

# Power Systems Operation and Control

## Lecture 9

### Modeling of Components for Power system control

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#### ***Lecture learning outcomes:***

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

- i. Understand the importance Modeling Power system Components
- ii. Knows the Speed governor systems and its importance
- iii. Differentiate the modeling of each components for controlling the frequency of system

# Content

1. Introduction
2. Basics of LFC and AVAR Control
3. Modeling of Speed Governor
4. Turbine Model
5. Generator model
6. Load Model

Summary

References

# 1. Introduction

- Modeling components for power system control involves representing various elements of the power grid such as **speed governor**, turbine, generators, transformers, transmission lines, and loads—using mathematical models.
- A steam turbine **governor is a component of** the turbine control system that **regulates rotational speed** in response to changing load conditions.
- The governor **output signal manipulates** the position of a steam **inlet** valve or nozzles which in turn regulates the steam flow to the turbine
- Turbine and generators are the main components that can be used as rescheduling the generation based on the changing load.
- These models help in analyzing system behavior, optimizing performance[1]:

# Introduction

# Cont....

- Power system control is the process of monitoring, coordinating and controlling the generation, transmission and distribution of electrical energy.
- The physical plant to be controlled comprises generating plants that produce energy and feed it to the load through transformers and the HV transmission network(grid), based on interconnected generating plants
- Either generation or load must balance supply and demand because transmission lines offer very little energy storage
- At **generating plants, turbine governors regulate production**, while computers in the control center, which is located far from the generating plants, handle automatic generation control.

# Introduction

# Cont....

- Residential, commercial, and industrial loads can all be remotely supervised and controlled using **load management**,
- **It's also known as demand-side** management, which is applied to sub-transmission and distribution circuits.
- Overall energy management is performed at control center, typically called system control centre's, by computer systems called energy management systems /EMS/, data acquisition and remote control is performed by SCADA etc.

# Introduction

# Cont....

- To balance **the generation against load** at the lowest possible cost, **AGC** operates online in real time and consists of **two main functions as well as a number of smaller ones**.
- Controlling load frequency and economic dispatch are the **main tasks**.
- Minor tasks are the reserve monitoring, which ensures that the system has adequate reserve, interchange scheduling, which starts and finishes scheduled interchanges,
- In addition, other comparable monitoring and record tasks, such as load forecasting, fault allocation, and fault analysis, are examples of minor services.
- With the constraints of the controls at hand, generation **control and ED reduce the present cost of** energy production and transmission.

# Introduction

# Cont....

- Energy control, the supervisory layer, is responsible for efficiently scheduling production and transmission on a worldwide scale and at intervals that correspond with cost optimization.
- In a power system, there are numerous variables to regulate, but we primarily control voltage and frequency by adjusting the generators', load's, and other system components' other characteristics.
- Maintaining dependability, security, stability, operating in the most cost-effective manner, and improved quality (frequency within the limit of 3%), as well as voltage (5% HV, 10% LV), are imperative for an efficient and secure power system.

# Introduction

# Cont....

- Frequency is **global phenomena**, it's the same in one node and other[2].
- Whereas, the voltage is local phenomena that voltage in each substation is different.
- However, both of, change in frequency and deviation of voltage from nominal value affect normal operation of the system, and needs to be monitored very well.
- This needs modeling and developing the transfer function of each component for effective control of both frequency and Voltage.

# Introduction

# Cont....

- Frequency can be controlled by controlling the active power and load
- which is active power is controlled at generation or the injected power and the load can be controlled by monitoring the consumed power.
- It is preferred to control the power **at generation side and rather than controlling from demand side, the load end** control advisable during emergency case. Generally the control approach is given as:
- **Case 1:** When the total generation  $<$  demand , results in = **reduction in system frequency.**
- **Thus, the recommended solution is just increasing the generation** increase, or decreasing the load.
- Decreasing the load is not advisable as it affect power reliability.

# Introduction

# Cont....

- Case 2: when the total generation  $>$  demand, the system frequency rises
- The mitigation technique is rescheduling the generation( decrease it) and increasing the load , but increasing the load is not possible from utility side.
- The two cases scenario is presented in Fig.1
- Finally, it is observed that energy is stored in the form of kinetic energy and can go no where.
- Accordingly, when load increases, this stored energy will be taken to feed the demand , the stored kinetic energy will decrease and hence speed decrease.

# Introduction

- The frequency of the system will decrease because of the reduction of speed of generator.

# Cont....

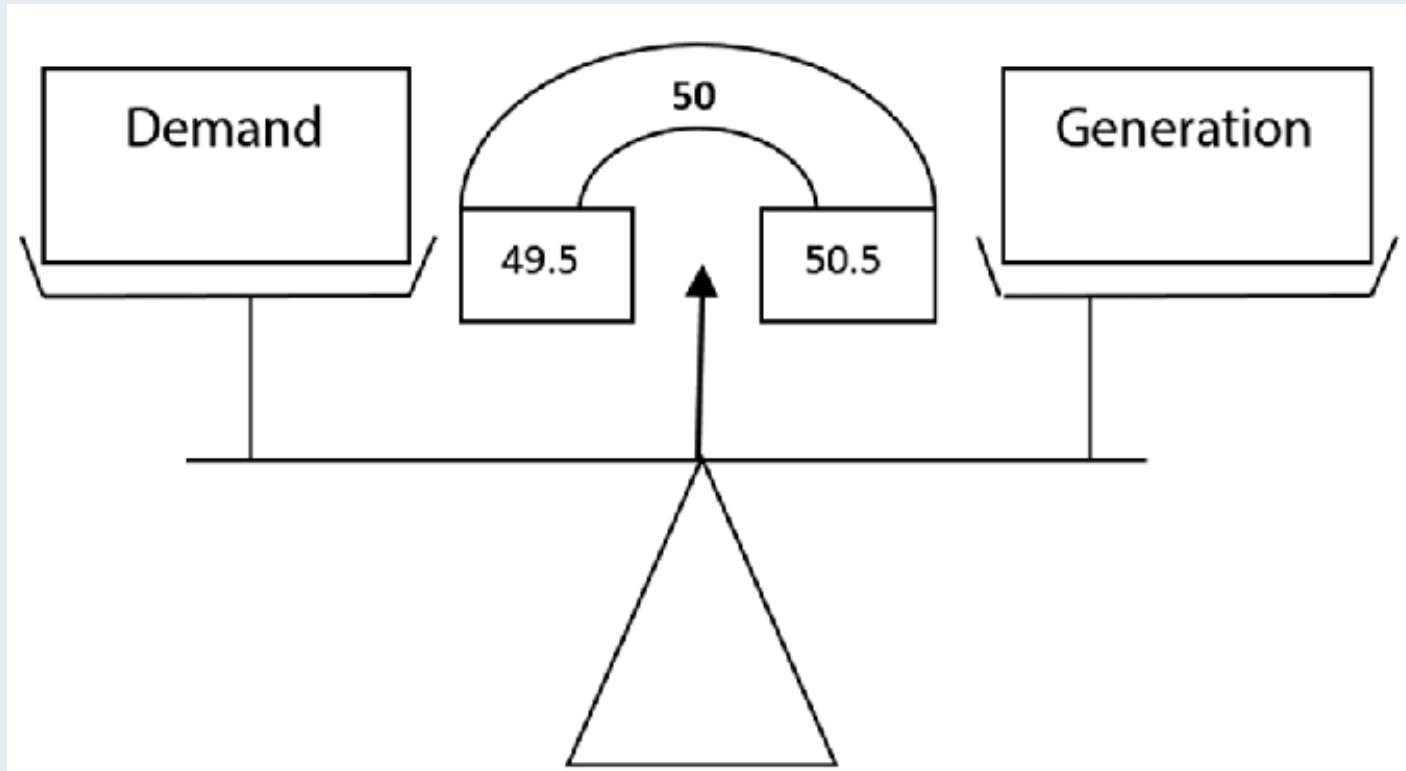


Figure 1: The variation in Frequency based on generation-demand relation.

Url: <https://www.researchgate.net/publication/325567506/figure/fig1/AS:634404896522241@1528265322297/Relation-of-frequency-with-generation-and-demand.png>

# Introduction

# Cont....

- When load decrease, further kinetic energy will be stored and results in the increments of speed and frequency
- On other hands, the reactive power control is responsible mainly for controlling the voltage, which is a local problem.
- Based on the above presentation , it's noted that there are two basic generation control loops:
  1. Frequency control loop or LFC, AGC, MW-F control loop
  2. MVAR-Voltage, Q-V control loop

The overall, block diagram is presented in Fig.2

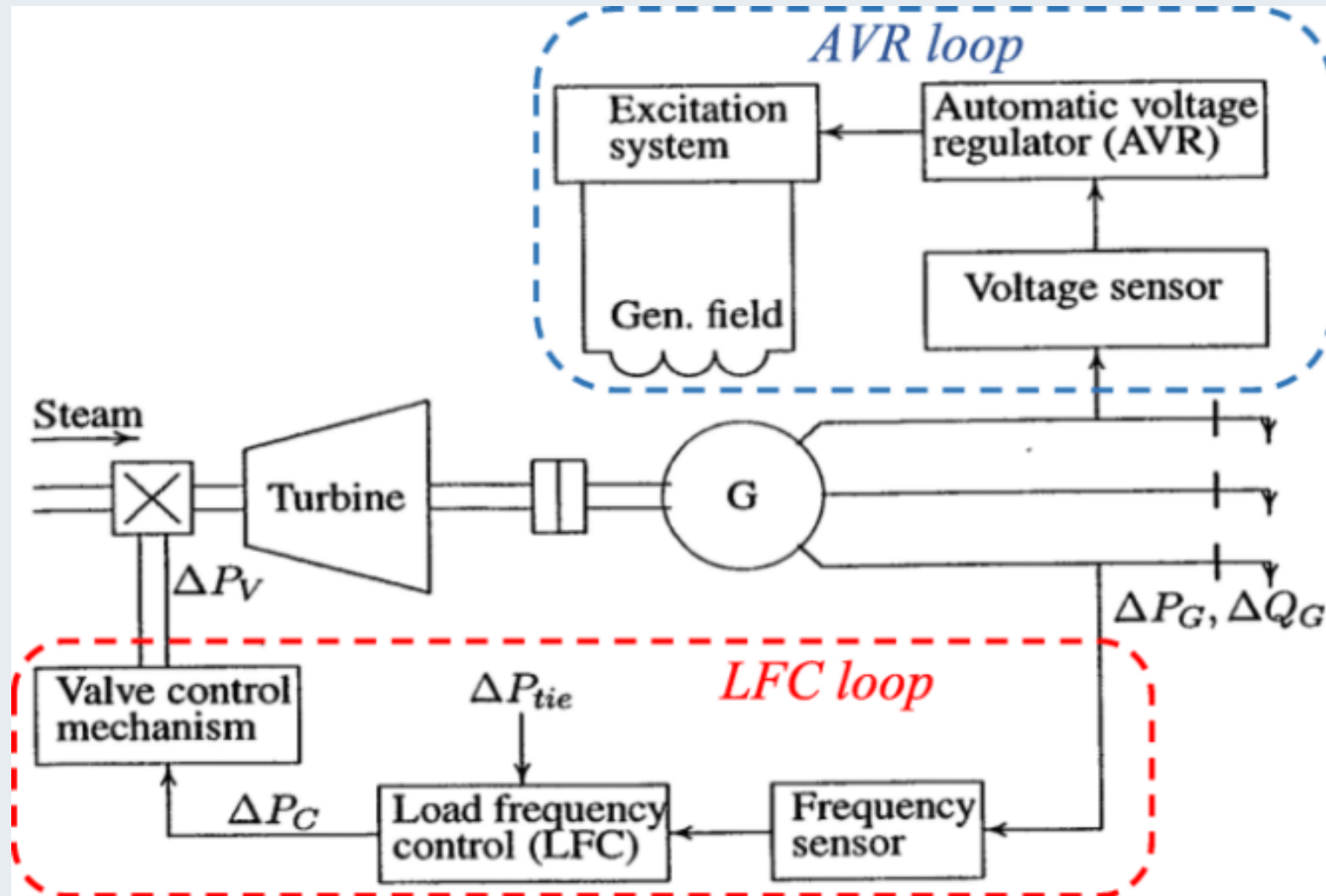


Figure 2: LFC and AVR control Loop.

## 2. Basics of LFC and AVAR Control

- Controlling the power flow in the tie-lines and preserving power balance among interconnected areas are the goals of load frequency control.
- Electric power must always be produced at a rate equal to its consumption because it cannot be stored in vast quantities.
- AVR, or automatic voltage regulator: The excitation utilized affects how the AVR is constructed. When the generator turns, the stator provides input to all.
- For non-linear load applications, AVRs that may receive a second input are utilized to lessen or completely eliminate internal harmonics brought on by load feedback signals.
- The two most popular kinds are: The silicon controlled rectifier (SCR) senses the stator's power level and decides when to fire the exciter voltage. can lead to issues when utilized

- Accordingly, the knowledge, modeling and controlling of the following three components is very important for efficient control of frequency in power systems.
  - a. Speed governing system
  - b. Turbine and generator, the spinning components
  - c. The load and its behavior
- **Speed governing system:** The speed governor is the main primary tool for the LFC, whether the machine is used alone to feed a smaller system or a part of the most elegant arrangement.

- The key components of a speed-governing system, such as those used in steam turbines, are schematically arranged in Fig. 3 to regulate the generator's output and maintain a steady frequency.

- The main components are:

## a. Fly Ball Speed Governor

- **It's the heart of the** system which senses the change in speed (frequency).
- As the speed **increases the fly balls move outwards and** the point B on linkage mechanism moves downwards. The reverse happens when the speed decreases.

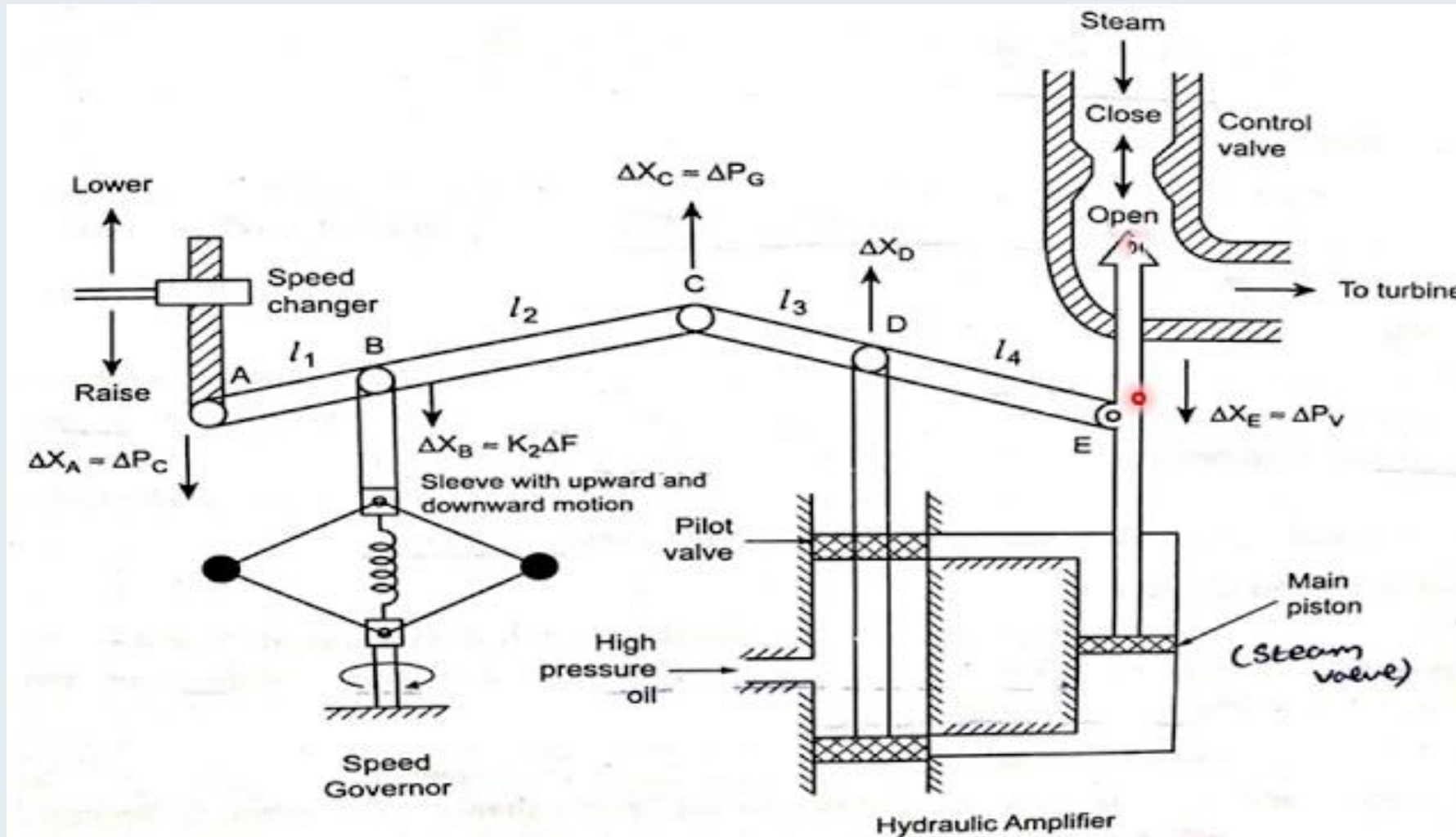


Figure 3. Speed Governor System.

Url: <https://i.ytimg.com/vi/DXopWjWpYcY/sddefault.jpg>

- The centrifugal fly-balls driven either directly or through gearing by the turbine shaft.
- The mechanism provides upward and downward vertical movements proportional to the change in speed.

## B- Linkage Mechanism

- These are links for transforming the fly-balls movement to the turbine valve through a hydraulic amplifier and providing a feedback from the turbine valve movement.
- ABC is a rigid link pivoted at B and CDE is another rigid link pivoted at D.
- This link mechanism provides a movement to the control valve in proportion to change in speed.
- It also provides a feedback from the steam valve movement.

## C- Hydraulic Amplifier:

- It comprises a **pilot valve and main piston** arrangement, low power level pilot valve movement is converted into high power level piston valve movement.
- This is necessary in order to open or close the steam valve against high pressure steam.
- Very large mechanical forces are needed to operate the steam valve.
- Therefore, the governor movements are transferred into high power forces via several stages of hydraulic amplifiers.

## D- Speed Changer

- **The speed changer consists of a servomotor which can be operated manually or automatically for scheduling load at nominal frequency.**
- By adjusting this set point, a desired load dispatch can be scheduled at nominal frequency.

# 3. Modeling of Speed Governor

- The Speed governor **senses the change in speed** (or frequency) and hence it can be regarded as heart of the system[3].
- The standard model **of a speed governor operates by the fly-ball mechanism**.
- The speed governing system is the primary LFC loop and its simple schematic representation is shown in Fig.3.
- Fly-balls moves **outward** when speed increases and the point B on the linkage **mechanism moves downward**, the reverse happens when the speed decreases.
- The movement of point B is **proportional to the change in shaft speed**

- In order to understand the operation, we should consider two cases
- The **first is** when speed changer is **given Raise** or Lower command but speed of the turbine remains constant
- **second** when speed of turbine is changed but command is not given to the speed changer.
- Under these conditions, the position of the joints will be changed according to the applied phenomena.

# Modeling of Speed Governor

Cont.....

- Option One: Speed changer is given Raise command and speed is constant.

$$\Delta x_a = \text{downward}$$

$$\Delta x_b = 0$$

$$\Delta x_c = \text{upward}$$

$$\Delta x_d = \text{upward}$$

$$\Delta x_e = \text{downward}$$

eqn.(1)

- Option II: Speed changer is constant and speed is increased.

$$\Delta x_a = 0$$

$$\Delta x_b = \text{downward}$$

$$\Delta x_c = \text{downward}$$

$$\Delta x_d = \text{downward}$$

$$\Delta x_e = \text{upward}$$

eqn.(2)

# Modeling of Speed Governor

Cont.....

- Hence a relation can be established based on the above facts.

$$\Delta x_c = k_1 \Delta f - k_2 \Delta P_{ref}$$

$$\Delta x_d = k_3 \Delta x_c + k_4 \Delta x_e$$

eqn.(3)

$$\Delta x_e = -k_5 \int x_d \partial t$$

- Where  $k_1$  ,  $k_2$ ,  $k_3$  and  $k_4$  are constants and depend on the length of arms and  $k_5$  depends on oil pressure and geometries of cylinder.

# Modeling of Speed Governor

## Cont.....

- **Let us assume** that the steam is **operating under steady state and** is delivering power  $P_G^0$  from the generator at nominal speed or frequency  $f_0$
- Under this condition, the prime mover valve has a constant setting  $\chi_E^0$ , the pilot valve is closed, and the linkage mechanism is stationary.
- Now, we will increase the turbine power by  $\Delta P_C$  with the help of **the speed changer**.
- For this, the movement of linkage point A moves downward by a small distance  $\Delta x_A$  and is given by;

$$\Delta x_A = K_c \Delta P_C$$

eqn.(4)

# Modeling of Speed Governor

Cont.....

- The link point 'C' will move upward because of linkage (A-B-C) action.
- Let it be further, the link point 'D' moves the piston in pilot servo (V), resulting in higher pressure oil flow in the upper part of the main piston
- The piston moves downward by an amount  $\Delta X_D$  and the steam valve opening increases
- It increases the torque developed by the turbine.
- This increased torque increases the speed of generator and frequency ( $\Delta f$ )

# Modeling of Speed Governor

## Cont.....

- This change of speed results in the outward movement of fly ball of the speed regulator.
- Thus the link 'B' moves **slightly downward** a small distance  $\Delta X_B$ .
- Due to the movement of link point B, the link point 'C' also moves downward by an amount  $\Delta X_C$  which is also proportional to  $\Delta f$ .
- Thus the net movement of link point C is

$$\Delta X_C = \Delta X'_C + \Delta X''_C \quad \text{eqn.(5)}$$

$$-\Delta X'_C (l_{AB}) = \Delta X_A (l_{BC})$$

$$\Rightarrow -\Delta X'_C = \Delta X_A \frac{l_{BC}}{l_{AB}} \quad \text{eqn.(6)}$$

# Modeling of Speed Governor

Cont.....

- From eqn.(5), it's observed that  $\Delta X_A = K_C \Delta P_C$  and by subst., let:

$$K_1 = \frac{l_{AB}}{l_{BC}}$$

$$\Delta X'_C = -K_C K_1 \Delta P_C \quad \text{eqn.(7)}$$

- And  $\Delta X''_C = K_2 \Delta f$
- Thus, the net movement of C is given by:

$$\Delta X = -K_C K_1 \Delta P_C + K_2 \Delta f$$

eqn.(8)

# Modeling of Speed Governor

## Cont.....

- The movement D,  $\Delta X_D$  is the amount by which pilot valve opens, which the function of  $\Delta X_C$  and  $\Delta X_E$  and written as

$$\Delta X_D = \Delta X'_D + \Delta X''_D \quad \text{eqn.(9)}$$

$$\Delta X'_D (l_{CD} + l_{DE}) = \Delta X_C (l_{DE})$$

$$\Delta X'_D = \frac{(l_{CD} + l_{DE})}{l_{DE}} * \Delta X_C \quad \text{eqn.(10)}$$

$$\Leftrightarrow \Delta X'_D = K_3 \Delta X_C$$

$$\Delta X''_D (l_{CD} + l_{DE}) = \Delta X_E (l_{CD})$$

$$\Delta X''_D = \frac{(l_{CD} + l_{DE})}{l_{CD}} * \Delta X_E$$

$$\Leftrightarrow \Delta X''_D = K_4 \Delta X_E \quad \text{eqn.(11)}$$

# Modeling of Speed Governor

Cont.....

- It, can be rewritten as:

$$\Leftrightarrow \Delta X_D = K_3 \Delta X_C + K_4 \Delta X_E \quad \text{eqn.}(12)$$

- Now , assume the flow of oil to the servomotor is proportional to the position of change in  $\Delta X_D$  of the pilot valve 'V', Then the movement of  $\Delta X_E$  is given by

$$\Delta X_E = \Delta X_V = K_5 \int_0^t (-\Delta X_D) \partial t \quad \text{eqn.}(13)$$

# Modeling of Speed Governor

Cont.....

- Taking the Laplace transform of each

$$\Delta X_C(s) = -K_1 K_C \Delta P_C(s) + K_2 \Delta f(s) \quad \text{eqn.(14)}$$

$$\Delta X_D(s) = K_3 \Delta X_C(s) + K_4 \Delta X_E(s)$$

$$\Delta X_E(s) = K_5 \frac{1}{s} \Delta X_D(s)$$

- and by substitution:

eqn.(15)

$$\Delta X_E(s) \left[ 1 + \frac{K_4 K_5}{s} \right] = \frac{-K_5 K_3}{s} [-K_1 K_C \Delta P_C(s) + K_2 \Delta f(s)]$$

$$\Delta X_E(s) = \frac{K_5 K_3 K_1 K_C (\Delta P_C(s)) \frac{K_2}{K_3 K_C}}{K_4 K_5 \left[ 1 + \frac{s}{K_4 K_5} \right]} \Delta f(s)$$

$$\Delta X_E(s) = \frac{K_3 K_1 K_C}{K_4} \left( \frac{(\Delta P_C(s)) \frac{K_2}{K_3 K_C}}{\left[ 1 + \frac{s}{K_4 K_5} \right]} \right) \Delta f(s)$$

# Modeling of Speed Governor

Cont.....

- If:

eqn.(16)

$$K_G = \frac{K_3 K_1 K_C}{K_4};$$

$$T_G = \frac{1}{K_4 K_5};$$

$$\frac{1}{R} = \frac{K_2}{K_1 K_C};$$

- Where, the value of  $T_G < 100$  m/s and the above eqn. is rewritten as:

$$\Delta X_E(s) = [\Delta P_C(s) - \frac{1}{R} \Delta f(s)] * \frac{K_G}{1 + sT_G} \quad \text{eqn.(17)}$$

# Modeling of Speed Governor

Cont.....

- Substituting and Simplifying , we get: This can be represented using block diagram as shown in Fig.4.

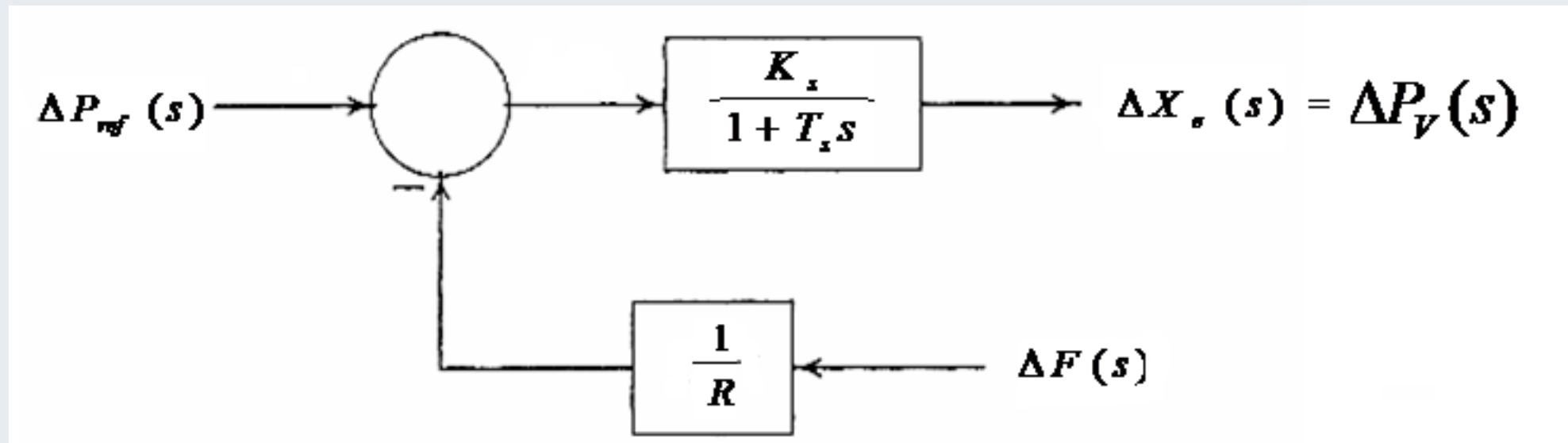


Figure 4: Block diagram representation of speed governing system.

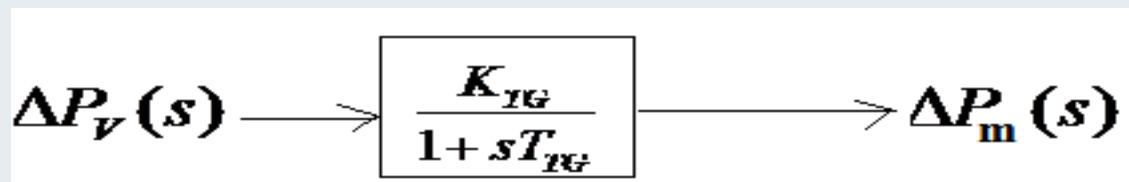
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## 4. Turbine model

- Figure 5 illustrate the turbine-generator mechanical connection.
- The turbine-generator model depends on whether we have hydro-turbines, or in case of steam turbines we have reheat or non-reheat type of steam turbines.
- For a simple a non-reheat type turbine model is given by a single time constant,

$$G_{TG}(s) = \frac{K_{TG}}{1 + sT_{TG}} \quad \text{eqn.(18)}$$

- Taking input power to the turbine is  $P_v$  /power from the valve opening/ and output power is mechanical power  $P_m$ , the block diagram becomes



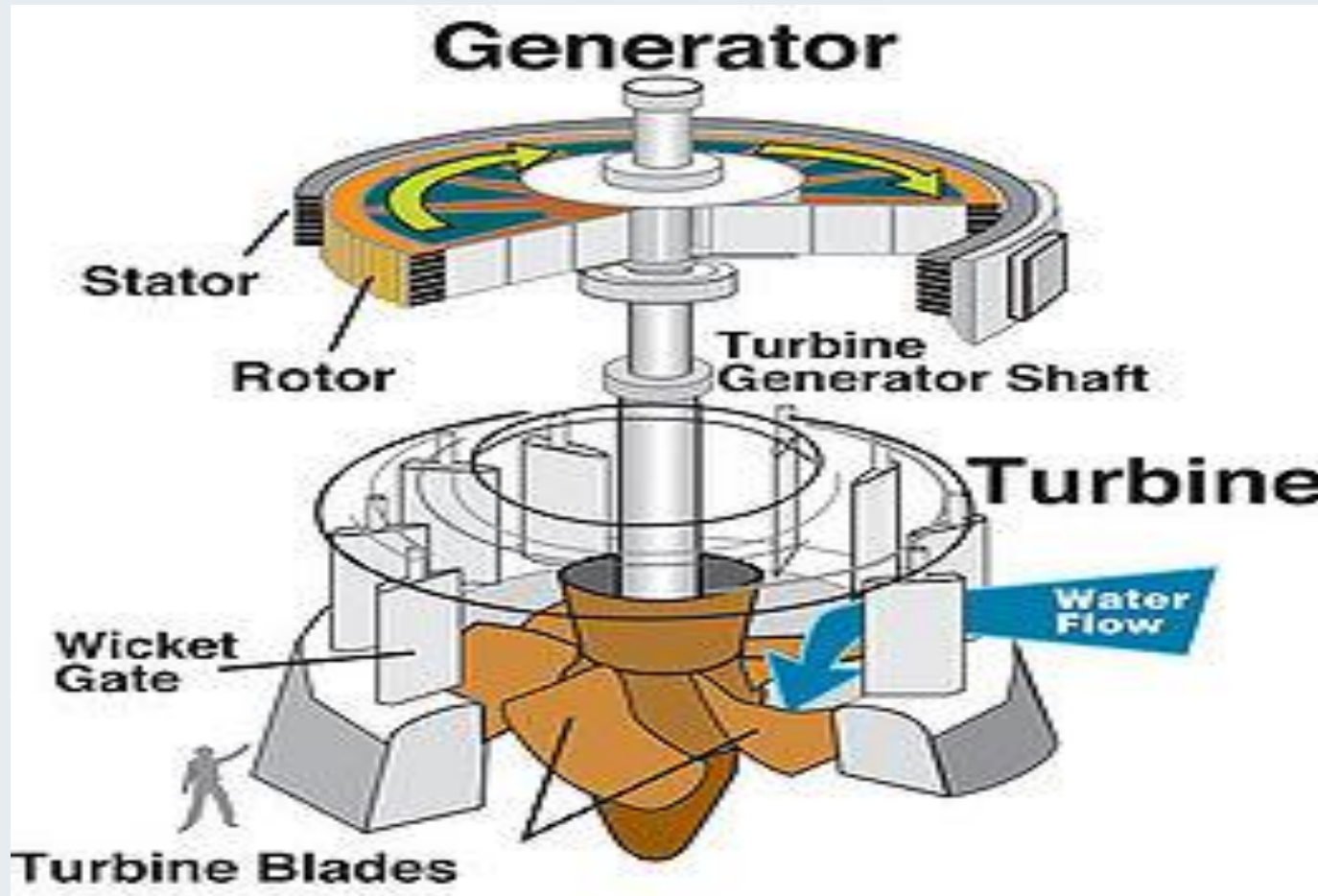


Figure 5. The turbine Generator Mechanical coupling.

Url: <https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/thumbnails/image/wss-wu-hydropower-turbine-diagram.jpg>

# 5. Generator Model

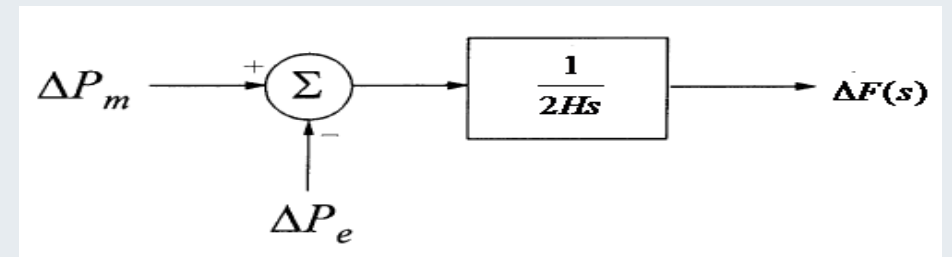
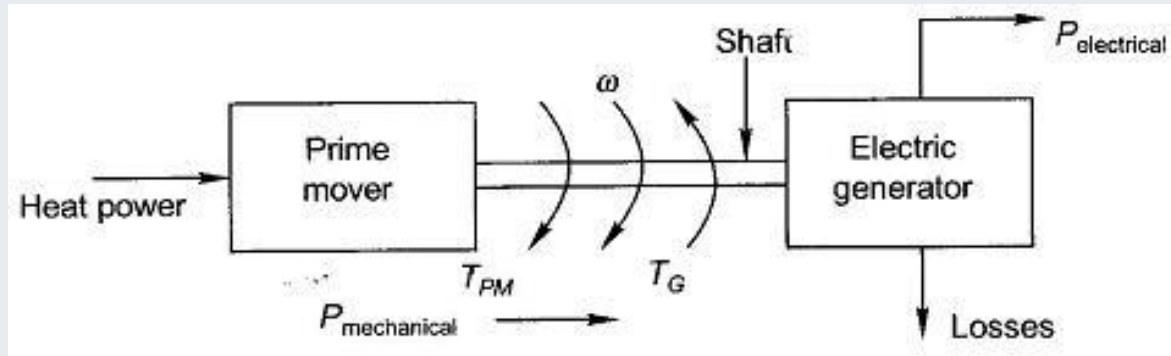
- The basic configuration of turbine and generator is shown in Fig.6. Here, based on swing equation,

$$J \frac{d^2 \theta}{dt^2} = T_m - T_e = T_a$$

eqn.(19)

$$J \omega_r \frac{d^2 \delta}{dt^2} = P_m - P_e = P_a$$

- For a change  $\Delta$  in mechanical and electrical power, the above equation using per unit system become S,
- Taking Laplace transform, we get



$$2H \frac{d\Delta f}{dt} = \Delta P_m - \Delta P_e \quad \text{eqn.(20)}$$

$$\frac{1}{2Hs} (\Delta P_m(s) - \Delta P_e(s)) = \Delta F(s)$$

Figure 6. Turbine-generator block diagram.

url: <https://www.eeeguide.com/wp-content/uploads/2015/10/Introduction-to-Electrical-Machines.jpg>

## 6. Load Model

- Power system loads are typically a combination of various electrical equipment, Electrical power for resistive loads, such heating and lighting loads, is frequency independent.
- When motor loads, like fans and pumps, are involved, variations in motor speed cause the electrical power to fluctuate with frequency.
- A composite load's total frequency-dependent properties can be stated as

$$\Delta P_e = \Delta P_L + D\Delta f \quad \text{eqn.(21)}$$

- Where  $\Delta P_L$  is the non-frequency-sensitive load change,  $\Delta f$  is the frequency-sensitive load change, and  $D$  is expressed as percent change in load divided by percent change in frequency.
- Substituting the above equation to the previous model (generator model), we get the following block diagram

# Load Model

# Cont.....

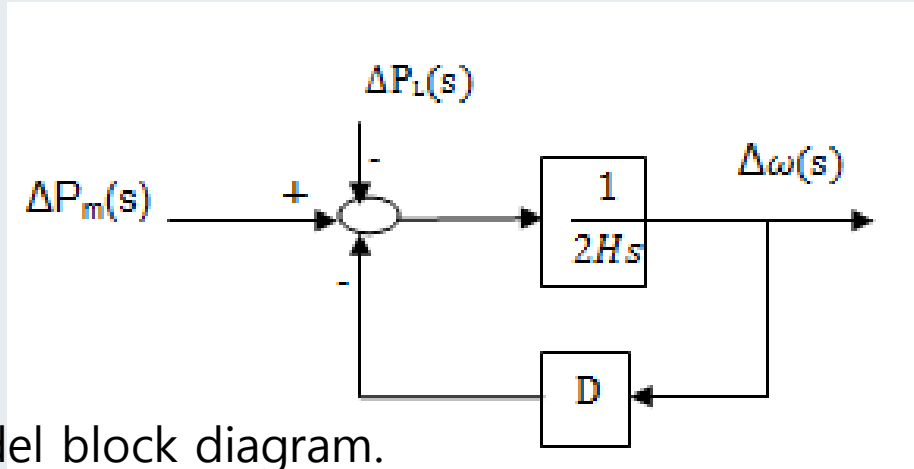
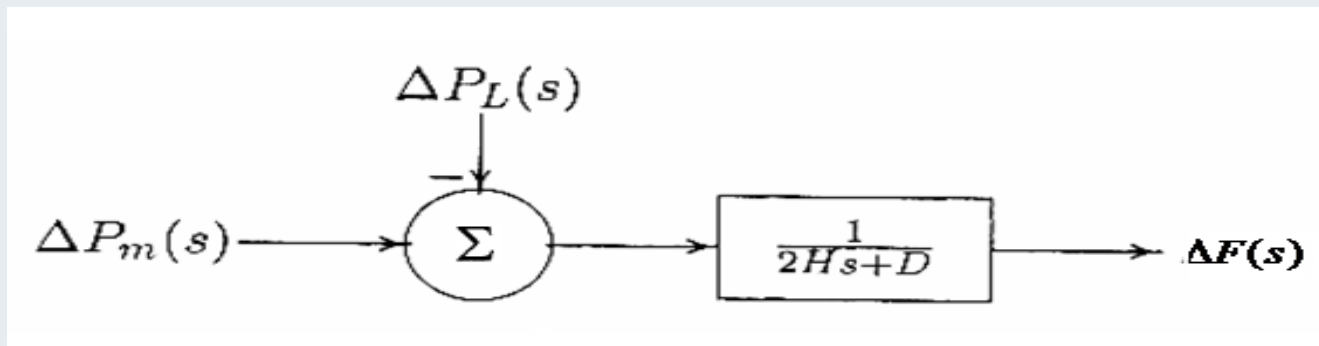


Figure 7. Load model block diagram.

<https://www.researchgate.net/publication/275351560/figure/fig2/AS:650470800510986@1532095732402/a-The-block-diagram-representation-of-the-generator-and-load-Eliminating-the-simple.png>

- Using transfer function of closed loop can be  $G(s)/1 + G(s) H(s)$ , the above model can be further simplified as follows [taking  $G(s) = 1/2Hs$  and  $H(s) = D$ ]



# Summary

- The brief overview power systems modeling like the speed governor, turbine, generator and load is modeled in this lecture.
- It is observed that speed governor system takes paramount in controlling the generator frequency, which needs to be modeled properly.
- The other fundamental components are modeling the turbine, generator and load (frequency independent and frequency dependent loads) also takes special attention in system frequency control,
- besides this, the relationship between load variation and generation rescheduling to maintain acceptable system frequency is also discussed in detail
- The behavior of frequencies and Voltage control is also discussed well.

# References

- [1]. E., İlyas. "Governors for hydro-turbine speed control in power generation: a SIMO robust design approach". Elsevier: Energy Conversion and Management. V.45(13–14), 2004, Pp:2207-2221. <https://doi.org/10.1016/j.enconman.2003.11.008>.
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Thank you !