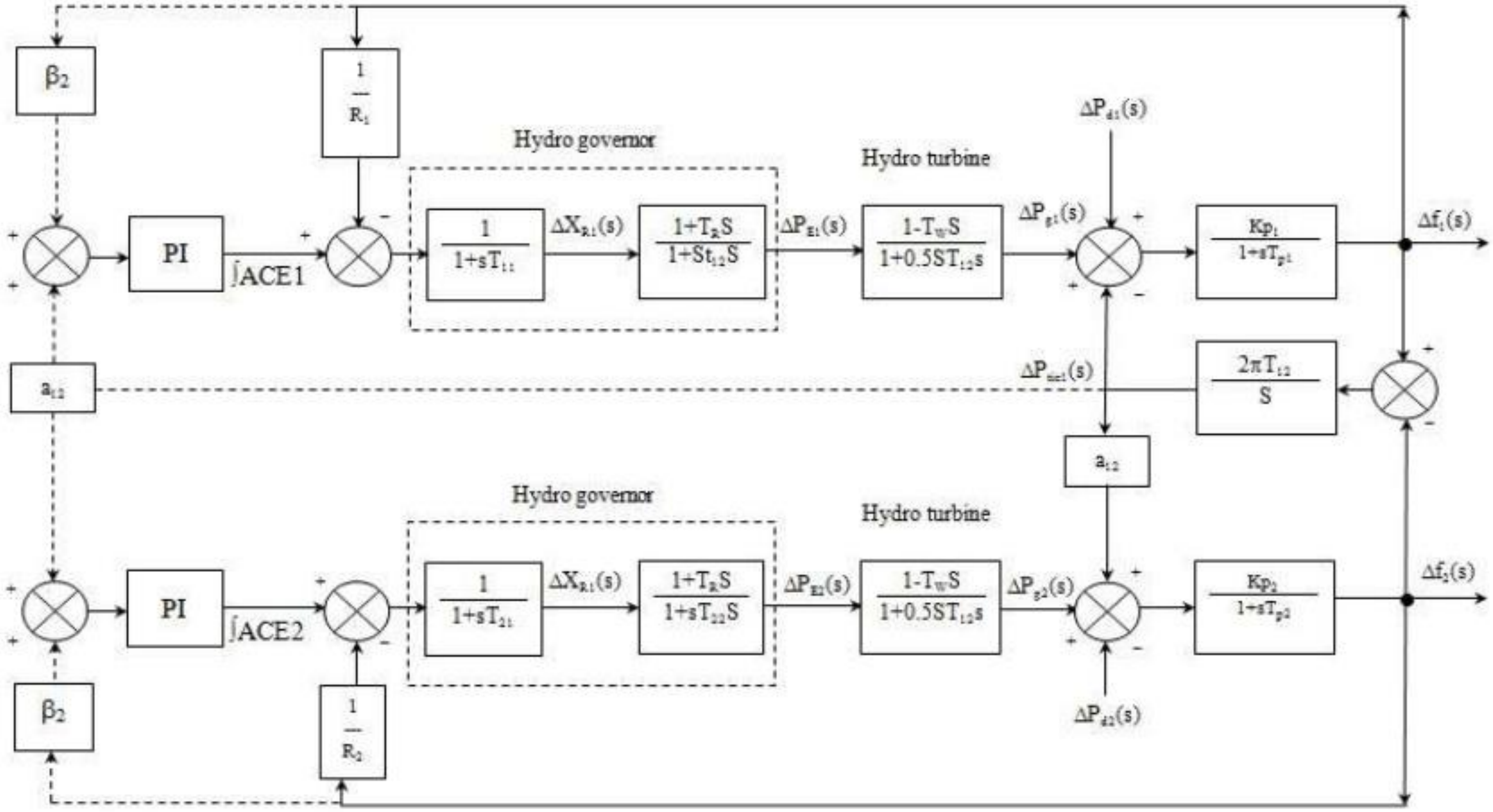


Fig: Two Area system with primary loop LFC

DESIGN OF LOAD FREQUENCY CONTROLLER FOR TWO AREA INTERCONNECTED HYDRO POWER SYSTEMS



Transfer Function Model of an Interconnected Two Area Hydro Power Systems (Closed Loop)

UNIT-5

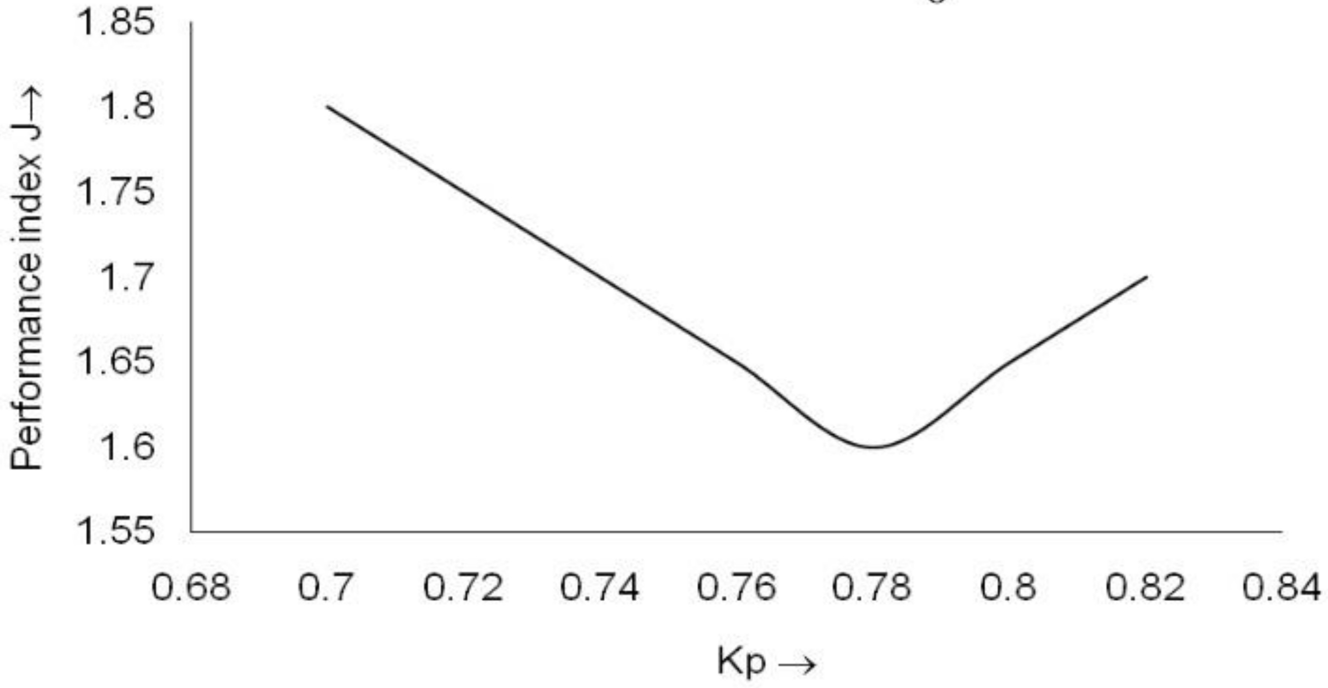
LOAD FREQUENCY CONTROLLER

DESIGN OF DIGITAL CONTROLLER

Proportional Controller:

$$P_{out} = K_p\, e(t)$$

$$J = \int_0^t w1(ACE)^2\, dt$$



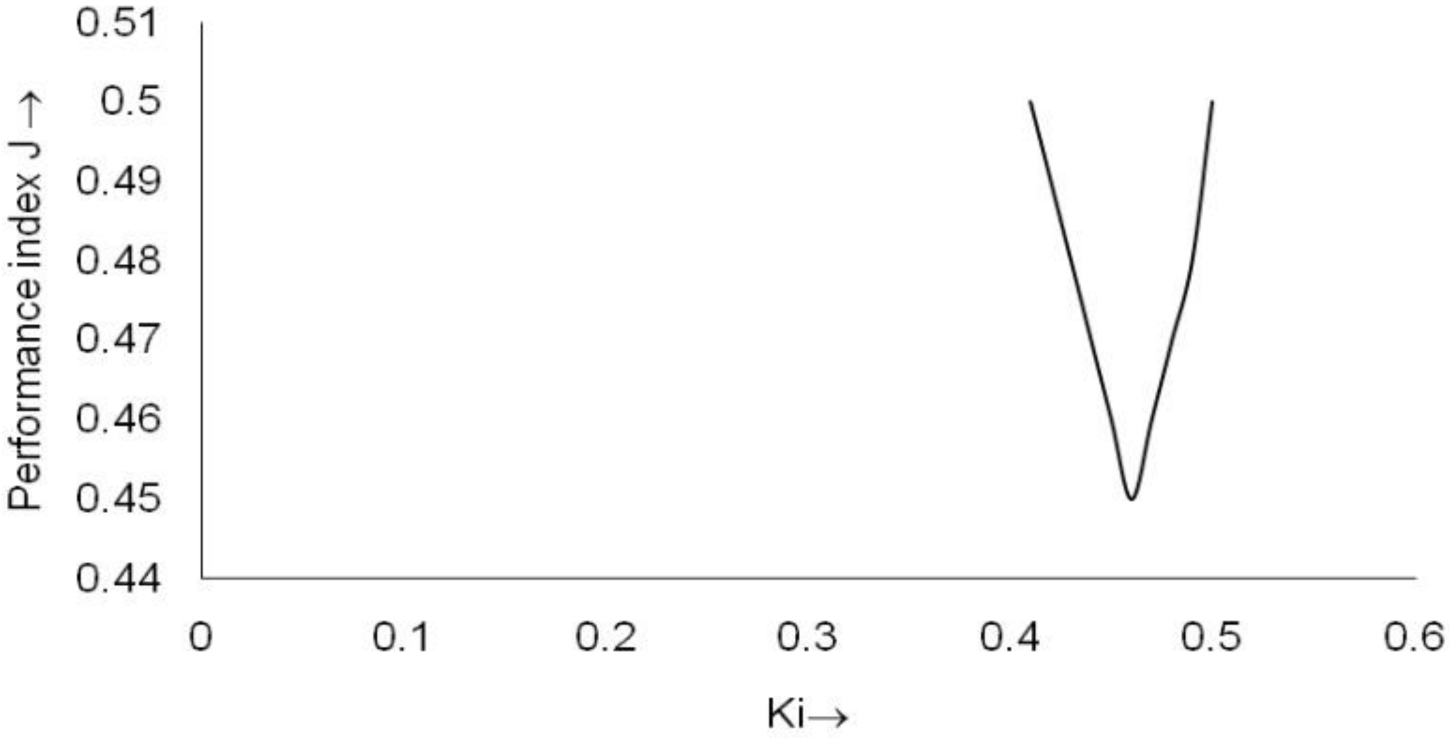
Two Area Hydro Electric Power System - P controller Design

Integral Controller:

$$I_{\text{out}} = K_i \int_0^t e(\tau)\, d\tau$$

$$J = \int_0^t ACEi^2 dt$$

$$ACEi = \beta \Delta F_i + \Delta P_{tiei}$$

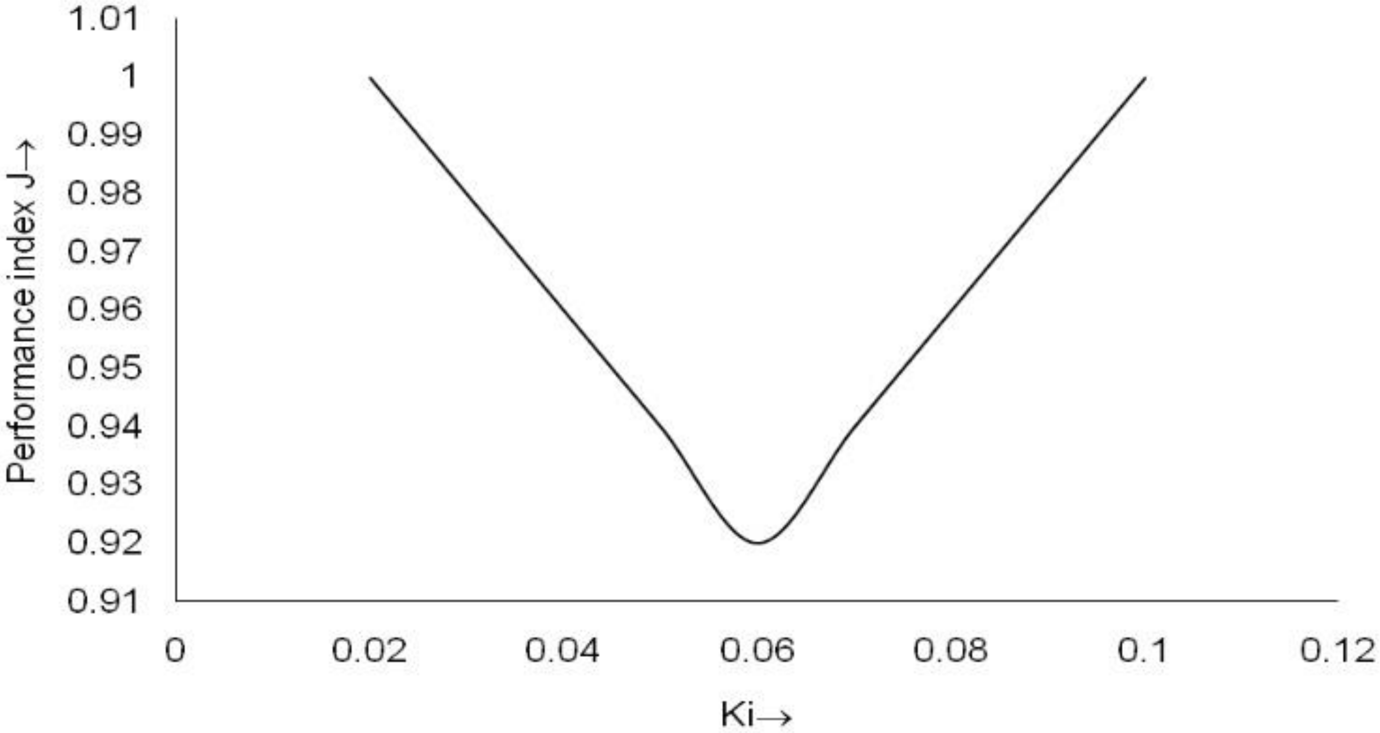


Two Area Hydro Electric Power System - I controller design

PI Controller :

$$\text{PI out} = Kp\ ACEi + Ki \int ACE_{\mathrm{i}}^{2}\, dt$$

$$\mathrm{u}(t) = \mathrm{MV}(t) = K_p \mathrm{e}(t) + K_i \int_0^t \mathrm{e}(\tau)\, d\tau + K_d \frac{d}{dt}\mathrm{e}(t)$$



Two Area Hydro Electric Power System - PI controller design

UNIT-6

REACTIVE POWER CONTROL

Reactive Power and Voltage Control

Control objectives contributing to efficient and reliable operation of power system:

- Voltage at terminals of all equipment are within acceptable limits
  - both utility and customer equipment designed to operate at certain voltage rating
  - prolonged operation outside allowable range could cause them damage

- System stability is satisfactory
  - voltage levels and reactive power control have significant impact on stability

- The reactive power flow is minimized so as to reduce I^2R and I^2X losses to a practical minimum
  - ensures transmission system operates efficiently

Production and Absorption of Reactive Power (Q)

- Synchronous Generators
  - can generate or absorb Q depending on excitation
  - capability limited by field current, armature current, and end-region heating limits
  - automatic voltage regulator continuously adjusts excitation to control armature voltage
  - primary source of voltage support!

- Overhead lines
  - at loads below natural or surge impedance load (SIL), produce Q
  - at loads above SIL, absorb Q

- Underground cables
  - have high SIL due to high capacitance
  - always loaded below SIL, and hence generate Q

Transformers

absorb Q due to shunt magnetizing reactance and series leakage inductance

Loads

a typical "load bus" is composed of a large number of devices
composite characteristics are normally such that a load bus absorbs Q
industrial loads usually have shunt capacitors to improve power factor

As power flow conditions vary, reactive power requirements of transmission network vary

Since Q cannot be transmitted over long distances, voltage control has to be effected using special devices dispersed throughout the system

Methods of Voltage Control

- Control of voltage levels is accomplished by controlling the production, absorption, and flow of reactive power at all levels in the system

- Generating units provide the basic means of voltage control

- Additional means are usually required to control voltage throughout the system:

    - sources or sinks of reactive power, such as shunt capacitors, shunt reactors, synchronous condensers, and static var compensators (SVCs)

    - line reactance compensators, such as series capacitors

    - regulating transformers, such as tap-changing transformers and boosters

Methods of Voltage Control

- Shunt capacitors and reactors, and series capacitors provide passive compensation
  - are either permanently connected to the transmission and distribution system, or switched
  - contribute to voltage control by modifying the network characteristics

- Synchronous condensers and SVCs provide active compensation; the reactive power absorbed/ supplied by them are automatically adjusted so as to maintain voltages of the buses to which they are connected
  - together with the generating units, they establish voltages at specific points in the system
  - voltages at other locations in the system are determined by active and reactive power flows through various circuit elements, including the passive compensating devices

Objectives of Reactive Power Compensation

- To control voltage and/or improve maximum power transfer capability
- Achieved by modifying effective line parameters:
  - characteristic impedance,
  - electrical length, $\theta = \beta l$
- The voltage profile is determined by Z_C
- The maximum power that can be transmitted depends on Z_C as well as β

Shunt Reactors

- Used to compensate the undesirable voltage effects associated with line capacitance
  - limit voltage rise on open circuit or light load
- Shunt compensation with reactors:
  - increases effective Z_C
  - reduces the effective natural load , i.e., voltage at which flat voltage profile is achieved
- They are connected either:
  - directly to the lines at the ends, or
  - to transformer tertiary windings; conveniently switched as var requirements vary
- Line reactors assist in limiting switching surges
- In very long lines, at least some reactors are required to be connected to lines

Shunt Capacitors

- Used in transmission systems to compensate for I^2X losses
- Connected either directly to H.V. bus or to tertiary winding of transformers
- Normally distributed throughout the system so as to minimize losses and voltage drops
- Usually switched: a convenient means of controlling voltage
- Shunt capacitor compensation of transmission lines in effect
  - decreases Z_C
  - increases θ, i.e., electrical length
- Advantages: low cost and flexibility of installation and operating
- Disadvantages: Q output is proportional to square of the voltage; hence Q output reduced at low voltages

- Shunt capacitors are used extensively in distribution systems for power factor correction and feeder voltage control

Series Capacitors

- Connected in series with the line
- Used to reduce effective inductive reactance of line
  - increases maximum power
  - reduces I^2X loss
- Series capacitive compensation in effect reduces both:
  - characteristic impedance Z_C, and
  - electrical length θ
- Reactive power produced increases with increasing power transfer
  - Self regulating !
- Typical applications
  - improve power transfer compatibility
  - alter load division among parallel lines
  - voltage regulation

Synchronous Condenser

- A synchronous machine running without a prime mover or a mechanical load
- Depending on field excitation, it can either absorb or generate vars
- With a voltage regulator, it can automatically adjust vars to maintain constant voltage
- Started as an induction motor and then synchronized
- Normally connected to tertiary windings of transformers
- Unlike a SVC, a synchronous condenser has an <u>internal voltage</u>
- Speed of response not as fast as that of an SVC

Static VAR Compensators (SVC)

- Shunt connected static var generators and/or absorbers whose outputs are varied so as to control specific power system quantities

- The term static is used to denote that there are no moving or rotating components

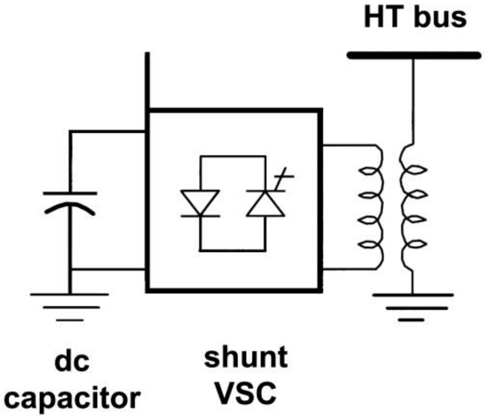
- Basic types of SVCs:
  - thyristor-controlled reactor
  - thyristor-switched capacitor
  - saturated reactor

- A static var system (SVS) is an aggregation of SVCs and mechanically switched capacitors or reactors whose outputs are coordinated

- When operating at its capacitive limit, an SVC behaves like a simple capacitor

Static Synchronous Compensator (STATCOM)

- Can be based on a voltage-sourced or current-sourced converter
- Figure below shows one with voltage-sourced converter
  - driven by a dc voltage source: capacitor



- Effectively an alternating voltage source behind a coupling reactance
  - controllable in magnitude
- Can be operated over its full output current range even at very low (typically 0.2 pu) system voltage levels
- Requires fewer harmonic filters and capacitors than an SVC, and no reactors
  - significantly more compact

Tap-Changing Transformers

- Transformer with tap-changing facilities constitute an important means of controlling voltages throughout the power system

- Control of a single transformer will cause changes in voltages at its terminals
  - in turn this influences reactive power flow
  - resulting effect on the voltages at other buses will depend on network configuration and load/generation distribution

- Coordinated control of the tap changers of all transformers interconnecting the subsystems required to achieve overall desired effect

- During high system load conditions, network voltages are kept at highest practical level to
  - minimize reactive power requirements
  - increase effectiveness of shunt capacitors and line charging

- The highest allowable operating voltage of the transmission network is governed by
  - requirement that insulation levels of equipment not be exceeded
  - need to take into consideration possible switching operations and outage conditions

- During light load conditions, it is usually required to lower network voltages
  - reduce line charging
  - avoid underexcited operation of generators

- Transformers with under-load tap-changers (ULTC) are used to take care of daily, hourly, and minute-by-minute variations in system conditions

- Off-load tap-changing transformers used to take care of long-term variations due to system expansion, load growth, or seasonal changes