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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE3602 - POWER SYSTEM OPERATION AND CONTROL
UNIT I – PRELIMINARIES ON POWER SYSTEM OPERATION AND CONTROL

1. POWER STATION

A power plant or a power generating station is basically an industrial location that is utilized for the generation and distribution of electric power in mass scale, usually in the order of several 1000 Watts. These are generally located at the sub-urban regions or several kilometres away from the cities or the load centres, because of its requisites like huge land and water demand, along with several operating constraints like the waste disposal etc. For this reason, a power generating station has to not only take care of efficient generation but also the fact that the power is transmitted efficiently over the entire distance and that's why, the transformer switch yard to regulate transmission voltage also becomes an integral part of the power plant. At the centre of it, however, nearly all power generating stations has an AC generator or an alternator, which is basically a rotating machine that is equipped to convert energy from the mechanical domain (rotating turbine) into electrical domain by creating relative motion between a magnetic field and the conductors. The energy source harnessed to turn the generator shaft varies widely, and is chiefly dependent on the type of fuel used.

2. TYPES OF POWER STATION

A power plant can be of several types depending mainly on the type of fuel used. Since for the purpose of bulk power generation, only thermal, nuclear and hydro power comes handy, therefore a power generating station can be broadly classified in the 3 above mentioned types. Let us have a look in these types of power stations in details.

A) THERMAL POWER STATION:

A thermal power station or a coal fired thermal power plant is by far, the most conventional method of generating electric power with reasonably high efficiency. It uses coal as the primary fuel to boil the water available to superheated steam for driving the steam turbine. The steam turbine is then mechanically coupled to an alternator rotor, the rotation of which results in the generation of electric power. Generally in India, bituminous coal or brown coal are used as fuel of boiler which has volatile content ranging from 8 to 33% and ash content 5 to 16 %. To enhance the thermal efficiency of the plant, the coal is used in the boiler in its pulverized form. In coal fired thermal power plant, steam is obtained in very high pressure inside the steam boiler by burning the pulverized coal. This steam is then super heated in the super heater to extreme high temperature. This super heated steam is then allowed to enter into the turbine, as the turbine blades are rotated by the pressure of the steam. The turbine is mechanically coupled with alternator in a way that its rotor will rotate with the rotation of turbine blades. After entering into the turbine, the steam pressure suddenly falls leading to corresponding increase in the steam volume. After having imparted energy into the turbine rotors, the steam is made to pass out of the turbine blades into the steam condenser of turbine. In the condenser, cold water at ambient temperature is circulated with the help of pump which leads to the condensation of the low pressure wet steam. Then this condensed water is further supplied to low pressure water heater where the low pressure steam increases the temperature of this feed water, it is again heated in high pressure. This outlines the basic working methodology of a thermal power plant.

❖ ADVANTAGES OF THERMAL POWER PLANTS:

- Fuel used i.e coal is quite cheaper.
- Initial cost is less as compared to other generating stations.
- It requires less space as compared to hydro-electric power stations.

❖ DISADVANTAGES OF THERMAL POWER PLANTS:

- It pollutes atmosphere due to production of smoke & fumes.
- Running cost of the power plant is more than hydro electric plant.

B) NUCLEAR POWER STATION:

The nuclear power generating stations are similar to the thermal stations in more ways than one. However, the exception here is that, radioactive elements like uranium and thorium are used as the primary fuel in place of coal. Also in a nuclear station the furnace and the boiler are replaced by the nuclear reactor and the heat exchanger tubes. For the process of nuclear power generation, the radioactive fuels are made to undergo fission reaction within the nuclear reactors. The fission reaction propagates like a controlled chain reaction and is accompanied by unprecedented amount of energy produced, which is manifested in the form of heat. This heat is then transferred to the water present in the heat exchanger tubes. As a result, super heated steam at very high temperature is produced. Once the process of steam formation is accomplished, the remaining process is exactly similar to a thermal power plant, as this steam will further drive the turbine blades to generate electricity.

C) HYDRO-ELECTRIC POWER STATION:

In Hydro-electric plants the energy of the falling water is utilized to drive the turbine which in turn runs the generator to produce electricity. Rain falling upon the earth's surface has potential energy relative to the oceans towards which it flows. This energy is converted to shaft work where the water falls through an appreciable vertical distance.

The hydraulic power is therefore a naturally available renewable energy given by the eqn:

$$\mathbf{P = g\rho\, QH}$$

Where,

g = acceleration due to gravity = 9.81 m/sec ^{2}

ρ = density of water = 1000 kg/m ^{3}

H = height of fall of water.

This power is utilized for rotating the alternator shaft, to convert it to equivalent electrical energy. An important point to be noted is that, the hydro-electric plants are of much lower capacity compared to their thermal or nuclear counterpart. For this reason hydro plants are generally used in scheduling with thermal stations, to serve the load during peak hours. They in a way assist the thermal or the nuclear plant to deliver power efficiently during periods of peak hours.

❖ ADVANTAGES OF HYDRO ELECTRIC POWER STATION

- It requires no fuel; water is used for generation of electrical energy.
- It is neat and clean energy generation.
- Construction is simple, less maintenance is required.
- It helps in irrigation and flood control also.

❖ DISADVANTAGES HYDRO ELECTRIC POWER STATION:

- It involves high capital cost due to dam construction.
- Availability of water depends upon weather conditions.
- It requires high transmission cost as the plant is located in hilly areas.

TYPES OF POWER GENERATION:

As mentioned above, depending on the type of fuel used, the power generating stations as well as the types of power generation are classified. Therefore the 3 major classifications for power production in reasonably large scale are,

- Thermal power generation.
- Nuclear power generation.
- Hydro-electric power generation.

Apart from these major types of power generations, we can resort to small scale generation techniques as well, to serve the discrete demands. These are often referred to as the alternative methods or non conventional energy of power generation and can be classified as ,

- Solar power generation. (making use of the available solar energy)
- Geo-thermal power generation. (Energy available in the Earth's crust)
- Tidal power generation.
- Wind power generation (energy available from the wind turbines)

These alternative sources of generation has been given due importance in the last few decades owing to the depleting amount of the natural fuels available to us. In the centuries to come, a stage might be reached when several countries across the globe would run out of their entire reserve for fossil fuels. The only way forward would then lie in the mercy of these alternative sources of energy which might play an instrumental role in shaping the energy supplies of the future. For this reason these might rightfully be referred as the energy of the future.

3. STRUCTURE OF ELECTRIC POWER SYSTEM

- **1. Transmission and pool level**
- **2. Sub-transmission level**
- **3. Distribution level**

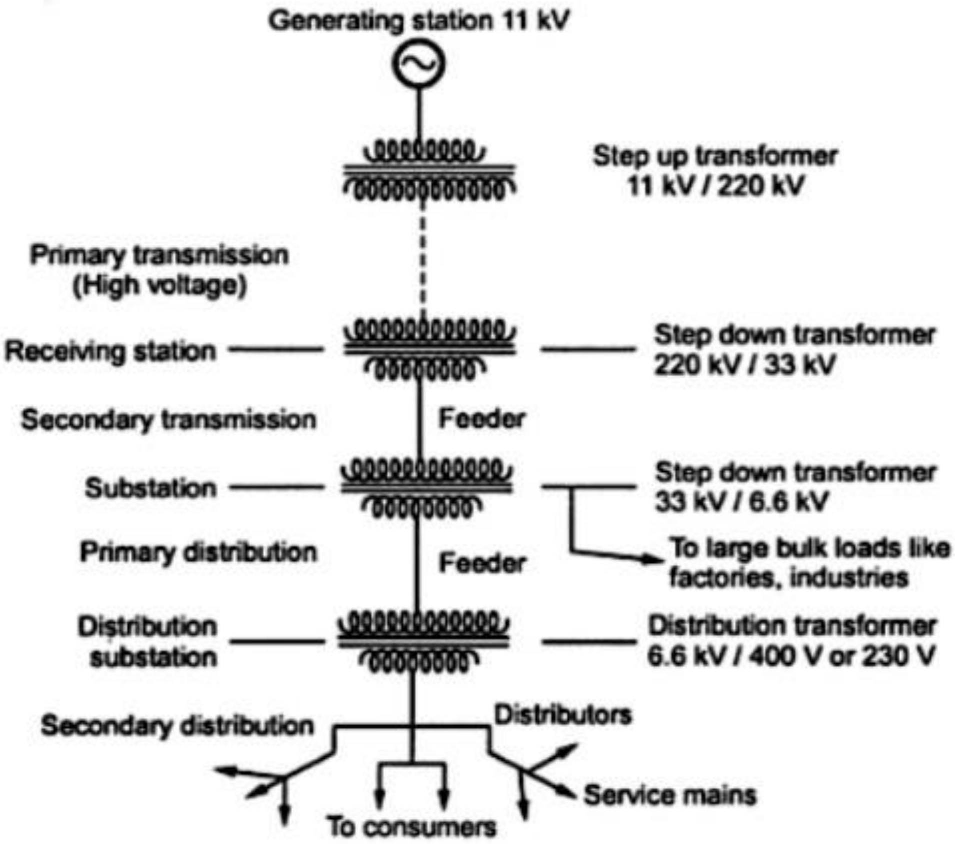


Fig1: Structure of Electric Power System

A) TRANSMISSION:

The power plants typically produce 50 cycle/second (Hertz), alternating-current (AC) electricity with voltages between 11kV and 33kV. At the power plant site, the 3-phase voltage is stepped up to a higher voltage for transmission on cables strung on cross-country towers. High voltage (HV) and extra high voltage (EHV) transmission is the next stage from power plant to transport A.C. power over long distances at voltages like; 220 kV & 400 kV. Where transmission is over 1000 kM, high voltage direct current transmission is also favoured to minimize the losses. Sub-transmission network at 132 kV, 110 kV, 66 kV or 33 kV constitutes the next link towards the end user. Distribution at 11 kV / 6.6 kV / 3.3 kV constitutes the

last link to the consumer, who is connected directly or through transformers depending upon the drawl level of service. The transmission and distribution network include sub-stations, lines and distribution transformers. High voltage transmission is used so that smaller, more economical wire sizes can be employed to carry the lower current and to reduce losses. Sub-stations, containing step-down transformers, reduce the voltage for distribution to industrial users. The voltage is further reduced for commercial facilities. Electricity must be generated, as and when it is needed since electricity cannot be stored virtually in the system.

B) DISTRIBUTION:

There is no difference between a transmission line and a distribution line except for the voltage level and power handling capability. Transmission lines are usually capable of transmitting large quantities of electric energy over great distances. They operate at high voltages. Distribution lines carry limited quantities of power over shorter distances. Voltage drops in line are in relation to the resistance and reactance of line, length and the current drawn. For the same quantity of power handled, lower the voltage, higher the current drawn and higher the voltage drop. The current drawn is inversely proportional to the voltage level for the same quantity of power handled. The power loss in line is proportional to resistance and square of current. (i.e. PLOSS=I2R). Higher voltage transmission and distribution thus would help to minimize line voltage drop in the ratio of voltages, and the line power loss in the ratio of square of voltages. For instance, if distribution of power is raised from 11 kV to 33 kV, the voltage drop would be lower by a factor 1/3 and the line loss would be lower by a factor (1/3)2 i.e., 1/9. Lower voltage transmission and distribution also calls for bigger size conductor on account of current handling capacity needed.

4. NEED OF POWER SYSTEM CONTROL

- Power system normally operates under steady state condition.
- In the steady state it is essential to maintain a power balance in the system.
- Under steady state operation both the system frequency and bus voltages are maintained constant.
- In reality, the system is never under steady state, as the load on the system changes continuously.
- The power output of generators must be adjusted all times so that power balance is maintained.

5. POWER SYSTEM CONTROL

- **Plant Level Control.**
- **System Level Control.**

A) PLANT LEVEL CONTROL:

1. Governor Control (or) Prime Mover Control:

It is concerned with speed regulation of the governor and the control of energy supply system variables such as boiler pressure, temperature and flows.

Governor is a device used to control the speed of a prime mover. A governor protects the prime mover from overspeed and keeps the prime mover speed at or near the desired revolutions per minute. When a prime mover drives an alternator supplying electrical power at a given frequency, a governor must be used to hold the prime mover at a speed that will yield this frequency. An unloaded diesel engine will fly to pieces unless it is under governor control.

2. Automatic Voltage Regulator (AVR) or Excitation Control:

- The function of AVR excitation control is to regulate generator voltage and reactive power output.
- Regulate generator voltage and output power.
- Terminal voltage & reactive power is also met.

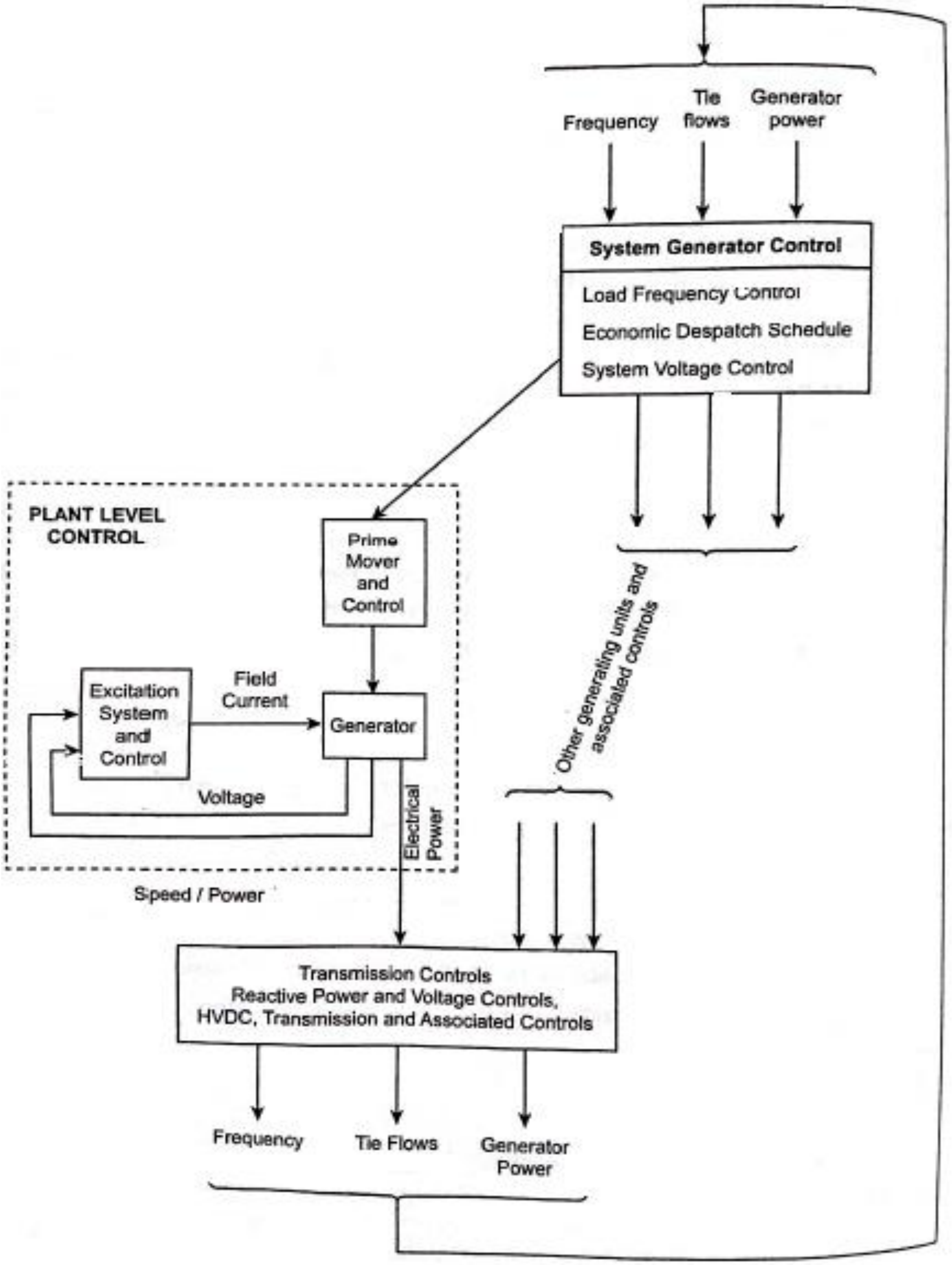


Fig2: Plant and System Level Control.

B) SYSTEM LEVEL CONTROL:

1) Load Frequency Control (LFC) :

- It involves the sensing of the bus bar frequency and compares with the tie-line power frequency.
- The frequency of tie-line is maintained as constant.
- Sense the bus bar frequency & power frequency
- Difference fed to the integrator & to speed changer.
- Tie line frequency maintained constant

2) Economic Dispatch Control (EDC):

- The purpose of economic dispatch (or) optimal dispatch is to minimize the fuel costs for the power system.
- When load distribution between a number of generator units considered optimum schedule affected when increase at one replaces a decreases at other.
- Optimum use of generators at each station at various load is known as economic dispatch control.

3) System Voltage Control (SVC):

- It involves the process of controlling the system voltage within tolerable limits.
- Control the voltage within the tolerable limits. Devices used are
    - Static VAR compensator.
    - Synchronous condenser.
    - Tap changing transformer.

4) Security Control:

- The main objective of real time power system operation requires a process guided by control and decisions based on constant monitoring of the system condition.

Level 1: Monitoring and Decision:

- The condition of the system is continuously observed in the control centres by protective relays for faults or contingencies caused by equipment trouble and failure.

Level 2: Control:

- At each sample, the proper commands are generated for correcting the abnormality on protecting the system from its consequences.
- If no abnormality is observed, then the system is in a normal condition.
- Proper commands are generated for correcting the abnormality in protecting the s ystem
- If no abnormality is observed, then the normal operation proceeds for next interval.
- Central controls are used to monitor the interconnected areas
- Inter connected areas can be tolerate larger load changes with smaller frequency deviations

- Central control centre monitors information about frequency, generating unit outputs and tie line power flows to interconnected areas.
- This information is used by automation load frequency control in order to maintain area frequency at its scheduled value.

6. SYSTEM LOAD VARIATION

- The variation of load on power station with respect to time.

SYSTEM LOADS:

From system point of view, there are 5 broad categories of loads:

- Domestic Load.
- Commercial Load.
- Industrial Load.
- Agriculture Load.
- Others - street lights, traction.

1. DOMESTIC LOAD:

- Lights, fans, domestic appliances like heaters, refrigerators, air conditioners, mixers, ovens, small motors etc.
- Demand factor = 0.7 to 1.0; Diversity factor = 1.2 to 1.3; Load factor = 0.1 to 0.15

2. COMMERCIAL LOAD:

- Lightings for shops, advertising hoardings, fans, AC etc.
- Demand factor = 0.9 to 1.0; Diversity factor = 1.1 to 1.2; Load factor = 0.25 to 0.3

3. INDUSTRIAL LOAD:

- Small scale industries: 0-20kW.
- Medium scale industries: 20-100kW.
- Large scale industries: above 100kW.
- Industrial loads need power over a longer period which remains fairly uniform throughout the day.

4. FOR HEAVY INDUSTRIES LOAD:

- Demand factor = 0.85 to 0.9; Load factor = 0.7 to 0.8.

5. AGRICULTURE LOAD:

- Supplying water for irrigation using pumps driven by motors.
- Demand factor = 0.9 to 1; Diversity factor = 1.0 to 1.5; Load factor = 0.15 to 0.25.

6.OTHER LOADS:

- Bulk supplies, street lights, traction, government loads which have their own peculiar characteristics.

7. BASE LOAD:

- It is the load that has been drawn constantly throughout the time.

7. SYSTEM LOAD CHARACTERISITICS

❖ **LOAD:** It is a device that taps energy from the network.

1. RESISTIVE LOADS (25%):

- Heating and lighting equipments. e.g. Toaster, iron, electric blankets, Incandescent lamps

2. MOTORS LOADS (70%):

- Compressors (air conditioner, refrigerator), Pumps (well, pool), Fans, Household appliances (washer, mixer, vacuum cleaner), Large commercial 3-phase motors (grocery store chiller), Power tools (hand drill, lawn mower), Electric street cars.

3. ELECTRONIC DEVICES (5%):

- Power supplies for computers etc. e.g. Transformers (adapter, battery charger).

TWO TYPES OF CHARACTERISITICS:

- Static characteristics.
- Dynamic characteristics.

1. STATIC CHARACTERISTICS:

A) LIGHTING AND HEATING LOADS: Assume impedance load (Lumped load),

$$\mathbf{P + jQ = |V|^2\, Y^* = |V|^2 \frac{1}{R-jX}} \qquad \mathbf{\left[Y = \frac{1}{Z} = \frac{1}{R+jX}\right]}$$

Multiplying by complex conjugate of denominator and numerator, we get

$$\frac{|V|^2}{\mathbf{R-jX}} \;\mathbf{x}\; \frac{\mathbf{R+jX}}{\mathbf{R+jX}} = |\mathbf{V}|^2 \cdot \frac{\mathbf{R+jX}}{R^2+X^2}$$

Equating real and imaginary parts, we get

$$\mathbf{P} = |\mathrm{V}|^2 \cdot \frac{\mathbf{R}}{R^2+X^2}\,; \qquad \mathbf{Q} = |\mathrm{V}|^2 \cdot \frac{\mathbf{X}}{R^2+X^2}$$

B) COMPOSITE LOADS:

For a small voltage perturbation ΔV, for the real power.

Differentiating P with respect to $|\mathrm{V}|$,

$$\frac{\Delta\,\mathbf{P}}{\Delta\,\mathbf{V}} \approx \frac{\partial P}{\partial\,[V]} = 2\,|\mathbf{V}| \cdot \frac{\mathbf{R}}{R^2+X^2}$$

$$\frac{2}{|V|} \cdot |\mathrm{V}|^2 \cdot \frac{\mathrm{R}}{R^2+X^2} = \frac{2\,\mathrm{P}}{|\mathrm{V}|}$$

$$\frac{\Delta P}{P} = \frac{2\,\Delta\,|V|}{|V|}$$

❖ So a small change in voltage results in twice the relative change in MW.

Differentiating P with respect to f,

$$\frac{\Delta P}{\Delta f} \approx \frac{\partial P}{\partial f} = V^2R\left(-\frac{1}{(R^2+(2\pi f L)^2)^2}\right) x\ 2\ x\ 2\pi fL\ x\ 2\pi L$$

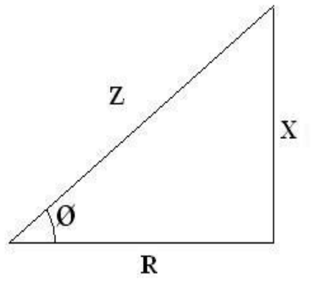
$$\frac{\Delta P}{\Delta f} = \frac{-|V|^2\, 4RX\pi L}{(R^2+X^2)^2}$$

Multiplying Numerator and Denominator by X, and substituting $\frac{2\pi L}{X} = \frac{1}{f}$, we get

$$= \frac{-|V|^2\, 2R\, X^2}{f\,(R^2+X^2)^2} = \frac{-P\, 2\, X^2}{f\,(R^2+X^2)}$$

$$\therefore \frac{\Delta P}{P} = \frac{-2\,X^2}{R^2+X^2} \cdot \frac{\Delta f}{f}$$

For cos ϕ = 0.8,



From the Impedance triangle,

$$\sin\phi = \frac{X}{Z} = \frac{X}{\sqrt{R^2+X^2}}$$

$$\frac{X^2}{R^2+X^2} = \sin^2\phi = 0.36$$

$$\therefore \frac{\Delta P}{P} = -0.72 \cdot \frac{\Delta f}{f}$$

∴2% frequency drop results in a 1.44% load increase.

8. ECONOMICS OF GENERATION

- Load Curve.
- Load Duration Curve.

A) LOAD CURVE:

- Curve between load variations on power station with respect to time.
  - Daily load curve.(load variation for 24hrs).
  - Monthly load curve (load variation for month).
  - Yearly or Annual load curve (load variation for year).

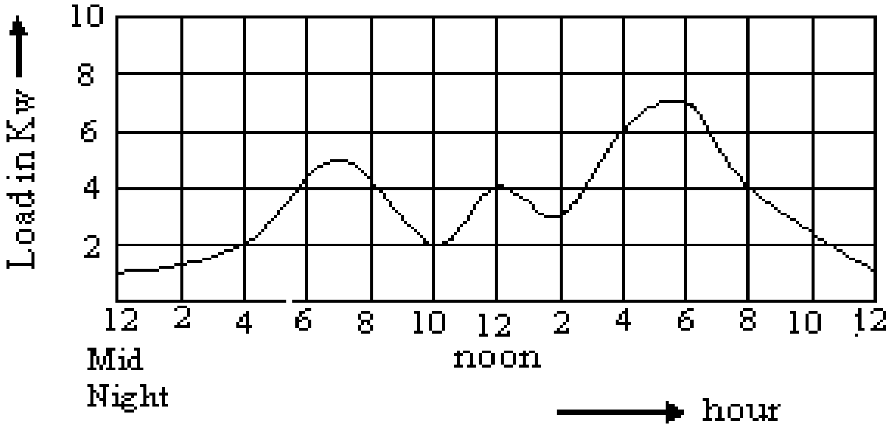


Fig3: Load Curve

- **DAILY LOAD CURVE:**

  - The load variation during the whole day are recorded hourly or half hourly and plotted against the time to get daily load curve.

- **MONTHLY LOAD CURVE :**

  - Obtained by calculating the average value of power at a particular time of the day from daily load curve.

- **ANNUAL LOAD CURVE:**

  - Obtained from monthly load curve of a particular year by calculating average value of power at a particular time of the day.

NEEDS OF LOAD CURVES:

- Load variation.
- Total number of power generated.
- Maximum demand.
- Average load.
- Load factor (curve Area and total rectangle area (Max Demand)).

B) LOAD DURATION CURVE:

- It is also load variation curve, but with loads arranged in descending order of magnitude.
- Can find load factor.
- When the load elements of a load curve are arranged in the order of descending magnitudes, the curve thus obtained is called load duration curve.
- The curve shows the number of hours during which the given load has prevailed.
- Area under this curve is same as that of the daily load curve.
- It can be extended to include any period of time.

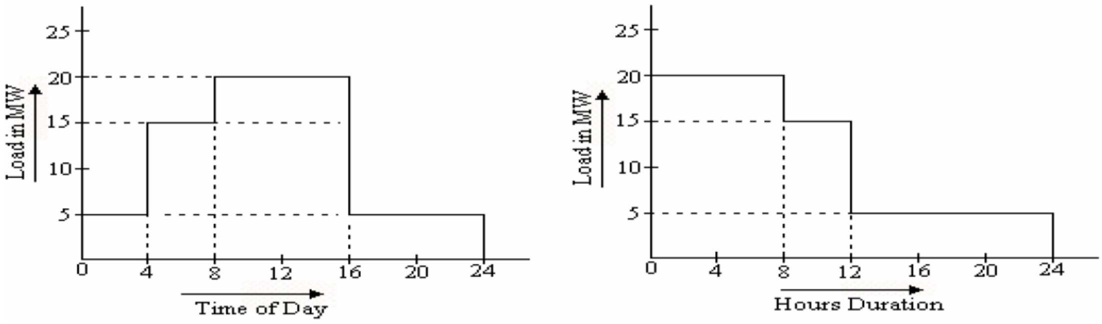


Fig4: Load Duration Curve

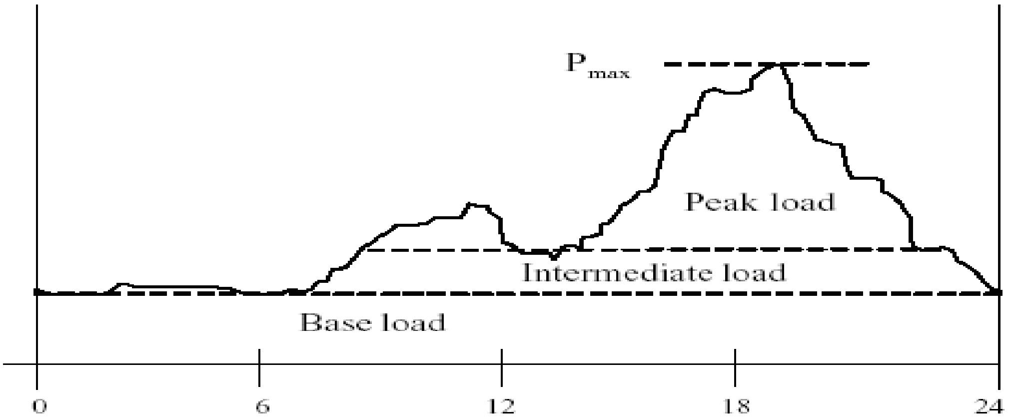


Fig5: Peak and Base Load

- **<u>BASE LOAD:</u>**
  - The unvarying load which occurs almost the whole day on the station is known as base load.
- **<u>PEAK LOAD :</u>**
  - The various peak demands of load over and above the base load of the station is known as peak load.

<u>1. CONNECTED LOAD:</u>

- Sum of continuous ratings of all electrical equipments connected to supply system.

<u>2. MAXIMUM DEMAND:</u>

- Greatest of all short time interval averaged.
- It determines cost and size of installation.

<u>3. DEMAND FACTOR:</u>

$$Demand\ Factor = \frac{\text{Actual Maximum Demand}}{\text{Total Connected Load}}$$

<u>4. AVERAGE LOAD OR DEMAND:</u>

$$\text{Daily Avg Load or Avg Demand} = \frac{\text{KWhr supplied ina day}}{24}$$

$$\text{Monthly Avg Load or Avg Demand} = \frac{\text{KWhr supplied in a month}}{24 \text{ x } 30}$$

$$\text{Annual Avg Load or Avg Demand} = \frac{\text{KWhr supplied in a year}}{24 \text{ x } 365}$$

5. LOAD FACTOR: (<1)

$$Load\ Factor = \frac{\text{Average Load over a given time period}}{\text{Peak Load during the same time period}}$$

$$Load\ Factor = \frac{\text{Average Demand}}{\text{Maximum Demand}}$$

$$Load\ Factor = \frac{\text{Units Generated over a given time period (T)}}{\text{Maximum Demand during the same time period (T)}}$$

6. DIVERSITY FACTOR:

$$Diversity\ Factor = \frac{\text{Sum of individual maximum demands}}{\text{Maximum demand of power Station}}$$

7. COINCIDENCE FACTOR: 1/ Diversity Factor

8. CAPACITY FACTOR:

$$Capacitor\ Factor = \frac{\text{Average Demand}}{\text{Rated Capacity of power plant}}$$

$$Capacitor\ Factor = \frac{\text{Units or KWhr Generated}}{\text{Plant Capacity x No of Hours}}$$

$$Utilisation\ Factor = \frac{\text{Max.Demand on the Power Satation}}{\text{Rated Capacity of the Power Station}}$$

9. RESERVE CAPACITY: Plant Capacity – M.D

9. LAOD FORECASTING

LAOD FORECASTING:

- Calculate the future power demand from given historical power data.

❖ **NEEDS OF LAOD FORECASTING:**

- To meet out the future demand.
- Long-term forecasting is required for preparing the maintenance schedule.
- For day-to-day operation, short term load forecasting is needed.
- Very short term load forecasting are used for generation and distribution.

Classification of load forecasting :

Forecast	Lead Time	Application
Very short term	Few minutes to half an hour	Real time control, real time security evaluation
Short term	Half an hour to a few hours	Allocation of spinning reserve, unit commitment, maintenance scheduling
Medium term	Few days to a few weeks	Planning or seasonal peak-winter, summer
Long term	Few months to a few years	To plan the growth of the generation capacity

❖ STRAIGHT LINE CURVE:

$\mathbf{PD_i = Y_i = a + bX_i}$, Here $(\mathbf{X_i = x_i - x_b})$, ($\mathbf{x_b}$ **is Base year)**

The matrix equation is,

$$\begin{bmatrix} n & \sum_{i=1}^{n} Xi \\ \sum_{i=1}^{n} Xi & \sum_{i=1}^{n} Xi^2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{N} \mathrm{Yi} \\ \sum_{i=1}^{N} \mathrm{Yi\ Xi} \end{bmatrix}$$

From this we can calculate $\Delta, \Delta1, \Delta2$ from this can calculate **a, b** values.

❖ EXPONENTIAL CURVE:

$\mathbf{PD_i} = e^{\mathbf{a + bXi}}$, but here $\mathbf{Y_i = \ln(PD_i)}$, Here $(\mathbf{X_i = x_i - x_b})$, ($\mathbf{x_b}$ **is Base year)**

The matrix equation is

$$\begin{bmatrix} n & \sum_{i=1}^{n} Xi \\ \sum_{i=1}^{n} Xi & \sum_{i=1}^{n} Xi^2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{N} \mathrm{lnYi} \\ \sum_{i=1}^{N} \mathrm{lnYi\ Xi} \end{bmatrix}$$

From this we can calculate $\Delta, \Delta1, \Delta2$ from this can calculate **a, b** values.

❖ PARABOLA (OR) QUADRATIC CURVE:

$\mathbf{PD_i = Y_i = a + b\,X_i + c\,X_i^2}$ Here $(\mathbf{X_i = x_i - x_b})$, ($\mathbf{x_b}$ **is Base year)**

The matrix equation is

$$\begin{bmatrix} n & \sum_{i=1}^{N} \mathbf{Xi} & \sum_{i=1}^{N} \mathbf{Xi}^2 \\ \sum_{i=1}^{N} \mathbf{Xi} & \sum_{i=1}^{N} \mathbf{Xi}^2 & \sum_{i=1}^{N} \mathbf{Xi}^3 \\ \sum_{i=1}^{N} \mathbf{Xi}^2 & \sum_{i=1}^{N} \mathbf{Xi}^3 & \sum_{i=1}^{N} \mathbf{Xi}^4 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{N} \mathbf{Yi} \\ \sum_{i=1}^{N} \mathbf{Yi\ Xi} \\ \sum_{i=1}^{N} \mathbf{Yi\ Xi}^2 \end{bmatrix}$$

From this we can calculate $\Delta, \Delta 1, \Delta 2$ from this can calculate **a, b** values.

10. RESERVE REQUIREMENTS

- Installed Reserves - Generating capacity which is the power intended to be always available.
- Spinning Reserves - Generating capacity which is connected to the bus and is ready to take load.
- Cold Reserves - it is available for service but not in operation.
- Hot Reserves - it is available for operation not in service.

PROBLEMS

SYSTEM LOAD CHARACTERISITCS PROBLEMS

1. Consider an inductive load of type Z=R+jX. By how many percent will the real load drop if the voltage is reduced by 5%? (6)

Solution:

$$\mathbf{P + jQ = |V|^2\, Y^* = |V|^2\, \frac{1}{R-jX} \left[Y = \frac{1}{Z} = \frac{1}{R+jX}\right]}$$

Multiplying by complex conjugate of denominator and numerator, we get

$$\frac{|V|^2}{\mathbf{R-jX}} \ \mathbf{x}\ \frac{\mathbf{R+jX}}{\mathbf{R+jX}} = |\mathbf{V}|^2 \cdot \frac{\mathbf{R+jX}}{R^2+X^2}$$

Equating real and imaginary parts, we get

$$\mathbf{P} = |\mathbf{V}|^2 \cdot \frac{\mathbf{R}}{R^2+X^2}; \qquad \mathbf{Q} = |\mathbf{V}|^2 \cdot \frac{\mathbf{X}}{R^2+X^2}$$

For a small voltage perturbation ΔV, for the real power.

Differentiating P with respect to $|V|$,

$$\frac{\Delta\, \mathbf{P}}{\Delta\, \mathbf{V}} \approx \frac{\partial P}{\partial\, [V]} = \mathbf{2}\, |\mathbf{V}| \cdot \frac{\mathbf{R}}{R^2+X^2}$$

$$\frac{\mathbf{2}}{|V|} \cdot |V|^2 \cdot \frac{R}{R^2+X^2} = \frac{2\,P}{|V|}$$

$$\frac{\Delta P}{P} = \frac{2\,\Delta\,|V|}{|V|}$$

A small change in voltage results in twice the relative change in MW. In this case **5% drop in voltage** causes a **10% drop in load**.

2. Consider an inductive load of type Z=R+jX. How would a 2 percent drop in frequency affect the real load, if the load is assumed to have a power factor of 0.8.

Solution:

$$P = |V|^2 \cdot \frac{R}{R^2+X^2} = \frac{V^2\,R}{R^2+(2\pi f L)^2}\;[\text{Where } X = 2\pi f L]$$

Differentiating P with respect to f,

$$\frac{\Delta P}{\Delta f} \approx \frac{\partial P}{\partial f} = V^2R\left(-\frac{1}{(R^2+(2\pi f L)^2)^2}\right) \text{x } 2 \text{ x } 2\pi f L \text{ x } 2\pi L$$

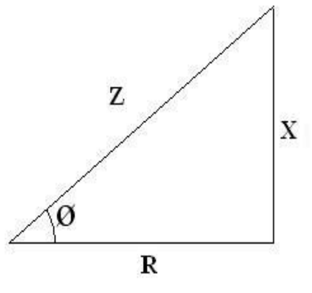
$$\frac{\Delta P}{\Delta f} = \frac{-|V|^2\,4RX\pi L}{(R^2+X^2)^2}$$

Multiplying Numerator and Denominator by X, and substituting $\frac{2\pi L}{X} = \frac{1}{f}$, we get

$$= \frac{-|V|^2\,2R\,X^2}{f\,(R^2+X^2)^2} = \frac{-P\,2\,X^2}{f\,(R^2+X^2)}$$

$$\therefore \frac{\Delta P}{P} = \frac{-2\,X^2}{R^2+X^2} \cdot \frac{\Delta f}{f}$$

For cos ϕ = 0.8,



From the Impedance triangle,

$$\sin\phi = \frac{X}{Z} = \frac{X}{\sqrt{R^2+X^2}}$$

$$\frac{X^2}{R^2+X^2} = \sin^2\phi = 0.36$$

$$\therefore \frac{\Delta P}{P} = -\,0.72 \cdot \frac{\Delta f}{f}$$

∴**2% frequency drop** results in a **1.44% load increase**.

LOAD AND LOAD DURATION CURVE PROBLEMS

3. The maximum demand on a power system is 100 MW. If the annual load factor is 40%, evaluate the total energy generated in a year.

Solution:

Maximum Demand = 100MW

Annual Load Factor = 40% = 0.4

$$\text{Load Factor} = \frac{Energy\ generated\ per\ annum}{Maximum\ demand\ X\ 365\ X\ 24}$$

Energy generated in a year = Load factor x Maximum Demand x 8760

= 0.4 x 100 x 8760 = **350.4 x10^3 MWhr**.

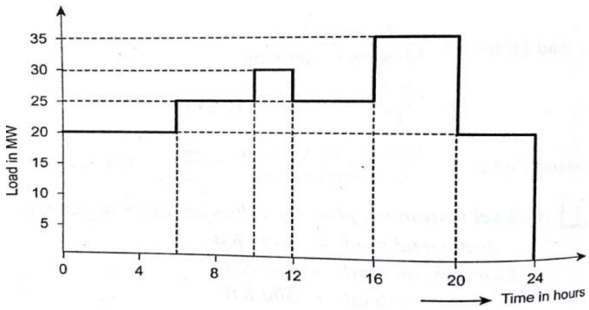
4. A generating station has the following daily load cycle:

Time (hours):	0-6	6-10	10-12	12-16	16-20	20-24
Load (MW):	20	25	30	25	35	20

Construct the load curve and evaluate,
1. Max.demand,
2. Units generated/day,
3. Average load,
4. Load factor.

Solution:

Load Curve:



(i) Maximum Demand = 35 MW = **35x10^3 kW**

(ii) Units generated per day= Area under the load curve in kWhr

= ((6x20) + (4x25) + (2x30) + (4x25) + (4x35) + (4x20)) x 10^3

=**600 x 10^3 kWhr**

(iii) Average Load= $\frac{Units\ generated\ per\ day}{Hours\ in\ a\ day}$

$= \frac{600 \text{ x } 10^3}{24}$= **25000 kW**

(iv) Load factor = $\frac{Average\ demand}{Maximum\ demand}$

$=\frac{25000}{35x10^3}$= 0.7143 = **71.43%**

---

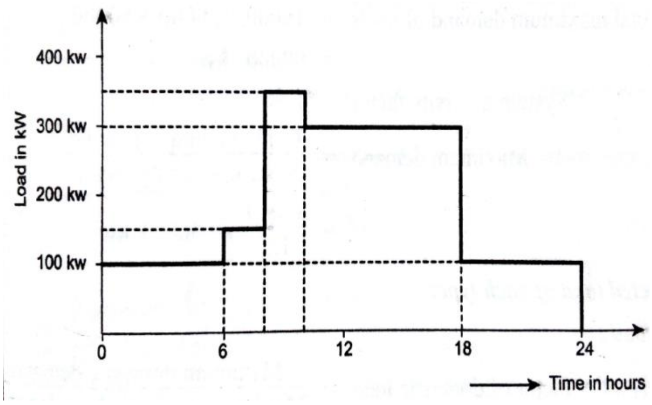
5. A power station has to meet the following demand:
Group A: 200 kW between 8 A.M and 6 P.M
Group B: 100 kW between 6 A.M and 10 A.M
Group C: 50 kW between 6 A.M and 10 A.M
Group D: 100 kW between 10 A.M and 6 P.M and then between 6 P.M and 6 A.M.
Construct the daily load curve and determine:
(i) Diversity factor, (ii) Units generated per day, (iii) Load factor.

Solution:

The given load cycle can be tabulated as follows:

Time (hours) / Group	0 - 6	6 – 8	8 - 10	10 - 18	18 - 24
A	-	-	200 kW	200 kW	-
B	-	100 Kw	100 kW	-	-
C	-	50 Kw	50 kW	-	-
D	100 kW	-	-	100 kW	100 kW
Total Load on Power station	100 kW	150 Kw	350 kW	300 kW	100 kW

Load Curve:



(i) Maximum Demand = **350 kW**

Diversity factor $= \frac{Sum\ of\ individual\ maximum\ demands}{Maximum\ demand\ on\ station}$

$= \frac{(200+100+50+100)}{350} = $ **1.286**

(ii) Units generated per day= Area under the load curve

= ((100x6) + (150x2) + (350x2) + (300x8) + (100x6) = 4**600 kWhr**

(iii) Load factor = $\dfrac{\text{Average demand}}{\text{Maximum demand}}$

Average Load= $\dfrac{\text{Units generated per day}}{\text{Hours in a day}}$

$= \dfrac{4600}{24} =$ **191.666 kW**

Load factor = $\dfrac{191.666}{350}$ = 0.5476 = **54.76%**

LOAD FORECASTING PROBLEMS

6. The recorded peak loads from 2006 to 2012 of an area are shown below.

Year	2006	2007	2008	2009	2010	2011	2012
Peak Load (MW)	570	590	740	750	810	890	990

Estimate the load upto 2019 by using quadratic curve method.

Solution:

Base year is taken as 2009.

$x_b = 2009$

Year (xi)	Peak Load MW (Y_i)	$X_i = xi - xb$ (xb = 2009)	X_i^2	X_i^3	X_i^4	Y_iX_i	$Y_iX_i^2$
2006	570	-3	9	-27	81	-1710	5130
2007	590	-2	4	-8	16	-1180	2360
2008	740	-1	1	-1	1	-740	740
2009	750	0	0	0	0	0	0
2010	810	1	1	1	1	810	810
2011	890	2	4	8	16	1780	3560
2012	990	3	9	27	81	2970	8910
	5340	**0**	**28**	**0**	**196**	**1930**	**21510**

Parabola (or) quadratic curve equation is

$$Y_i = a + b\,X_i + c\,X_i^2$$

The matrix equation is

$$\begin{bmatrix} n & \sum_{i=1}^{N} Xi & \sum_{i=1}^{N} Xi^2 \\ \sum_{i=1}^{N} Xi & \sum_{i=1}^{N} Xi^2 & \sum_{i=1}^{N} Xi^3 \\ \sum_{i=1}^{N} Xi^2 & \sum_{i=1}^{N} Xi^3 & \sum_{i=1}^{N} Xi^4 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{N} Xi \\ \sum_{i=1}^{N} Yi\ Xi \\ \sum_{i=1}^{N} Yi\ Xi^2 \end{bmatrix}$$

$$\begin{bmatrix} 7 & 0 & 28 \\ 0 & 28 & 0 \\ 28 & 0 & 196 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 5340 \\ 1930 \\ 21510 \end{bmatrix}$$

By applying Cramer's rule,

$$\Delta = \begin{vmatrix} 7 & 0 & 28 \\ 0 & 28 & 0 \\ 28 & 0 & 196 \end{vmatrix} = 7\,(28\text{x}196-0) + 28\,(0-28\text{x}28) = \mathbf{16464}$$

$$\Delta_1 = \begin{vmatrix} 5340 & 0 & 28 \\ 1930 & 28 & 0 \\ 21510 & 0 & 196 \end{vmatrix} = 5340\,(28\text{x}196) + 28\,(0\text{-}28\text{x}21510) = \mathbf{12442080}$$

$$\Delta_2 = \begin{vmatrix} 7 & 5340 & 28 \\ 0 & 1930 & 0 \\ 28 & 21510 & 196 \end{vmatrix} = 7\,(1930\text{x}196) - 5340\,(0\text{-}0) + 28\,(0\text{-}28\text{x}1930) = \mathbf{1134840}$$

$$\Delta_3 = \begin{vmatrix} 7 & 0 & 5340 \\ 0 & 28 & 1930 \\ 28 & 0 & 21510 \end{vmatrix} = 7\,(28\text{x}21510) + 5340\,(-28\text{x}28) = \mathbf{29400}$$

$a = \frac{\Delta_1}{\Delta} = \mathbf{755.714}$ $\qquad b = \frac{\Delta_2}{\Delta} = \mathbf{68.929}$ $\qquad c = \frac{\Delta_3}{\Delta} = \mathbf{1.786}$

Future demand is

Year (xi)	**X_i = xi – xb (xb = 2009)**	**X_i^2**	**$Y_i = a + b\,X_i + c\,X_i^2$** $= 755.14 + 68.929\,X_i + 1.786\,X_i^2$
2013	4	16	**1060**
2014	5	25	**1145**
2015	6	36	**1234**
2016	7	49	**1326**
2017	8	64	**1421**
2018	9	81	**1521**
2019	10	100	**1624**

UNIT II - REAL POWER AND FREQUENCY CONTROL

TECHNICAL TERMS

Control area: Most power systems normally control their generators in unison. The individual control loops have the same regulation parameters. The individual generator turbines tend to have the same response characteristics then it is possible to let the control loop in the whole system which then would be referred to as a control area.

Power Pool: An association of two or more interconnected electric systems having an agreement to coordinate operations and planning for improved reliability and efficiencies.

Prime Mover: The engine, turbine, water wheel, or similar machine that drives an electric generator; or, for reporting purposes, a device that converts energy to electricity directly (e.g., photovoltaic solar and fuel cell(s)).

Pumped-Storage Hydroelectric Plant: A plant that usually generates electric energy during peak-load periods by using water previously pumped into an elevated storage reservoir during off-peak periods when excess generating capacity is available to do so. When additional generating capacity is needed, the water can be released from the reservoir through a conduit to turbine generators located in a power plant at a lower level.

Regulation: The governmental function of controlling or directing economic entities through the process of rulemaking and adjudication

Reserve Margin (Operating): The amount of unused available capability of an electric power system at peak load for a utility system as a percentage of total capability.

Restructuring: The process of replacing a monopoly system of electric utilities with competing sellers, allowing individual retail customers to choose their electricity supplier but still receive delivery over the power lines of the local utility. It includes the reconfiguration of the vertically-integrated electric utility.

Retail Wheeling: The process of moving electric power from a point of generation across one or more utility-owned transmission and distribution systems to a retail customer.

Revenue: The total amount of money received by a firm from sales of its products and/or services, gains from the sales or exchange of assets, interest and dividends earned on investments, and other increases in the owner's equity except those arising from capital adjustments.

Scheduled Outage: The shutdown of a generating unit, transmission line, or other facility, for inspection or maintenance, in accordance with an advance schedule.

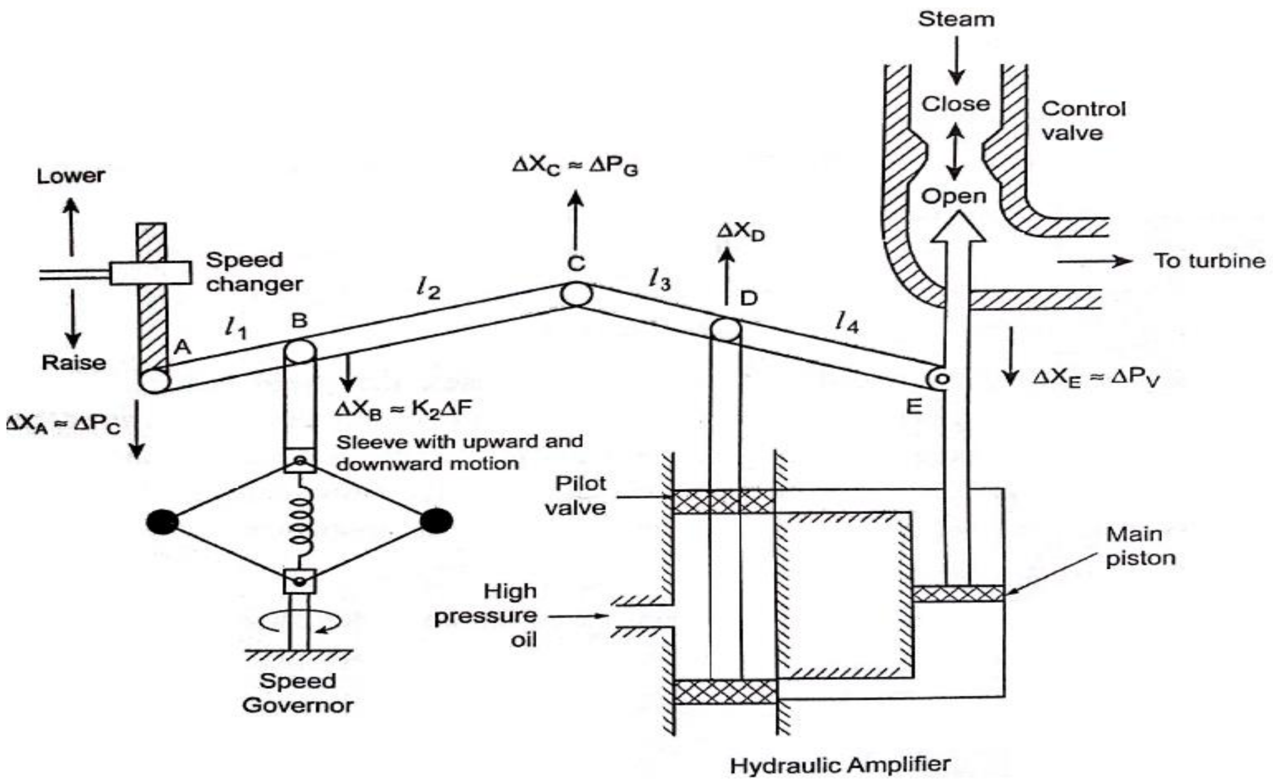
Real power: The real power in a power system is being controlled by controlling the driving torque of the individual turbines of the system.

LOAD FREQUENCY CONTROL

The following basic requirements are to be fulfilled for successful operation of the system:

1. The generation must be adequate to meet all the load demand
2. The system frequency must be maintained within narrow and rigid limits.
3. The system voltage profile must be maintained within reasonable limits and
4. In case of interconnected operation, the tie line power flows must be maintained at the specified values.

BASICS OF SPEED GOVERNING MECHANISM AND MODELING



This diagram represents the Speed Governing System of the steam Turbine. By controlling the position of the control valve or gate, we can exert control over the flow of high pressure Steam (or water) through the turbine.

Components of Speed Governing Systems:

Fly Ball Speed Governor:

- It is purely mechanical speed – sensitive device coupled directly to the hydraulic amplifier which adjusts the control valve opening via the linkage mechanism.
- As the load increase, speed of the Turbine decrease and the speed changer gives raise command, so the fly balls move outwards and the point B moves downwards and the reverse happens with the increased speed.

Speed Changer:

- It makes it Possible to restore the frequency to the initials (nominal) value after the operation of the speed governors which has steady state characteristics.
- A Small download movement of the linkage point A Corresponds to an increase ΔPc in the reference power setting.

•

Hydraulic Amplifier :

- It constists of pilot valve and main piston. With this arrangement, a low power pilot valve movement is converted into high power level movement of the oil – servomotor piston. The input to this amplifier is the position X_D of the pilot Valve. The output is the position X_E of the main piston.
- Hydraulic amplification is necessary so that the steam valve or gate could be operated against high pressure steam.

Linkage Mechanism:

- ABC is a rigid link pivoted at B and CDE is another rigid link pivoted at D. The function of the link mechanism is to control the steam valve or gate.
- We get feedback from the movement of the steam valve via link CD.

Working:

As load increases, the speed of the turbine decreases, the speed changer gives raise command and fly balls outwards and the point B moves downloads and D moves upwards and high pressure oil enters into the upper pilot valve and presses the main piston downwards and opens the valve or gate (i.e) increases the flow of steam to the turbine. Thereby, speed of flow of steam to the turbine increases and maintains constant frequency.

SINGLE AREA STATIC ANALYSIS OF UNCONTROLLED CASE

Consider the speed changer has a fixed setting. Under this condition $\Delta P_C = 0$and the load demand changes. This is known as "**Free Governor Operation**". (1)

The block diagram is shown below drawn from substituting $\Delta P_C = 0$in Fig. a.

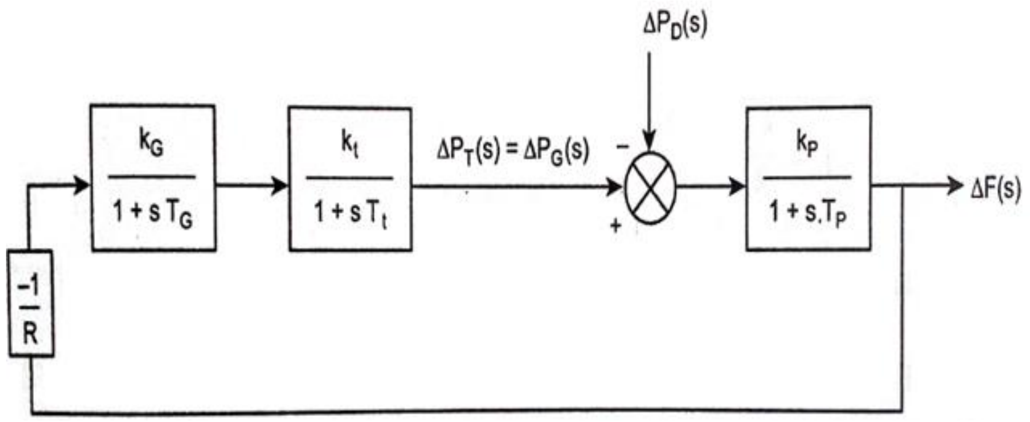


Fig. a.

Using block reduction technique, the block diagram is shown in Fig. b.

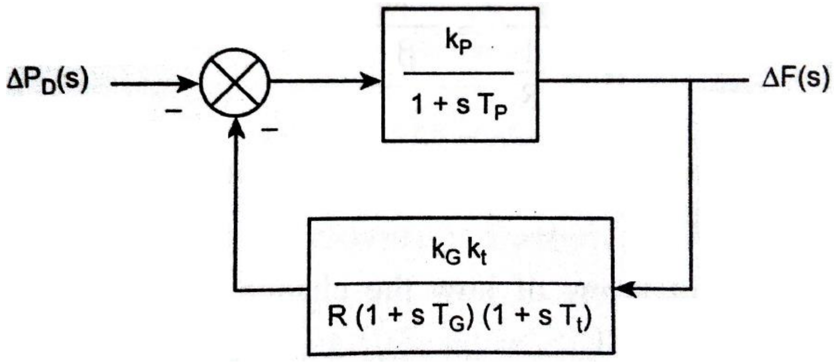


Fig. b.

$$\Delta F(s) = \frac{\frac{k_p}{1+sT_p}}{1+\frac{k_p}{1+sT_p} X \frac{k_G\, k_t}{R\,(1+sT_G)(1+sT_t)}}[-\Delta P_D(s)] \qquad [\text{T.F} = \frac{G\,(s)}{1+G(s)H(s)}]$$

$$\Delta F\,(s) = \frac{k_p}{1+s\,T_p+\frac{k_p\,k_G\,k_t}{R\,(1+sT_G)(1+sT_t)}}[-\Delta P_D(s)]$$

For a step load change $\Delta P_D(s) = \frac{\Delta P_D}{s}$

$$\Delta F\,(s) = \frac{-k_p}{1+s\,T_p+\frac{k_p\,k_G\,k_t}{R\,(1+sT_G)(1+sT_t)}} \text{ X } \frac{\Delta P_D}{s}$$

Applying final value theorem,

$$\boldsymbol{\Delta f_{stat} = \lim_{s\to 0} s.\Delta F\,(s) = \frac{-k_p}{1+\frac{k_p\,k_G\,k_t}{R}} \text{ X } \Delta P_D} \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(1)}$$

Practically $k_G\;k_t = 1$. [k_t is fixed and k_G can beadjusted by changing the links.]

Equation (1) becomes,

$$\Delta f_{stat} = \frac{-k_p}{1+\frac{k_p}{R}}\Delta P_D$$

Since $k_p = \frac{1}{B}$ and $\Delta P_D = M$

Where,

B = Load damping constant (normally expressed in percent. A value of B = 2 means that 1.0% change in frequency would cause a 2% change in load).

ΔP_D = Increase in load

$$\Delta f_{stat} = \frac{-\frac{1}{B}\Delta P_D}{1+\frac{1}{BR}} = \frac{-M}{B+\frac{1}{R}} = \frac{-M}{\beta} \text{ where } \beta = B + \frac{1}{R}.$$

β = Area frequency Response coefficient (or) characteristics (AFRC) in p.u. MW/Hz.

The system performance in terms of how the change in power affects the change in frequency is evaluated through AFRC.

In practice B << $\frac{1}{R}$, neglecting B.

Δf_{stat} = - R ΔP_D Hz

$$\boxed{\frac{\Delta f_{stat}}{\Delta P_D} = -R} \ \textbf{Hz / MW} \qquad \ldots\ldots\ldots\ldots\ldots \ \textbf{(2)}$$

Where R = Speed regulation

Δf_{stat} = Change in steady state frequency

Δf_{stat} = - R x ΔP_D Hz

When several generators with governor speed regulations R_1, R_2, ... R_n are connected to the system, the steady state deviation in frequency is given by:

$$\Delta f_{stat} = \frac{-\Delta P_D}{\left(B + \frac{1}{R1} + \frac{1}{R2} \ \ldots\ldots\ldots + \frac{1}{Rn}\right)}$$

The droop of the load frequency curve is shown in Fig. c is mainly determined by regulation.

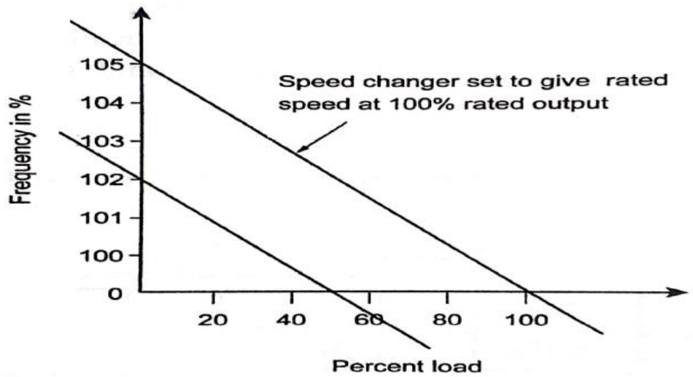


Fig. c. Speed – Load Characteristics

<u>Case (ii) : Static Analysis of Controlled Case</u>

In this case, there is a **step change ΔP_C** force for speed changer setting and the load demand remains fixed. i.e., **ΔP_D = 0.**

The block diagram is shown in Fig. d.

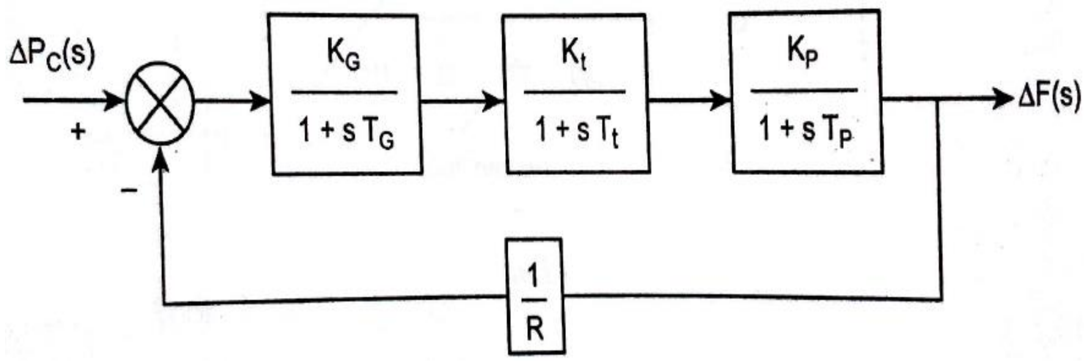


Fig. d. (1)

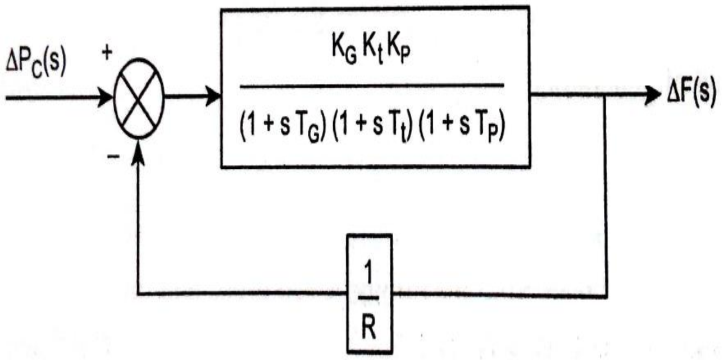


Fig. e.

$$\Delta F\,(s) = \frac{k_G\,k_t\,k_p}{(1+s\,T_G)(1+s\,T_t)\left(1+s\,T_p\right)+\frac{k_G\,k_t\,k_p}{R}}\Delta P_C(s)$$

Since $k_G\,k_t = 1$, $T_t = T_G = 0$

For a step change ΔP_C,

$$\Delta P_C(s) = \frac{\Delta P_C}{s}$$

$$\mathbf{\Delta F\,(s)} = \frac{k_p}{(1+s\,T_G)(1+s\,T_t)\left(1+s\,T_p\right)+\frac{k_p}{R}} \times \frac{\Delta P_C}{s}$$

Applying final value theorem, $\Delta f_{stat} = \lim_{s\to 0} s.\Delta F\,(s)$

$$\Delta f_{stat} = \frac{k_p}{1+\frac{k_p}{R}}\Delta P_C$$

$$\Delta f_{stat} = \frac{\frac{1}{B}}{1+\frac{1}{BR}}\Delta P_C = \frac{1}{B+\frac{1}{R}}$$

$$\boxed{\frac{\Delta f_{stat}}{\Delta P_c} = \frac{1}{B+\frac{1}{R}}}\quad \textbf{Hz / MW}$$

TIE-LINE WITH FREQUENCY BIAS CONTROL OF TWO AREA SYSTEM

Inadvertent Exchange:

The persistent static frequency error is intolerable in the single control area case. A persistent static error in tie-line power flow called *"**Inadvertent Exchange**"* – would mean that one area would have to support the other on a steady state basis.

Principle of tie line bias control (Pool Operation):

All operating pool (interconnected) members must contribute their share to frequency control in addition to taking care of their own net interchange.

In two-area system, we could conceive of an arrangement that area 1 be responsible for frequency reset and area 2 takes care of the tie-line power.
This arrangement gives rise to following ***Area Control Errors*** (**ACE**):

$$\mathbf{ACE_1} \;\; \Delta f_1$$

$$\mathbf{ACE_2} \;\; \Delta P_{tie\,2}$$

Area Control Error:
ACE is the change in area frequency which when used in integral control loop forced the steady state frequency error to zero.

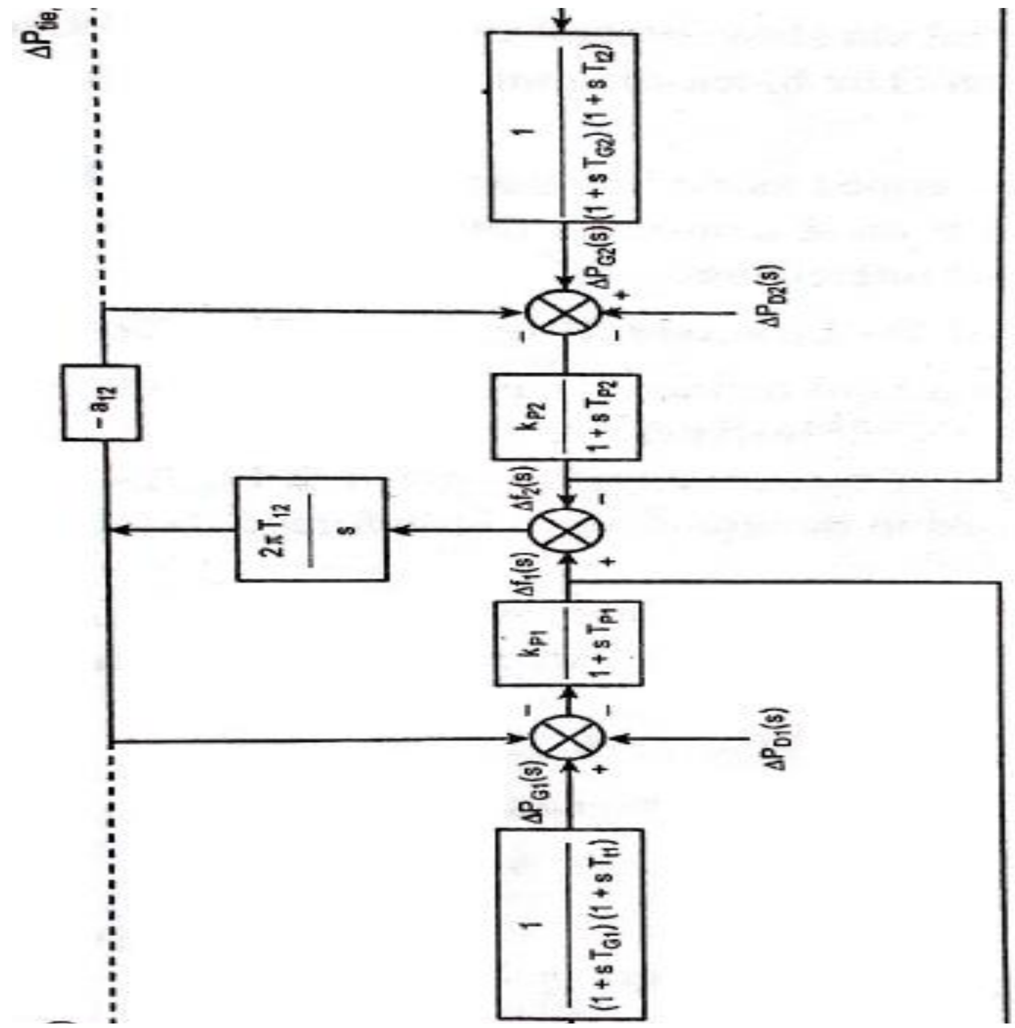
ACE = ΔP tie + b. Δf p.u. MW (for multi area system)
ACE = Δf (for single area system)

Where, b – Area frequency bias
ΔP tie – Change in tie-line power, Δf - Change in frequency

The ACE's would be fed via slow integrators (or) to the respective speed changers. But this arrangement is not so good.

Tie-line Bias Control:

- A control strategy which has been developed and adopted by most operating systems, is termed "tie-line bias control".
- It is based on the principle that all operating pool (interconnected) members must contribute their share to frequency control in addition to taking care of their own net interchange.



Block Diagram of Two Area Load Frequency Control with Tie-line Bias Control

Determination of Tie Line with Frequency Bias Control of Two Area System:

In order to make the steady state tie line power to zero, another integral control loop (one for each area) must be introduced to integrate the incremental tie line power signal and fed it back to speed changer.

$$\mathbf{ACE_1 = \Delta P_{tie,1} + b_1 . \Delta f_1 \ldots\ldots (1)}$$

$$\mathbf{ACE_2 = \Delta P_{tie,2} + b_1 . \Delta f_2 \ldots\ldots (2)} \quad (1)$$

Taking Laplace transform on equations (1) and (2), we get,

$$\mathbf{ACE_1 (s) = \Delta P_{tie,1} (s) + b_1 . \Delta F_1 (s)}$$

$$\mathbf{ACE_2 (s) = \Delta P_{tie,2} (s) + b_2 . \Delta F_2 (s)}$$

Speed changer commands are,

$$\mathbf{\Delta P_{c1} = - k_{11} \int (\Delta P_{tie,1} + b_1 . \Delta f_1)\, dt \quad \ldots\ldots (3)}$$

$$\mathbf{\Delta P_{c2} = - k_{12} \int (\Delta P_{tie,2} + b_2 . \Delta f_2)\, dt \quad \ldots\ldots (4)}$$

The constants k_{11} and $k_{12}$are integrator gains and constants b_1 and b_2 are the frequency bias parameters.

The minus sign must be included, since each area should increase its generation if either its frequency error or tie line power increment is negative.

MODELLING OF MULTI AREA (TWO AREA) SYSTEM

Static Analysis of Uncontrolled Case:

Case (i): For uncontrolled case,

$\mathbf{\Delta P_{c1} = \Delta P_{c2} = 0}$,i.e., No need to change the position of speed changer.

Suppose there is a sudden increase in load demand in the two areas by incremental steps ΔP_{D1}& ΔP_{D2}. Frequency drops in the steady state and these drops will be equal.

$$\Delta f_{1stat} = \Delta f_{2stat} = \Delta f_{stat}$$

At steady state condition, we will have incremental tie line power.

$$\left.\begin{aligned} \mathbf{\Delta P_{G1,\,stat}} &= -\frac{\mathbf{1}}{\boldsymbol{R_1}} \boldsymbol{\Delta f_{stat}} \\ \mathbf{\Delta P_{G2,\,stat}} &= -\frac{\mathbf{1}}{\boldsymbol{R_2}} \boldsymbol{\Delta f_{stat}} \end{aligned}\right\} \qquad \ldots\ldots\ldots\ldots \mathbf{(1)}$$

From the block diagram as shown in Fig.

$$[\Delta P_{G1,\,stat} - \Delta P_{D1} - \Delta P_{tie,1,\,stat}]\frac{k_{p1}}{1+s\,T_{p1}} = \Delta f_{stat}$$

$$[\Delta P_{G1,\,stat} - \Delta P_{D1} - \Delta P_{tie,1,\,stat}]\frac{\frac{1}{B}}{1+\frac{2\,H_S}{f^o B}} = \Delta f_{stat}$$

$$\Delta P_{G1,\,stat} - \Delta P_{D1} - \Delta P_{tie,1,\,stat} = [B + \frac{2\,H_S}{f^o}]\,\Delta f_{stat}$$

$$= \mathbf{B}\, \boldsymbol{\Delta f_{stat}} + \frac{\mathbf{2}\,\boldsymbol{H_S}}{\boldsymbol{f^o}} \frac{\boldsymbol{d}}{\boldsymbol{dt}} \boldsymbol{\Delta f_{stat}}$$

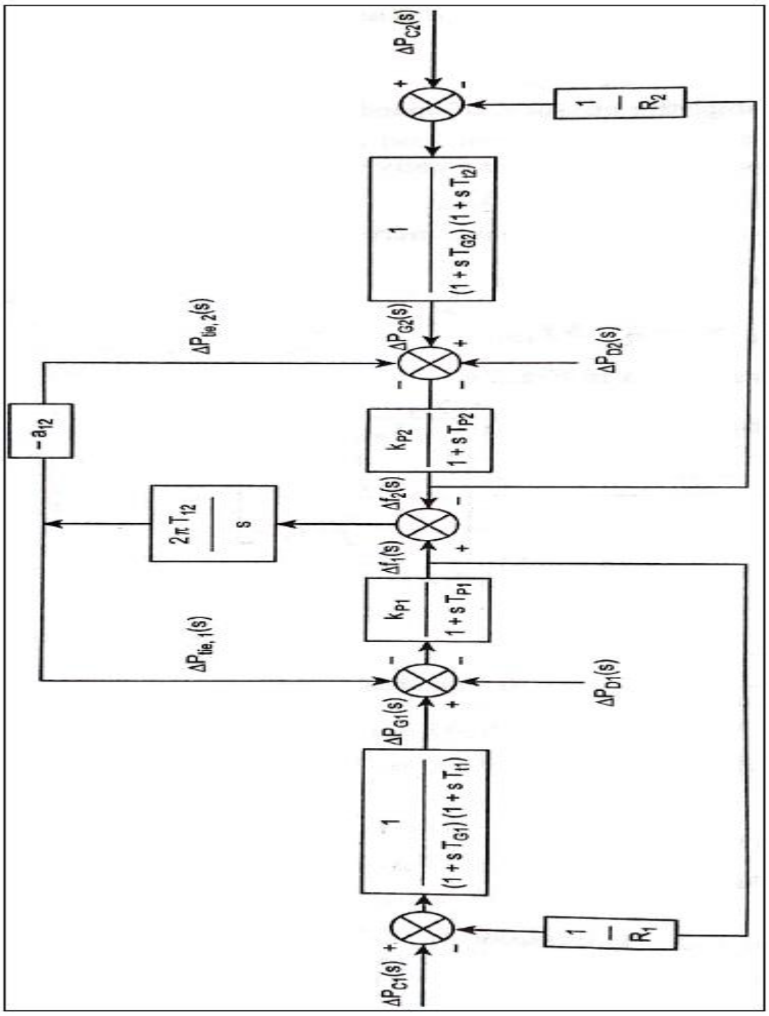


Fig. Block Diagram of Two Area Load Frequency Control

Put $\frac{d}{dt}\Delta f_{stat}$ = 0 for area 1, we get,

$\Delta P_{G1,\,stat} - \Delta P_{D1} - \Delta P_{tie,1,\,stat} = B_1\Delta f_{stat}$

$\boldsymbol{\Delta P_{tie,1,\,stat} = \Delta P_{G1,\,stat} - \Delta P_{D1} - B_1\Delta f_{stat}}$ **. . . . . (2)**

Similarly for area 2,

$\Delta P_{G2,\,stat} - \Delta P_{D2} = B_2\Delta f_{stat} + \Delta P_{tie,2,\,stat}$

$= B_2\Delta f_{stat} - a_{12}\Delta P_{tie,1,\,stat}$

$\boldsymbol{= B_2\Delta f_{stat} - a_{12}[\Delta P_{G1,\,stat} - \Delta P_{D1} - B_1\Delta f_{stat}]}$ **. . . . . . (3)**

Substituting equation (1) in equation (3), we get

$-\frac{1}{R_2}\Delta f_{stat} - \Delta P_{D2} = B_2\Delta f_{stat} + \frac{a_{12}}{R_1}\Delta f_{stat} - a_{12}\Delta P_{D1} + a_{12}B_1\Delta f_{stat}$

$\Delta f_{stat}\,[-\frac{1}{R_2} - B_2 - \frac{a_{12}}{R_1} - a_{12}B_1] = -a_{12}\Delta P_{D1} + \Delta P_{D2}$

$$\boldsymbol{\Delta f_{stat} = \frac{-[\Delta PD2 + a_{12}\Delta PD1]}{(B_2+\frac{1}{R_2}) + a_{12}\,(B_1+\frac{1}{R_1})}} \qquad \textbf{. . . . . (4)}$$

$\Delta P_{tie,1,\,stat} = \Delta P_{G1,\,stat} - \Delta P_{D1} - B_1\Delta f_{stat} = -\frac{1}{R_1}\Delta f_{stat} - \Delta P_{D1} - B_1\Delta f_{stat}$

$\boldsymbol{= -\Delta f_{stat}[B_1 + \frac{1}{R_1}] - \Delta P_{D1}}$ **.. . . . . . . (5)**

Substituting (4) in equation (5), we get,

$$\boldsymbol{\Delta f_{stat} = -\left[\frac{\Delta PD2 + a_{12}\Delta PD1}{\beta_2 + a_{12}\beta_1}\right]}$$

For two identical areas,

$$\beta_1 = \beta_2 = \beta$$
$$R_1 = R_2 = R$$
$$B_1 = B_2 = B$$

$$a_{12} = \frac{P_{r1}}{P_{r2}} = 1$$

$$\therefore \Delta f_{stat} = -\left[\frac{\Delta PD2 - \Delta PD1}{2\beta}\right]$$

$$\therefore \Delta P_{tie,1,\,stat} = -\Delta P_{tie,2,\,stat} = \frac{\Delta PD2 - \Delta PD1}{2}$$

Suppose a step load change occurs at area (1),

$$\Delta P_{D2} = 0$$

$$\Delta f_{stat} = \frac{-\Delta PD1}{2\beta} \text{Hz}$$

$$\Delta P_{tie,1,\,stat} = \frac{-\Delta PD1}{2} \text{p.u MW}$$

Suppose a step load change occurs at area (2),

$$\Delta P_{D1} = 0$$

$$\Delta f_{stat} = \frac{-\Delta PD2}{2\beta} \text{Hz}$$

$$\Delta P_{tie,1,\,stat} = \frac{-\Delta PD2}{2} \text{p.u MW}$$

For interconnected power system, the steady state frequency error is reduced by 50% and the change in tie line power is also reduced by 50%.

STATE VARIABLE MODEL OF SINGLE AREA LFC SYSTEM

The model of load frequency control of single area system is shown in Fig. a.

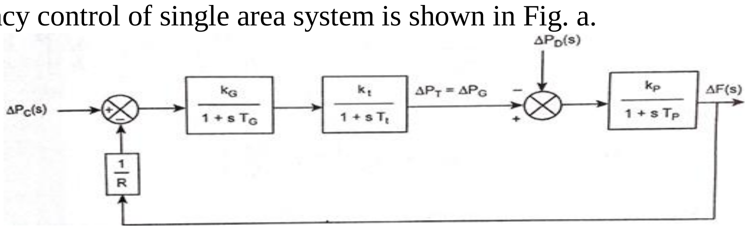


Fig. a. Model of LFC of Single Area

Assume $K_G K_T \approx 1$

Laplace transform equations are,

$$\Delta P_V(s) = \frac{1}{(1 + sT_G)}\left[\Delta P_C(s) - \frac{1}{R}\Delta F(s)\right] \quad \ldots\ldots\ldots (1)$$

$$\Delta P_T(s) = \frac{1}{(1 + sT_T)}\Delta P_V(s) \quad \ldots\ldots\ldots (2)$$

$$\Delta F(s) = \frac{kp}{(1 + sT_p)}\left[\Delta P_T(s) - \Delta P_D(s)\right] \quad \ldots\ldots\ldots (3)$$

We can write equations (1), (2) and (3) as,

$$\Delta P_V(s) + s\,T_G \Delta P_V(s) = \left[\Delta P_C(s) - \frac{1}{R}\Delta F(s)\right] \quad \ldots\ldots\ldots (4) \qquad (1)$$

$$\Delta P_T(s) + s\,T_T\,\Delta P_T(s) = \Delta P_V(s) \quad \ldots\ldots\ldots (5) \qquad (1)$$

$$\Delta F(s) + s\,T_P\,\Delta F(s) = k_p \Delta P_T(s) - k_p \Delta P_D(s) \quad \ldots\ldots\ldots (6) \qquad (1)$$

We can rewrite equations (4), (5) and (6) as,

$$\Delta P_V + T_G \frac{d(\Delta PV)}{dt} = \Delta P_C - \frac{\Delta F)}{R}$$

$$\Delta P_T + T_T \frac{d(\Delta PT)}{dt} = \Delta P_V$$

$$\Delta F + T_p \frac{d(\Delta F)}{dt} = k_p \Delta P_T - k_p \Delta P_D$$

Let us define control input ΔP_C = uand disturbance factor ΔP_D = P

In the domain form, $\frac{d(\Delta PV)}{dt} = \frac{-\Delta P_V}{T_G} - \frac{\Delta F}{R\,T_G} + \frac{u}{T_G}$

$$\frac{d(\Delta PT)}{dt} = \frac{\Delta P_V}{T_T} - \frac{\Delta P_T}{T_T}$$

$$\frac{d(\Delta F)}{dt} = \frac{k_p}{T_p}\Delta P_T - \frac{\Delta F}{T_p} - P\frac{k_p}{T_p}$$

Let ΔP_V, ΔP_T andΔF be the state variables.

$$\therefore \textbf{State vector } \mathbf{X} = \begin{bmatrix} x1 \\ x2 \\ x3 \end{bmatrix} = \begin{bmatrix} \Delta P_V \\ \Delta P_T \\ \Delta F \end{bmatrix}$$

Write the equations in state variable form as,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} \frac{-1}{T_G} & 0 & \frac{-1}{R\,T_G} \\ \frac{1}{T_T} & \frac{-1}{T_T} & 0 \\ 0 & \frac{k_p}{T_p} & \frac{-1}{T_p} \end{bmatrix} \begin{bmatrix} x1 \\ x2 \\ x3 \end{bmatrix} + \begin{bmatrix} \frac{1}{T_G} \\ 0 \\ 0 \end{bmatrix} \mathbf{U} + \begin{bmatrix} 0 \\ 0 \\ \frac{-k_p}{T_p} \end{bmatrix} \mathbf{P}$$

In compact form, X = AX + BU + ɼ P

Block diagram of linear model is as shown in Fig. b.

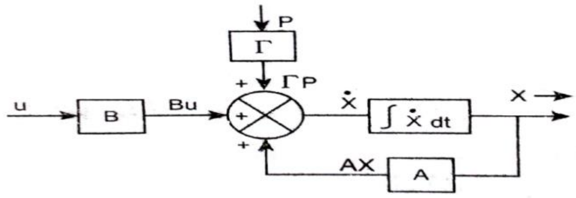


Fig. b. Block Diagram of Linear State Model

If we are considering economic dispatch controller, the optimum feedback controller is as shown in Fig.c.

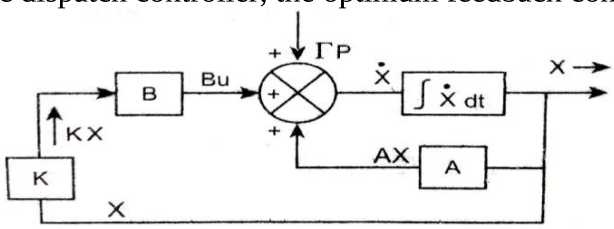


Fig. c. Optimum Feedback Controller

Consider two area system, we have two control and disturbance forces.

Let u be the control force & p be the disturbance force vector.

$$\mathbf{u} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \Delta \begin{bmatrix} \Delta P_{C1} \\ \Delta P_{C2} \end{bmatrix}; \qquad \mathbf{p} = \begin{bmatrix} p_1 \\ p_2 \end{bmatrix} \Delta \begin{bmatrix} \Delta P_{D1} \\ \Delta P_{D2} \end{bmatrix}$$

Advantages of Two Area Control:

Interconnection between areas is advantageous because:

(i) Under normal operating conditions, besides meeting respective area loads, scheduled interchange between areas can take place.

(ii) Under abnormal conditions, such as loss of generation in area, power can flow from other areas, through the interconnection.
(iii) Such pool (interconnected) operation where mutual assistance is possible which reduces the reserve capacity needed.
(iv) For a large system with many areas, the kinetic energy of the rotatory inertia is high. A sudden load change may not cause any considerable transient frequency deviation.

A two area system connected by a tie-line has the following parameters with base MVA for each area.

Area	1	2
Turbine output power	2000 MVA	1000 MVA
Nominal Frequency	50 Hz	50 Hz
Speed regulation	3%	5%
Power system gain (k_p)	50 Hz / p.u MW	40
Governor time constant	0.3	0.2
Turbine time constant	0.6	0.4

The synchronizing power coefficient is computed from the initial operating condition T_{12} = 2.0 p.u. A load change of 400 MW occurs in area 1. Determine the steady state frequency and the change in the tie-line flow, comment on the results. (13)

Solution:

$$B_1 = \frac{1}{k_{p1}} = \frac{1}{50} = \mathbf{0.02\ p.u\ MW / Hz}$$

$$B_2 = \frac{1}{k_{p2}} = \frac{1}{40} = \mathbf{0.025\ p.u\ MW / Hz}$$

$$R_1 = \frac{3}{100} X \frac{f_r}{P_r} = \frac{3}{100} X \frac{50}{2000} = 7.5 \times 10^{-4}\ Hz / MW$$

$$= \mathbf{7.5 \times 10^{-4} \times 2000 = 1.5\ Hz / p.u\ MW}$$

$$R_2 = \frac{5}{100} X \frac{f_r}{P_r} = \frac{5}{100} X \frac{50}{1000} = 2.5 \times 10^{-3}\ Hz / MW$$

$$= \mathbf{2.5 \times 10^{-3} x\ 1000 = 2.5\ Hz / p.u\ MW}$$

$$\Delta P_{D1} = 400\ MW = \frac{400}{2000} = \mathbf{0.2\ p.u}$$

$$\Delta P_{D2} = 0$$

$$\beta_1 = B_1 + \frac{1}{R_1} = 0.02 + \frac{1}{1.5} = \mathbf{0.6867}$$

$$\beta_2 = B_2 + \frac{1}{R_2} = 0.025 + \frac{1}{2.5} = \mathbf{0.425} \qquad (1)$$

$$a_{12} = \frac{P_{r1}}{P_{r2}} = \frac{2000}{1000} = \mathbf{2}$$

$$\Delta f = \frac{-(\Delta P_{D2} + a12 \Delta P_{D1})}{\beta 2 + a12\ \beta 1} = \mathbf{-} \left[\frac{0+2 x\ 0.2)}{0.425+2\ x\ 0.6867}\right] = -\ 0.2224\ Hz$$

System frequency, $f = f_0 + \Delta f$ = 50 + (0.2224) = **49.777 Hz** (2)

$$\Delta P_{\text{tie, 1 ,stat}} = \frac{\beta 1\ \Delta P_{D2} - \beta 2 \Delta P_{D1}}{\beta 2 + a12\ \beta 1} = \frac{0 - 0.425\ X(0.2)}{0.425 + 2\ X\ 0.6867}$$

$$= -\ 0.0472\ p.u$$

$$= -\ 0.0472 \times 2000 = \mathbf{-\ 94.52\ MW}$$

Change in generation for area 1, $\Delta P_{G1} = \frac{-\Delta f}{R_1} = \frac{0.2224}{1.5}$

$$= 0.149\ p.u = \mathbf{296.5\ MW}$$

Change in generation for area 2, $\Delta P_{G2} = \frac{-\Delta f}{R_2} = \frac{0.2224}{2.5}$

$$= 0.08896\ p.u = \mathbf{88.96\ MW}$$

Change in load for area 1, $\Delta P_{D1} = B_1 \Delta f = 0.02 \times - 0.2224$

$= - 4.448 \times 10^{-3}$ p.u = **- 8.896 MW**

Change in load for area 2, $\Delta P_{D2} = B_2 \Delta f = 0.025 \times - 0.2224$

$= - 5.56 \times 10^{-3}$ p.u = **- 5.56 MW**

Change in total load = $\Delta P_{D1} + \Delta P_{D2}$ = **- 14.456 MW**

i.e., 94.52 MW flows from area 2 to area 1 and 88.96 MW comes from the increased generation in area 2 and 5.56 MW comes from the reduction in area 2 load due to frequency drop.

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT III – REACTIVE POWER AND VOLTGE CONTROL

GENERATORS AND CONSUMERS OF REACTIVE POWER IN A POWER SYSTEM

❖ **Synchronous Generators:**

- Synchronous machine can generate or **absorb reactive power (Q).**
- **Reactive power (Q) supplied** by synchronous generators depending upon the **Short Circuit Ratio (SCR).**

$$SCR = 1 / X_s$$

Where, X_s – Synchronous reactance

- An **overexcited synchronous machine** operated either as **generator or motor** ***generates KVAR*** and acts as a **shunt capacitor** as viewed from the network.
- While the **under excited synchronous machine**, ***absorbs KVAR*** from the network and acts consequently, as a **shunt reactor.** *(2)*

❖ **Transformers:**

- Transformers **always absorb reactive power.**
- If X_T is the **transformer reactance per phase** and |I| is the current flowing through it then,
- The total reactive power absorbed is $Q_T = 3|I|^2 X_T$ VAR

Where, X_T is in ohms, |I| is in amperes. *(2)*

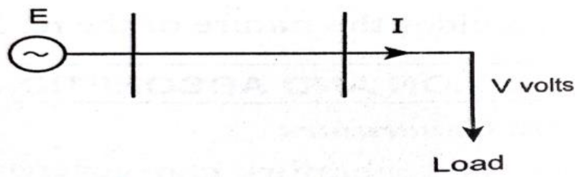
❖ **Cables:**

- Cables **generate** more **reactive power** than transmission line because the cables have **high capacitance.** *(1)*

❖ **Overhead Lines:**

- Transmission lines are considered as,
  - ✓ **Generating KVAR** in their **Shunt Capacitance**
  - ✓ **Consuming KVAR** in their **Series Inductance**
  - ✓ **Inductive KVAR Q_L** vary with **line current**
  - ✓ **Capacitive KVAR Q_C** vary with **system potential**

Consider **transmission line be loaded** such that ***load current*** ***'I'*** **amperes** and ***load voltage V'*** **volts** as shown below.



(2)

- If we assume the **transmission line to be lossless**, the **reactive power absorbed** by the line will be,

$$\Delta Q_L = |I|^2 \; X_L$$

$$\Delta Q_L = |I|^2 \; \omega \; L$$

- Due to the **capacitance of the line**, the **reactive power generated** by the line,

$$\Delta Q_C = \frac{|V|^2}{X_C} = |V|^2 \omega C$$

Suppose, $\Delta Q_L = \Delta Q_C$

$$|I^2| \omega L = |V|^2 \omega C$$

$$\left|\frac{V}{I}\right|^2 = \frac{\omega L}{\omega C} = \frac{L}{C}$$

$$Z_n = \frac{V}{I} = \sqrt{\frac{L}{C}}$$

Where **'Zn'** is called **Surge Impedance** of the line.

❖ ***Surge Power:***

- A **line** is said to be **operating** at its **surge impedance loading** when it is terminated by a resistance equal to its surge impedance. The **power transmitted** under this condition is called "**natural (or) surge power**". *(2)*

In general, $P = \frac{|E||V|}{X} \sin\delta$

At $\delta = 90°$, maximum power can be transferred.

$$P_{max} = \frac{|E||V|}{X} \quad MW$$

By varying X, δ, | V |, we can get the control of power transfer.

➢ ***Case (i) :***

$$\Delta Q_L > \Delta Q_C$$

$$|I|^2 \omega L > |V|^2 \omega C$$

- Here the **line is loaded below Zn** i.e., **light load condition**. The **net effect** of the ***line*** will be ***absorbed reactive power.*** *(1)*

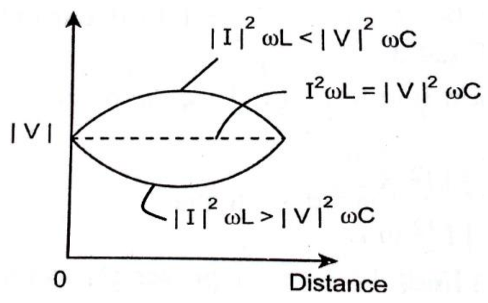
➢ ***Case (ii) :***

$$\Delta Q_L < \Delta Q_C$$

$$|I|^2 \omega L < |V|^2 \omega C$$

- Here we find that the voltage rises and maintains constant voltage at the ends.
- The **effect of shunt capacitors** is predominating and the ***line*** will ***generate reactive power.*** *(1)*

➢ The voltage sags if the voltages at the two ends are maintained constant; the variation of voltage along the line is shown below.



Variation of voltage as a function of distance of time

METHODS OF VOLTAGE CONTROL

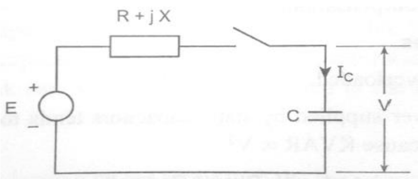
(i) Shunt Capacitors
(ii) Series Capacitors

❖ ***Static Shunt Capacitors:***

- **Shunt capacitor banks** are used to **supply reactive power** at both **transmission and distribution levels**; along lines or substations and loads.
- **Capacitors** are **either directly connected to a busbar (or) the tertiary winding of a main transformer.** They may be **switched ON and OFF** depending on the **changes in load demand.**
- When they are in **parallel with a load** having a **lagging power factor**, the **capacitors supply reactive power.**
- As the **voltage reduces**, so does the **reactive power output**, when it is required the most. This is called the "***destabilizing effect***" of power capacitors.

➢ **Rise in Voltage due to Shunt Capacitance:**

- The **equivalent circuit** of a **short transmission line with static shunt capacitor** is shown below.



Equivalent Circuit

- **Voltage drop without the shunt capacitor is,**

$$\Delta V = \frac{P_2 R + Q_2 X}{|V|}$$

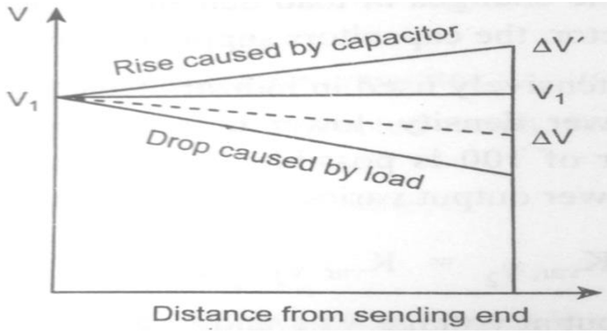
- **Voltage drop with shunt capacitor is,**

$$\Delta V' = \frac{P_2 R + (Q_2 - Q_C) X}{|V|}$$

- **Capacitor raises the voltage,**

$$\Delta V_C = \Delta V - \Delta V' = \frac{Q_C X}{|V|}$$

- **Voltage profile of a radial feeder having a capacitor is shown below.**



Voltage profile

Advantages:

- These are less costly and Flexibility of installation and operation
- Efficiency of transmission and distribution of power is high

Disadvantages:

- They cannot be overloaded
- The reactive power supplied by static capacitors tends to decrease in case of voltage dip on the bus because KVAR α V^2

Problems Associated with Shunt Capacitors :

- Switching inrush currents at higher frequencies and switching overvoltages
- Harmonic resonance problems
- Limited overvoltage withstand capability

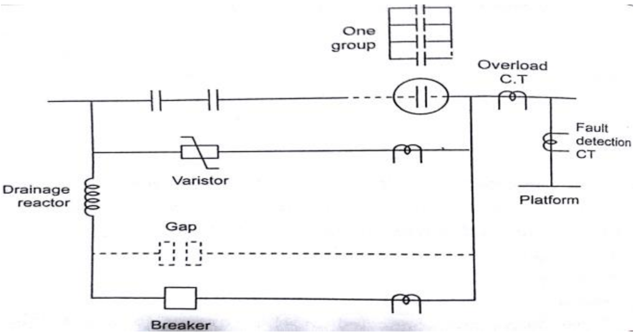
<u>Applications of using Shunt Capacitor to Distribution and Transmission System:</u>

- Shunt capacitors are used in distribution system to:
  - ✓ Improve power factor
  - ✓ Improve feeder voltage control
- Power factor correction
- Feeder voltage control
- Voltage regulation
- Reducing power loss

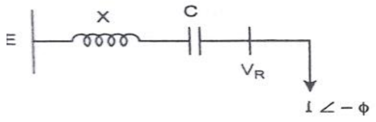
❖ ***<u>Static Series Capacitors:</u>***

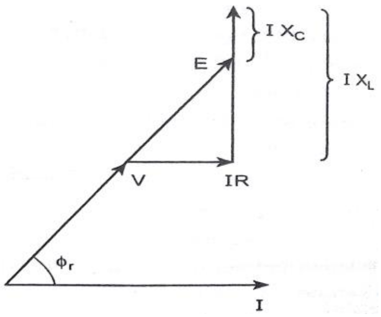
- It is **connected in series**to **compensate the inductive reactance of line.**This **reduces the transfer reactance between the buses** to which the line is connected.
- It **increases maximum power** that can be transmitted and **reduces the reactive power loss.**
- **Under fault conditions,**the **voltage across the capacitor rises,** and unlike a shunt capacitor, a series capacitor experiences many times its rated voltage due to fault currents.

➢ A **zinc oxide varistor in parallel with the capacitor**may be **adequate to limit this voltage.** The schematic diagram of a **series capacitor installation** is shown in below fig.



Schematic diagram of a series capacitor installation *(1)*





Phasor diagram when series capacitor is connected on a line *(1)*

- <u>**Drawbacks of Series Capacitor:**</u>
  - **High over-voltage is produced across the capacitor terminals** under **short circuit conditions.**Therefore, **very high protective equipment** is used. (**Ex: Spark gap**)
- <u>**Problems Associated with Series Capacitor:**</u>
  - **Locking of synchronous motor**during starting.
  - **Hunting of synchronous motor**at high load due to high R/X ratio.
  - **Ferro resonance**occurs between transformers and series capacitors which produces harmonic over voltages.
- <u>**Advantages:**</u>

  Series capacitors are used:
  - To **improve voltage regulation** of distribution and industrial feeders
  - To **reduce light flicker** problems
  - To **improve system stability**
- <u>**Applications:**</u>

  The applications of Series capacitors are:
  - Voltage rise due to reactive current.
  - By passing the capacitor during faults and reinsertion after fault clearing.

❖ <u>MODELLING OF TYPICAL EXCITATION SYSTEM (OR) MODELLING OF AUTOMATIC VOLTAGE REGULATOR (AVR)</u>

- Assume that for some reasons **generator terminal voltage** $|V|$ has been **decreased.**
- This results in **increased "error voltage" (e)** which in turn, causes **increased values of V_R, i_e, V_f** and **i_f.**
- The "direct axis" generator flux increases as a result of increase in if, thus, **raising** the **magnitude of the terminal voltage** to the required level.**(Thus Voltage is automatically regulated as our desired).**

❖ <u>**Potential Transformer and Rectifier:**</u>

- Using **potential transformer (P.T)**, the **terminal voltage of the generator** is **stepped down** to the value required for the control signal and then **rectified** to get **DC voltage** proportional to the r.m.s value of terminal voltage.

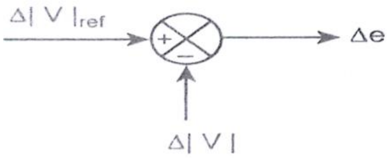
❖ <u>**Comparator:**</u>

- The **comparator compares** the **measured signal** $|V|$ against the **reference DC signal**. $|V|_{ref}$ The difference between these two signals produce an **error voltage 'V_e'** called "**error signal**".

The error signal, $\Delta e = \Delta |V|_{ref} - \Delta |V|$ . . . . . . **(1)**

Taking Laplace transform of equation (1),

$\Delta |V|_{ref}(s) - \Delta |V|(s) = \Delta e(s)$



Model of Comparator

❖ <u>**Amplifier:**</u>

- The ***amplifier*** **amplifies** the **input error signal** depending on the **amplification factor.**
- There are various ***types of amplifiers*** used in excitation system. They are **tuned generator**, **amplidyn**e and **electronic amplifier**.

$$\Delta V_R \, \alpha \, \Delta e$$
$$\Delta V_R = k_A \Delta e \; . \; . \; . \; . \; . \; . \; . \; . \; . \; \textbf{(2)}$$

Where, k_A = Amplifier gain, ΔV_R = Output voltage of an amplifier
Taking Laplace transform (L.T.) of equation (2).

$$\Delta V_R (s) = k_A \Delta e (s)$$

- Amplifier transfer function

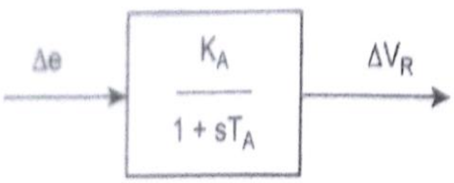
$$G_A = \Delta V_R (s) / \Delta e (s)$$
$$G_A = k_A$$

Where, k_A – Instantaneous amplifier gain, G_A – Amplifier transfer function.

In reality, the amplifier will have a time delay that can be represented by a time constant T_A shown in figure.

The amplifier transfer function becomes;

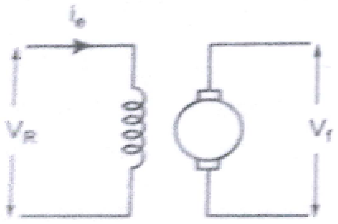
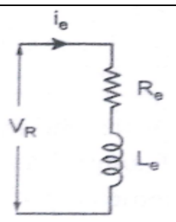
$$G_A = \frac{\Delta V_R(s)}{\Delta e(s)} = \frac{k_A}{1+sT_A}$$



Model of Comparator

- Typical value of **k_A**: **10 to 400 & T_A**: **0.02 to 0.1 sec***(2)*

- **Exciter:**
  - The ***purpose of exciter*** is to **supply field current** to **the rotor field of the synchronous generator.**

	
Circuit of an Exciter	**Equivalent circuit for field winding of an exciter**

Let R_e – exciter field resistor, L_e – exciter field inductance

From the equivalent circuit,

- **Input Voltage,**

$$\Delta V_R = R_e \Delta i_e + L_e \frac{d}{dt}(\Delta i_e)$$

- Output Voltage of an exciter or Field voltage of generator,

$$\Delta V_f \; \alpha \; \Delta i_e$$

$\Delta V_f = k_1 \Delta i_e$

Taking **Laplacetransform** of above equations,

$$\Delta V_R(s) = [R_e + L_e s]\, \Delta i_e(s)$$
$$\Delta V_f(s) = k_1 \, \Delta i_e(s)$$

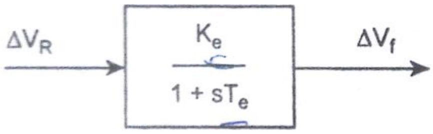
- **Transfer function of the exciter,**

$$G_e = \frac{\Delta V_f(s)}{\Delta V_R(s)} = \frac{k_1}{R_e + L_e s} = \frac{k_1}{R_e\left[1 + \left(\frac{L_e}{R_e}\right)s\right]}$$

$$G_e = \frac{\frac{k_1}{R_e}}{1 + \left(\frac{L_e}{R_e}\right)s}$$

$$G_e = \frac{k_e}{1 + s T_e}$$

Where, $k_e = k_1 / R_e$; $T_e = L_e / R_e$
k_e = Gain of the exciter, T_e = Time constant of the exciter in sec.
Values of time constant, **T_e ranges from 0.5 – 1.0 seconds**



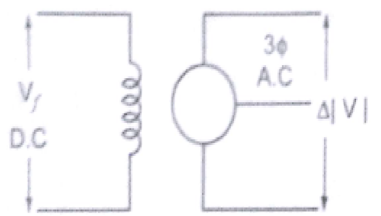
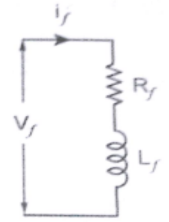
Model of an Exciter*(2.5)*

❖ **Synchronous Generator:**

- **Synchronous generator generates 3ϕ AC power** at its terminals. The **terminal voltage** of the generator is **maintained constant** during its **varying load conditions**, with the help of **excitation system**.
- The **terminal voltage (V)** of the generator equals to the **difference between induced emf (E)** and **drop across the armature (V_{drop}).**

$$\Delta V = \Delta E - V_{drop}$$

The relationship between V_f and V depends on the generator loading.
At no load the drop can be neglected, Hence, **V = E (neglect drop)**

	
Circuit diagram of a Synchronous Generator	**Equivalent circuit for field winding of a Synchronous Generator**

Taking Laplace transform,

Hence, $\Delta V(s) = \Delta E(s)$

Applying KVL to the field winding,

$$\Delta V_f = R_f \, \Delta i_f + L_f \frac{d}{dt} (\Delta i_f)$$

$$E_{max} = I_f X_L = I_f \cdot \omega L_{fa}$$

$$E_{rms} = \left(\frac{I_f}{\sqrt{2}}\right) \omega L_{fa}$$

$$I_f = \frac{\sqrt{2}}{\omega L_{fa}} E_{rms} = \frac{\sqrt{2}\ E}{\omega L_{fa}}$$

$$\Delta V_f = \frac{\sqrt{2}}{\omega L_{fa}} \left[R_f \Delta E + L_f \frac{d}{dt} \Delta E \right]$$

Taking Laplace transform,

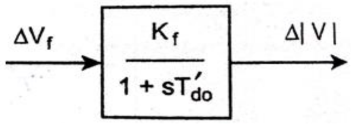
$$\Delta V_f(s) = \frac{\sqrt{2}}{\omega L_{fa}} [R_f + s L_f] \Delta E(s)$$

Transfer function of the generator,

$$\frac{\Delta V(s)}{\Delta V_f(s)} = \frac{\Delta E(s)}{\Delta V_f(s)} = \frac{\Delta E(s)}{\frac{\sqrt{2}}{\omega L_{fa}}[R_f + s L_f]\,\Delta E(s)}$$

$$= \frac{\omega L_{fa}}{\sqrt{2}\; R_f\left[1 + \frac{L_f}{R_f}s\right]} = \frac{K_f}{1 + s T'_{do}}$$

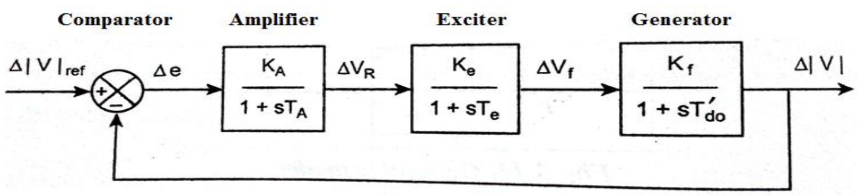
Where, $k_f = K_f = \frac{\omega L_{fa}}{\sqrt{2}\, R_f}$ ɔen circuit direct axis time constant



Generator Model

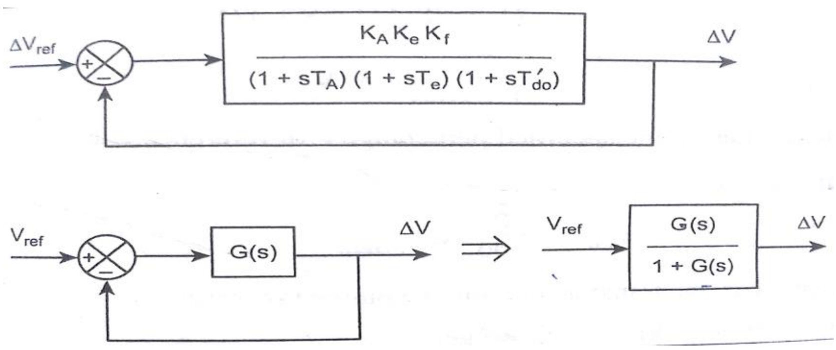
Typical values of **k_f: 0.7 to 1 and T_{do}: 1.0 to 2.0 sec***(2.5)*

Combining all the individual blocks, we get the **closed loop model of AVR** as shown below:



Closed Loop Model of AVR*(1)*

Applying **block reduction technique**, the reduced model as shown below:



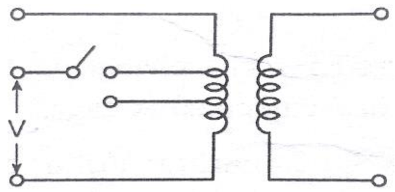
Open loop transfer function,

$$G(s) = \frac{K_A K_e K_f}{(1 + s T_A)(1 + s T_e)(1 + s T'_{do})}$$

Where, **Open loop gain**, $k = k_A\, k_e\, k_f$

TAP CHANGING TRANSFORMER IN VOLTAGE CONTROL:

❖ **Off-Load Tap Changing Transformer :**

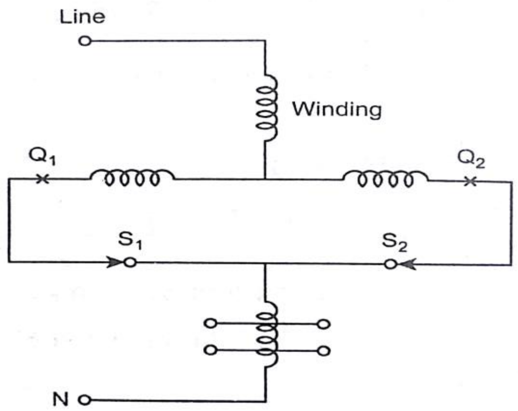


Off-load tap changing transformer

- The **off-load tap changing transformer** requires the **disconnection of the transformer** when the **tap setting is to be changed.**
- **Off-load tap changers** are used when it is to be operated in frequently **due to load growth (or) some seasonal change.**

❖ <u>**On-Load Tap Changing Transformer (OLTC):**</u>

- The **On-load tap changing transformer** is used when changes in transformer ratio to be needed frequently, and **no need to switch off the transformer** to change the tap of transformer.
- It is **used** on **power transformers**, **auto transformers** and **bulk distribution transformers** and at other points of load service.*(2)*
- The modern practice is to use **on-load tap changing transformer** which is shown in the following figure.



On-load tap changing transformer

- In the position shown, the voltage is maximum and since the currents divide equally and flow in opposition through the coil between Q_1 and Q_2, the resultant flux is zero and henceminimum impedance.

➢ <u>***Voltage Reduction in OLTC:***</u>

- To ***reduce the voltage***, the **following operations are required** in sequence.

1. Open $\mathbf{Q_1}$
2. Move selector switch $\mathbf{S_1}$to the next contact
3. Close $\mathbf{Q_1}$
4. Open $\mathbf{Q_2}$
5. Move selector switch $\mathbf{S_2}$to the next contact
6. Close $\mathbf{Q_2}$ *(3)*

- Thus, six operations are required for one change in tap position. The v**oltage change between taps** is often 1**.25 percent of the nominal voltage.**

❖ Applications of Tap-changing Transformers:

- **Transformer with tap-changing** facility constitute an important means of **controlling voltage** throughout the system **at all voltage levels.**
- These are **usually present throughout the network** interconnecting transmission systems of different levels.
- **During lightly loaded condition**, it is usually required **to lower the network voltage**, to reduce line charging and avoid under excited operation of generators.
- **Transformers with off-load tap –changing** facilities can also help **to maintain satisfactory voltage profiles**, while **transformers with OLTC** can be used to take care of **daily, hourly and minute-by-minute variation in system conditions.**

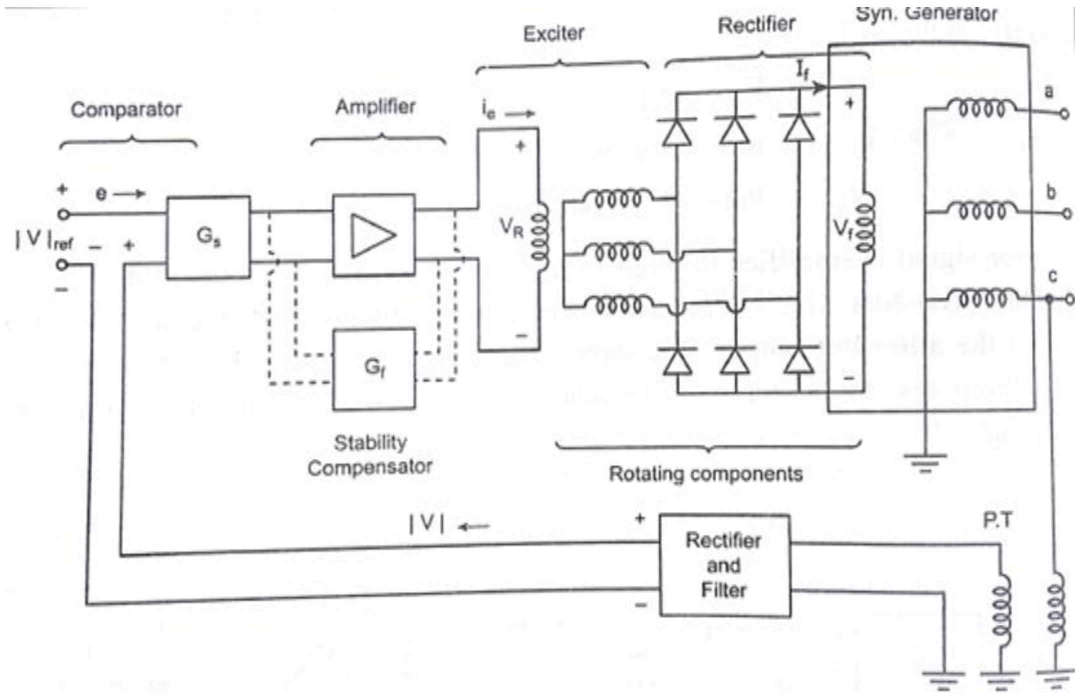
EXCITATION SYSTEM AND EXPLAIN THE OPERATION OF BRUSHLESS AVR WITH SUITABLE SCHEMATICS

❖ Types of Excitation system:

- D.C Excitation system.
- A.C Excitation system.
- Static excitation system.

❖ Brushless AVR:

- Out of the three types of excitation systems, the modern excitation system tend to be either "***brushless (or) static design***".
- Here the exciter consists of a 3ϕ alternator with "***rotating armature type and stationary field***". i.e., 3ϕ armature on the rotor&field on the stator
- The AC armature voltage is rectified by "diode bridge" mounted on the rotating shaft, and then fed directly into the main generator field.
- This design eliminates the need for slip rings and brushes. Hence it is called as "**Brushless Automatic Voltage Regulator** – ***Brushless AVR***". *(2)*



Brushless AVR

- Assume that for some reasons generator terminal voltage has been decreased.

- This results in increased"error voltage" (e) which in turn, causes increased values of V_R, i_e, V_f and i_f.
- The "direct axis" generator flux increases as a result of increase in if, thus, raising the magnitude of the terminal voltage to the required level. (Thus Voltage is automatically regulated as our desired).

❖ <u>**Potential Transformer and Rectifier:**</u>

- Using **potential transformer (P.T),** the **terminal voltage of the generator** is **stepped down** to the value required for the control signal and then **rectified** to get **DC voltage** proportional to the r.m.s value of terminal voltage. *(1)*

❖ <u>**Comparator:**</u>

- **The comparator compares the measured signal $|V|$ against the reference DC signal $|V|_{ref}$.**
- **The difference between these two signals produce an error voltage 'Ve' called "error signal".** *(1)*

❖ <u>**Amplifier:**</u>

- The **amplifieramplifies** the **input error signal** depending on the **amplification factor**.*(1)*

❖ <u>**Exciter:**</u>

- The **purpose of exciter** is to **supply field current** to the **rotor field of the synchronous generator.** *(1)*

❖ <u>**Synchronous Generator:**</u>

- **Synchronous generator generates 3ϕ AC power** at its terminals.
- The **terminal voltage** of the generator is **maintained constant** during its **varying load conditions**, with the help of **excitation system**.
    - ➢ The **terminal voltage (V)** of the generator equals to the **difference between induced emf (E)** and **drop across the armature (V_{drop}).**

$$\Delta V = \Delta E - V_{drop}$$

The **relationship** between **$V_f$and V** depends on thegenerator loading.

METHODS OF VOLTAGE CONTROL AND EXPLAIN ANY TWO IN DETAIL:

- Voltage level control is accomplished by controlling the generation, absorption and reactive power flow at all levels in the system.

➢ **The following are the methods of voltage control.**

1. By excitation control
2. By static shunt capacitors
3. By static series capacitors
4. By static shunt reactors
5. By synchronous condensers

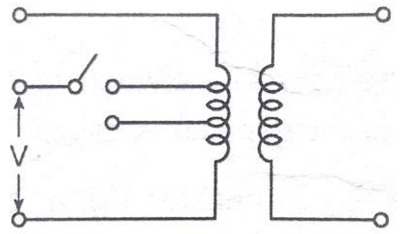
➢ **Other methods for voltage control:**

1. Tap-changing transformer
2. Booster transformer
3. Regulating transformer

4. Static VAR compensators (SVC: (TCR + TSC))
5. STATCOM *(2)*

➢ **Tap-Changing Transformer:**

❖ **Off-Load Tap Changing Transformer :**



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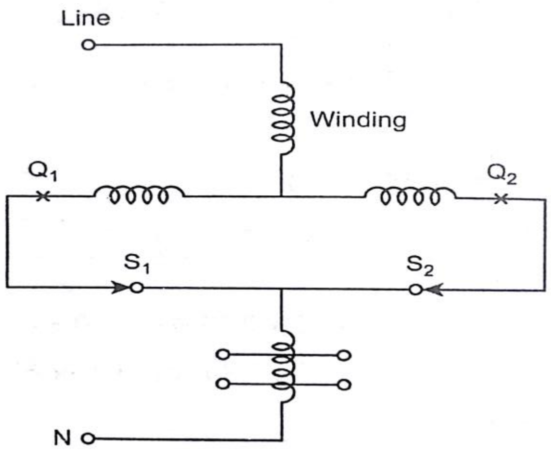

On-load tap changing transformer*(1)*

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3. Close **Q_1**
4. Open **Q_2**
5. Move selector switch **S_2**to the next contact
6. Close **Q_2***(1)*

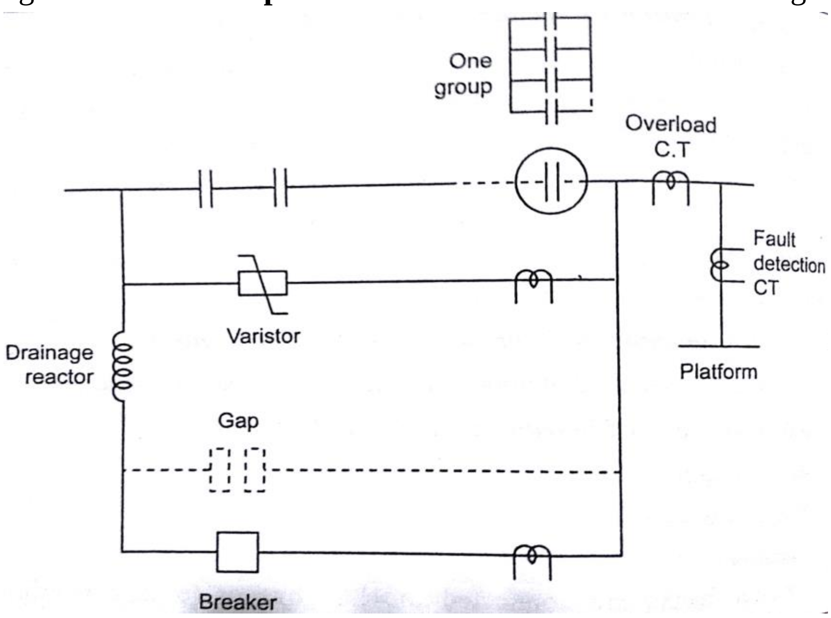
- Thus, six operations are required for one change in tap position. The v**oltage change between taps** is often 1**.25 percent of the nominal voltage.**

- **<u>By Static Series Capacitors:</u>**

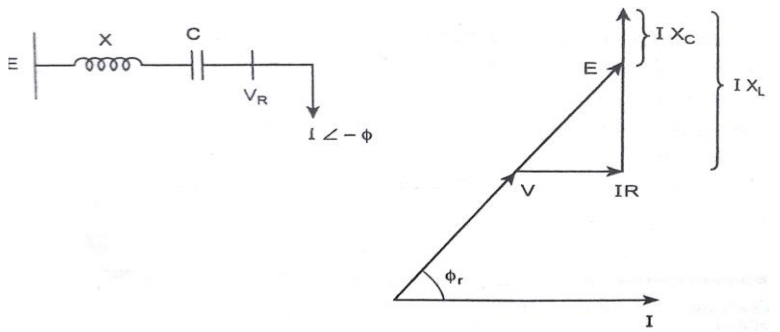
❖ ***<u>Static Series Capacitors:</u>***

- It is **connected in series**to **compensate the inductive reactance of line.**This **reduces the transfer reactance between the buses** to which the line is connected.
- It **increases maximum power** that can be transmitted and **reduces the reactive power loss.**
- **Under fault conditions,**the **voltage across the capacitor rises,** and unlike a shunt capacitor, a series capacitor experiences many times its rated voltage due to fault currents.
- A **zinc oxide varistor in parallel with the capacitor**may be **adequate to limit this voltage.** *(1)*

- The schematic diagram of a **series capacitor installation** is shown in below fig.



Schematic diagram of a series capacitor installation *(2)*



Phasor diagram when series capacitor is connected on a line *(1)*

- **<u>Drawbacks of Series Capacitor:</u>**

- **High over-voltage is produced across the capacitor terminals** under **short circuit conditions.** Therefore, **very high protective equipment** is used. (**Ex: Spark gap**)

➢ **Problems Associated with Series Capacitor:**

- **Locking of synchronous motor** during starting.
- **Hunting of synchronous motor** at high load due to high R/X ratio.
- **Ferro resonance** occurs between transformers and series capacitors which produces harmonic over voltages.

➢ **Advantages:**

Series capacitors are used:

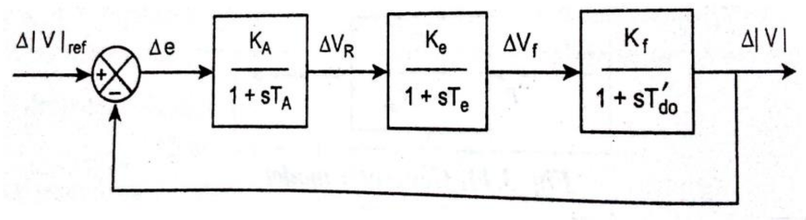
- To **improve voltage regulation** of distribution and industrial feeders
- To **reduce light flicker** problems
- To **improve system stability**

AVR WITH FEEDBACK STABILITY COMPENSATION

❖ ***Stability Compensation:***

- **Stability compensation *improves the dynamic response characteristics*** without affecting the static loop gain.
- Even for a small amplifier gain of k_A, AVR step response is not satisfactory.
- Thus, we must increase the relative stability by introducing a controller, which would add a zero to the AVR open loop transfer function.*(2)*

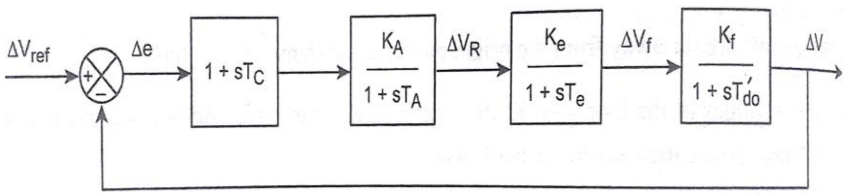
➢ The **block diagram of AVR** as shown below:



Block Diagram of an AVR *(2)*

- High loop gain is needed for static accuracy, but this causes undesirable dynamic response (i.e) possibly instability.
- This conflict situation can be avoided by adding series and/or feedback stability compensationto the AVR loop.

Consider the **addition of a series phase lead compensator**as shown below:



Series compensator with unity feedback *(2)*

- **Transfer function** of series compensator is:

$$G_s = 1 + s\,T_c$$

where, T_c is the compensator time constant

- **Open loop T.F** = $(1 + s\,T_c)\left[\dfrac{K_A K_e K_f}{(1 + s\,T_A)(1 + s\,T_e)(1 + s\,T'_{do})}\right]$

Series compensator network will not affect the **static loop gain (K)**

i.e., $\mathbf{K = K_A K_e K_f}$

and thus **maintains the static accuracy.**

But the **dynamic characteristics will change.**

If we tune, $T_c = T_e$

∴ **Open loop T.F becomes**

$$\frac{K}{(1 + s\,T_A)(1 + s\,T'_{do})(1 + s\,T_C)} \times (1 + s\,T_C)$$

$$\therefore G(s) = \frac{K}{(1 + s\,T_A)(1 + s\,T'_{do})} \qquad (1)$$

❖ <u>**Root Loci:**</u>

Number of zeros, z = 0
Number of poles, p = 2

$$i.e.,\ s_1 = \frac{-1}{T_A} \text{ and } s_2 = \frac{-1}{T'_{do}}$$

$$\because T'_{do} > T_A \Rightarrow -\frac{1}{T'_{do}} > -\frac{1}{T_A}$$

$$\text{Number of root locus, N} = p \quad [\because p > z]$$

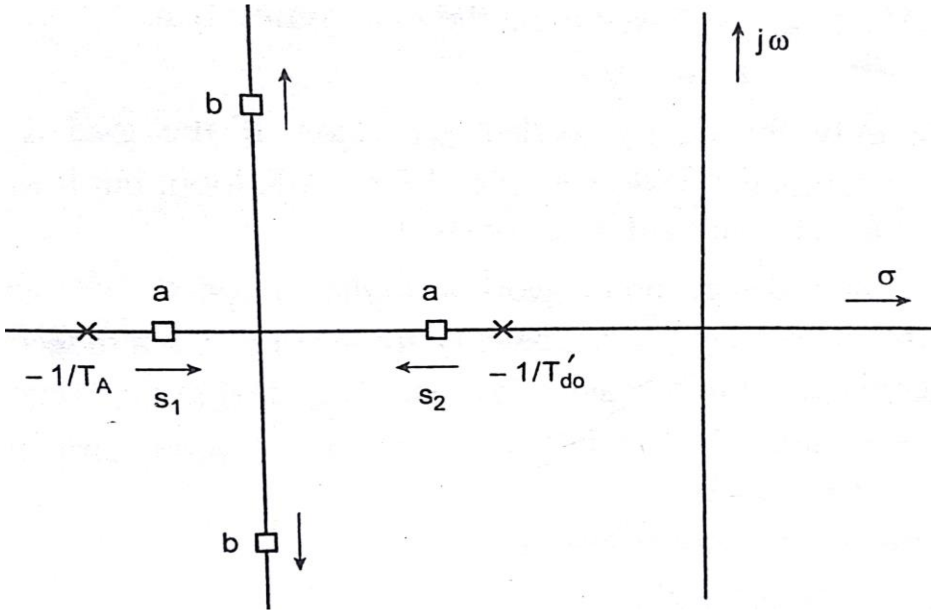
$$N = 2$$

$$\text{Asymptode angle } \phi = \frac{(2q+1)\pi}{p-z} \quad \text{where } q = 0, 1, \ldots\ldots, (p-z-1)$$

$$\text{Here } p - z - 1 = 2 - 0 - 1 = 1$$

$$\Rightarrow \phi_1 = \frac{\pi}{2}$$

$$\phi_2 = \frac{3\pi}{2} \qquad (2)$$



(1)

Root loci for zero compensated loop

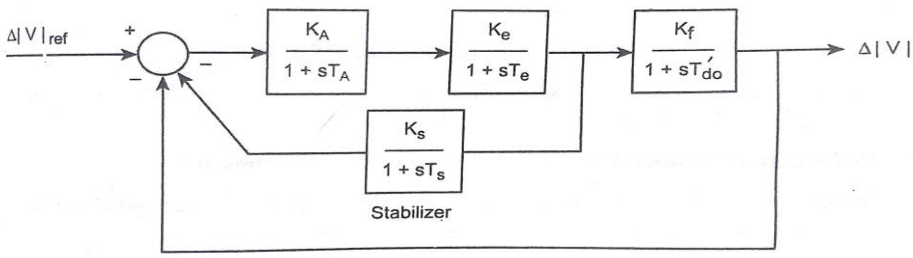
- Low loop gain (a) still results in negative eigen values, the dominant poles $s_2$yields sluggish (lethargic (or) inactive) response.

- Increasing loop gain (b) results in oscillatory response. The damping of the oscillatory term will however, not decrease with increasing gain as was the case in uncompensated system. So, the system is stable.

❖ ***Feedback Stability Compensation:***

- Consider the addition of feedback stability compensation (stabilizer).
- Even for a small amplifier gain of kA, AVR step response is not satisfactory.
- Thus, we must increase the relative stability by introducing a controller, which would add a zero to the AVR open loop transfer function.

The block diagram of AVR with feedback stability compensation is shown below:



Block Diagram of an AVR with feedback stability compensation *(2)*

- By proper adjustment of K_s and T_s , a satisfactory response can be obtained.

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT IV – ECONOMIC OPERATION OF POWER SYSTEM

INCREMENTAL COST IN POWER DISPATCH:

The **rate of change of fuel cost with active power generation** is called "***Incremental Cost***". It is represented by **'λ'**and expressed in **Rs. / MWhr.**

$$\lambda = dF_i/dP_{Gi}$$

Where,

F_i– Fuel cost expressed in **Rs. / hr.**

P_{Gi} – Power generation in **MW.**

PURPOSE OF ECONOMIC DISPATCH:

The purpose of ***Economic Dispatch (ED)*** (or) ***Optimal Dispatch (OD)*** is to **minimize the fuel costs** of the power system.

COORDINATION EQUATION TAKING THE EFFECT OF TRANSMISSION LOSSES:

The exact coordination equation is,

$$\lambda = \frac{(IC)_i}{1-(ITL)_i}$$

Where,

IC– Incremental Cost

ITL – Incremental Transmission Loss

DIFFICULTIES TO FIND UNIT COMMITMENT SOLUTION:

- Time consuming process.
- If the numbers of units are more, the number of combinations is more in a complex bus system.

If 'n' be the number of units, then the number of combinations will be **(2^n - 1).**

PRIORITY LIST METHOD:

- It is the simplest **unit commitment solution method** which consists of **creating a priority list of units.**
- The priority list can be obtained by noting Full-Load Average Production Cost **(FLAPC)** of each unit.

ALGORITHM FOR ITERATIVE SOLUTION OF ECONOMIC DISPATCH WITH LOSSES CO-ORDINATED:

❖ ***Solution by λ – iteration Method with Loss:***

Step 1 : Choose Lagrange multiplier λ as $\lambda°$ or $(IC)°$ (or)

Compute $\lambda°$ using $\lambda = \dfrac{P_D + \sum_{i=1}^{N} \dfrac{b_i}{2a_i}}{\sum_{i=1}^{N} \dfrac{1}{2a_i}}$

Step 2 : Assume $P_{Gi} = 0, \quad i = 1, 2, \ldots\ldots\ldots, N$ *(2)*

Step 3 : Solve for P_{Gi} using

$$P_{Gi} = \frac{1 - \dfrac{b_i}{\lambda} - 2 \sum_{\substack{j=1 \\ j \neq i}}^{N} B_{ij} P_{Gj}}{\dfrac{2a_i}{\lambda} + 2B_{ii}} \quad \text{where, } C = a_i P_{Gi}^2 + b_i P_{Gi} + c_i$$

Step 4 : Check if any P_{Gi} is beyond or below the inequality constraint

$$P_{Gi,\,min} \leq P_{Gi} \leq P_{Gi,\,max}$$

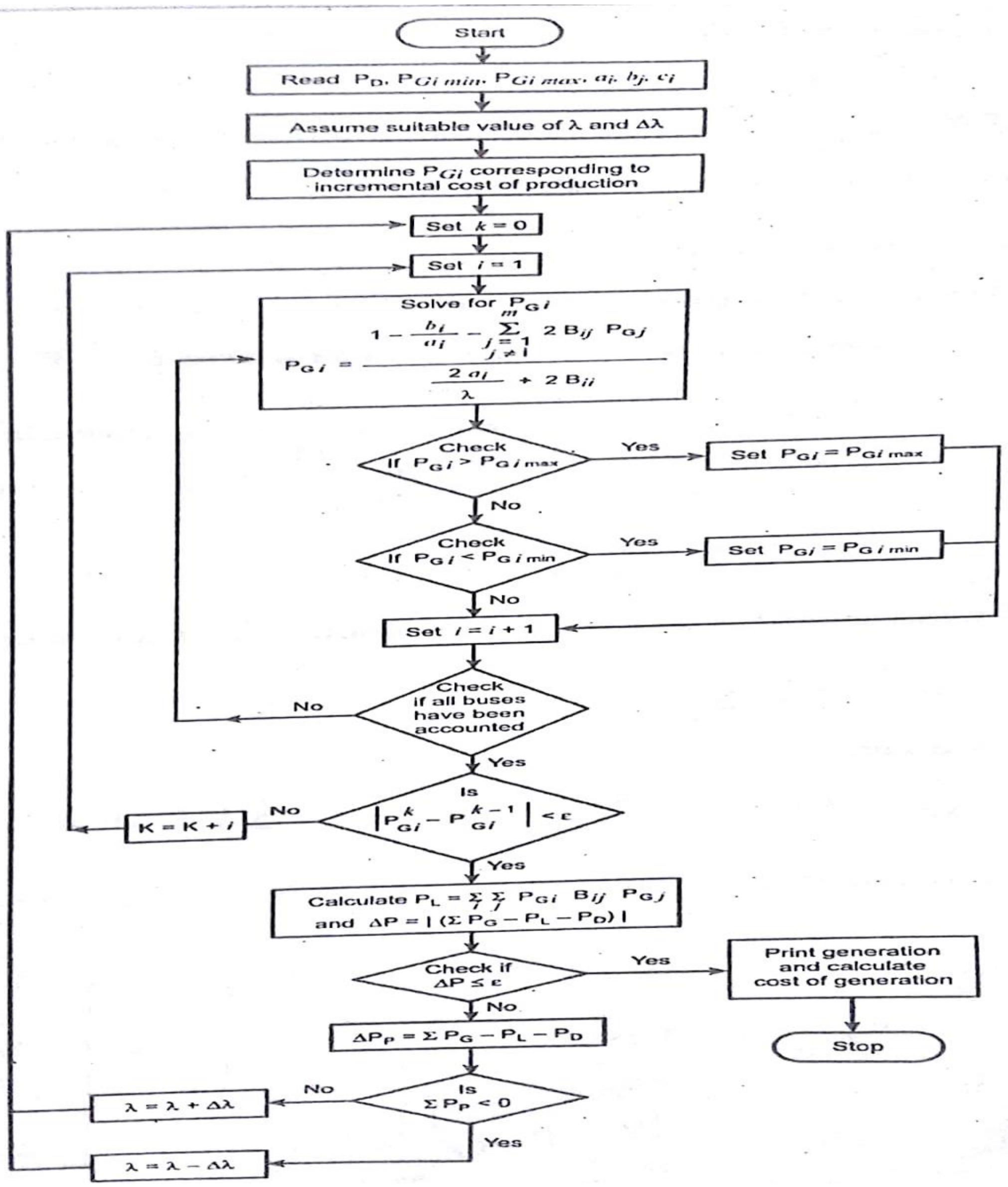
If $P_{Gi} < P_{Gi,\,min}$, fix $P_{Gi} = P_{Gi,\,min}$

$P_{Gi} > P_{Gi,\,max}$, fix $P_{Gi} = P_{Gi,\,max}$

Step 5 : Calculate transmission loss,

$$P_L = \sum_{i=1}^{N} \sum_{j=1}^{N} P_{Gi} B_{ij} P_{Gj}$$

(3)



Flowchart for Economic Dispatch including Losses

Step 6 : Check for power balance equation,

$$\left| P_D + P_L - \sum_{i=1}^{N} P_{Gi} \right| = 0$$

Value of P_{Gi} gives the optimum generation otherwise go to next step.

Step 7 : Increase $\lambda°$ by $\Delta\lambda$, if $\left| P_D + P_L - \sum_{i=1}^{N} P_{Gi} \right| < 0$ or

decrease $\lambda°$ by $\Delta\lambda$, if $\left| P_D + P_L - \sum_{i=1}^{N} P_{Gi} \right| > 0$.

Repeat from step (3), till the optimum solution is achieved.

VARIOUS CONSTRAINTS IN UNIT COMMITMENT:

- Each individual power system may impose different rules on the scheduling of units, depends on generation make-up and load curve characteristics, etc.
- The **constraints** to be considered for ***Unit Commitment*** are:
  - ***Spinning reserve***

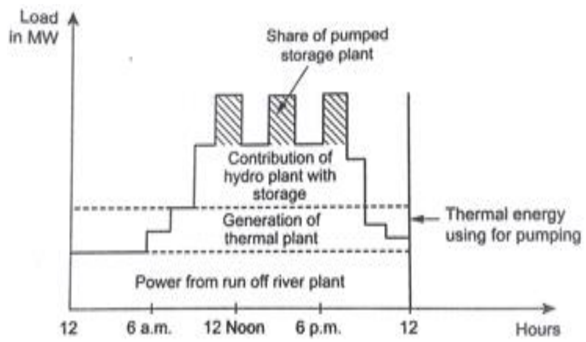
- ***Thermal Constraints***
  - Minimum uptime
  - Minimum downtime
  - Crew constraint

- ***Other Constraints***
  - Hydro constraint
  - Must run constraint
  - Fuel constraint *(2)*

- **Spinning Reserve:** It is the total amount of generation available from all the units synchronized on the system minus the present load and losses being supplied.
  - **Spinning reserve = ((Total amount of generation) – (Present load + Losses))**
  - Spinning reserve must be established so that the loss of one (or) more units does not cause drop in system frequency. (i.e., If one unit is lost, the spinning reserve unit has to make up for the loss in a specified time period) *(2)*
- **Reserve Capacity:**Capacity in excess of that required to carry peak load.
- **Reserve Generating Capacity:**
  - It includes quick-start diesel (or) gas turbine unit, (or) hydro unitsand pumped-storage hydro-units that can be brought on-line, synchronized and brought up to full capacity quickly.
- **Reserve Margin:**
  - The percentage of installed capacity exceeding the expected peak demand during a specified period. *(3)*

- **Thermal Unit Constraints:**
  - **Minimum up time:**Once the unit is running, it should not be turned off immediately.
  - **Minimum down time:**Once the unit is decommitted, there is a minimum time before it can be recommitted.
  - **Crew Constraints:**If a plant consists of two (or) more units, they cannot both be turned on at the same time. Since there are not enough crew membersto attend both units while starting up. *(3)*

- **Other Constraints:**
  - **Hydro Constraints:**
    - Unit commitment problem involves only thermal units.
    - In hydro-thermal scheduling, to allocate maximum hydro units during rainy seasons and to allocate thermal units during remaining periods.
    - We are not considering hydro units for unit commitment because start-up and shut-down time, operating costs are negligible. So we couldn't get the optimal solution.
  - **Must run Constraints:**
    - Some units like nuclear units are given a must-run status during certain times of the year to maintain the voltage in the transmission system.
  - **Fuel Constraints:**
    - If thermal and hydro sources are available, a combined operation is economic and advantageous i.e to minimize the fuel cost of thermal unit over a commitment period.



Daily Load Curve

PRIORITY LIST METHOD USING FULL LOAD AVERAGE PRODUCTION COST. STATE THE MERITS AND DEMERITS:

- Priority list method is the simplest unit commitment solution method which consists of creating a priority list of units.

- The priority list can be obtained by noting the full load average production cost of each unit.

  Full load average production cost={net heat rate at full load} x Fuel cost.

$$\textbf{FLAPC} = \frac{Ci(PGi)}{PGi} = \frac{K.Hi(PGi)}{PGi}$$

❖ **Assumptions:**

- No load costs are zero.
- Unit input – output characteristics are linear between zero output and full load.
- There are no other constraints.
- Start-up costs are a fixed amount.
- Ignore minimum up time and minimum down time.

❖ **Algorithm of Priority List Method:**

- Determine the full load average production cost for each units.

$$\textbf{FLAPC} = \frac{K.Hi(PGi)}{PGi}$$

- Form priority order based on average production cost, **(ascending order)**
- Commit number of units corresponding to the priority order.
- Calculate $\mathbf{P_{G1}, P_{G2} \ldots P_{GN}}$ from economic dispatch problem for the feasible combinations only.
- For the load curve in diagram each hour load is varying.
- Assume load is dropping or decreasing, determine whether dropping the next unit will supply generation and spinning reserve.
  - ➢ If not, continue as it is.
  - ➢ If yes, go to next step.
- Determine the number of hours H, before the unit will be needed again.
- Check H, Minimum shutdown time.
  - ➢ If yes, go to last step.

- If yes, go to next step.
- Calculate the two costs.
- Sum of hourly production costs for the next H hours with the unit up.
- Recalculate the same for the unit down + Start up cost for the either cooling or banking.
- If the second case is less expensive, the unit should be on.
- Repeat this procedure, until the priority list.

❖ **Merits:**

- No need to go for N combinations.
- Complications reduced.

❖ **Demerits:**

- Start up cost are fixed amount.
- No-load costs are not considered.

FORWARD DYNAMIC PROGRAMMING SOLUTION METHOD OF UNIT COMMITMENT PROBLEM:

- In dynamic programming method, the unit commitment table is to be arrived at for the **complete load cycle.**

❖ **Advantages:**

- Reduction in the dimensionality of the problem i.e., number of combinations to be tried are reduced in number.
- If a strict priority order is imposed, the number of combinations for a 4 unit case are:
  - **Priority 1 unit**
  - **Priority 1 unit + Priority 2 unit**
  - **Priority 1 unit + Priority 2 unit + Priority 3 unit**
  - **Priority 1 unit + Priority 2 unit + Priority 3 unit + Priority 4 unit***(2)*

❖ **Assumptions:**

- Total number of units available, their individual cost characteristics and the load cycle on the station are assumed priori (previously).
- A state consists of an array of units with specified units operating and the rest off-line.
- The start-up cost of a unit is independent of the time it has been off-line (i.e., fixed amount).
- There are no costs for shutting down a unit.
- There is a strict priority order and in each interval a specified minimum amount of capacity must be operating. *(2)*

❖ **Forward Dynamic Programming Method:**

- **Advantages:**
  - Algorithm to run forward in time from the initial hour to the final hour.
  - Forward dynamic programming is suitable if the start-up cost of a unit is a function of the time it has been off-line (i.e., fixed amount).
  - Initial conditions are easily specified. *(1)*
- **Algorithm:**
  - For a load cycle, at each load level, the algorithm is to run either of the units (or) both units with a certain load sharing. Determine the most economical cost curve of a single equivalent unit. Then add the third unit and repeat the steps. The process is repeated until all the units are added.

- Determine the possible number of combinations and determine the economic dispatch and total cost.
- Compute the minimum cost in hour K with combination I is,

$$F_{cost}(K, I) = \min_{(L)} \{ P_{cost}(K, I) + S_{cost}(K-1, L ; K, I) + F_{cost}(K-1, L) \}$$

where $F_{cost}(K, I)$ = Least total cost to arrive at state (K, I)

$P_{cost}(K, I)$ = Production cost for state (K, I)

$S_{cost}(K-1, L; K, I)$ = Transition cost from state (K − 1, L) to state (K, I)

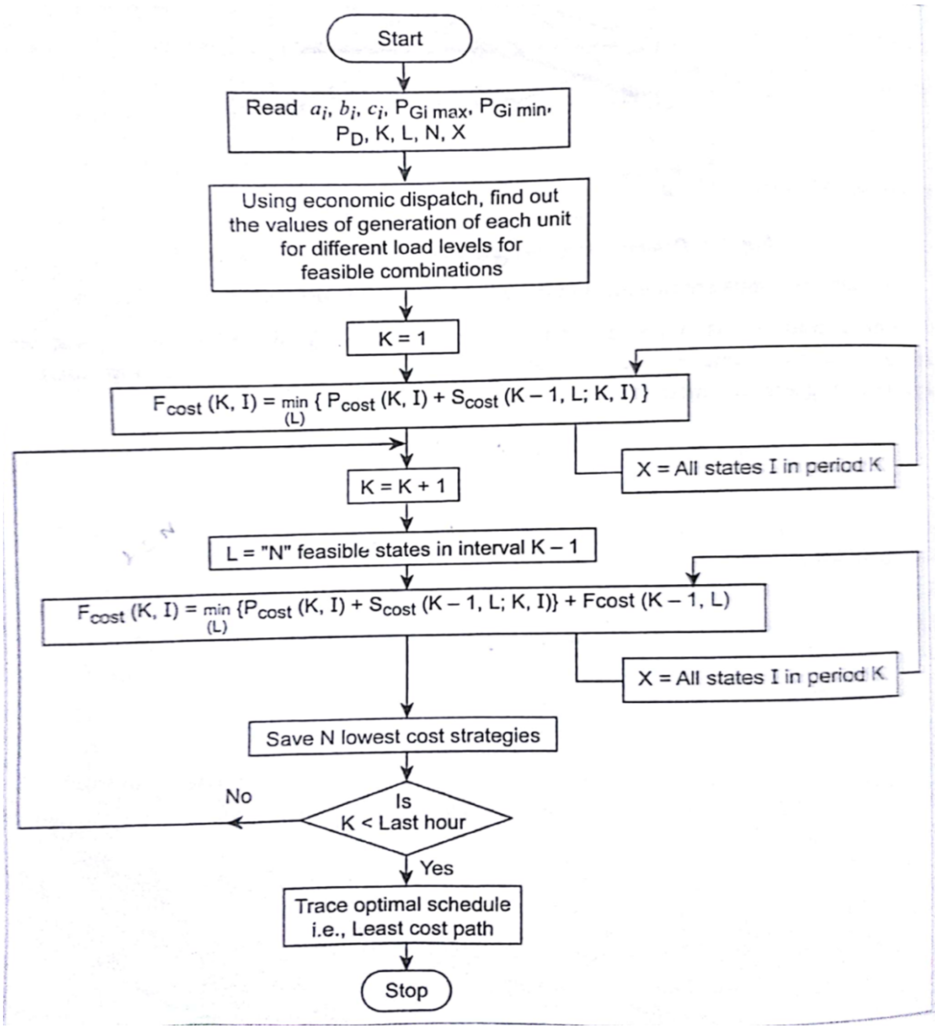
Transition from one state at a given hour to a state at the next hour.

State (K, I) = I^{th} combination in hour K

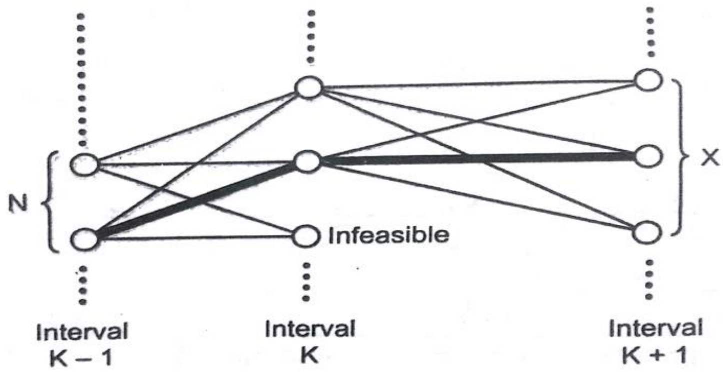
L = "N" feasible states in interval K − 1.

Let X be the number of states to search each period.

Let N be the number of strategies or paths, to save at each step. *(3)*



Flow chart for Dynamic Programming Method *(5)*



Dynamic Programming Algorithm with N=2 and X=3

LAMBDA ITERATION METHOD FOR SOLVING THE ECONOMIC DISPATCH PROBLEM WITHOUT LOSS:

❖ ***Case i:*** **Operating limits of Power generations are not specified**

- **Step 1:**Assign initial trail value of λ or calculate λ using

$$\lambda = \frac{PD + \sum_{i=1}^{N} \frac{bi}{2ai}}{\sum_{i=1}^{N} \frac{1}{2ai}}$$

- **Step2:** Compute P_{Gi} corresponding to **λ,**

$$\mathbf{P_{Gi} = \alpha_i + \beta_i \lambda + \gamma_i \lambda^2}$$

$$\mathbf{PGi} = \frac{\lambda - bi}{2ai} \text{i=1,2,......N}$$

- **Step 3:**Compute

$$\sum_{i=1}^{N} PGi$$

- **Step4:** Check power balance equation,

$$\sum_{i=1}^{N} PGi = \text{PD}$$

  - The power balance equation is satisfied.
  - Then the optimum solution is obtained, otherwise go to next step.

- **Step 5:** If$\sum_{i=1}^{N} PGi < \text{PD}$

  Assign **λ**= **λ**+ Δ**λ**, increment λ then go to step (2).

  If $\sum_{i=1}^{N} PGi > \text{PD}$

  Assign **λ**= **λ** -Δ**λ**, increment λ then go to step (2).

  Where, $\Delta\ \lambda = \frac{P}{\sum_{i=1}^{N} \frac{1}{2ai}}$

  ΔP=change in demand *(3)*

❖ ***Case ii:*** **Operating limits and production cost of generations are given**

- **Step 1:** Computeλ using the equation,

$$\lambda = \frac{PD + \sum_{i=1}^{N} \frac{bi}{2ai}}{\sum_{i=1}^{N} \frac{1}{2ai}}$$

- **Step 2:** Compute P_{Gi} corresponding to **λ,**

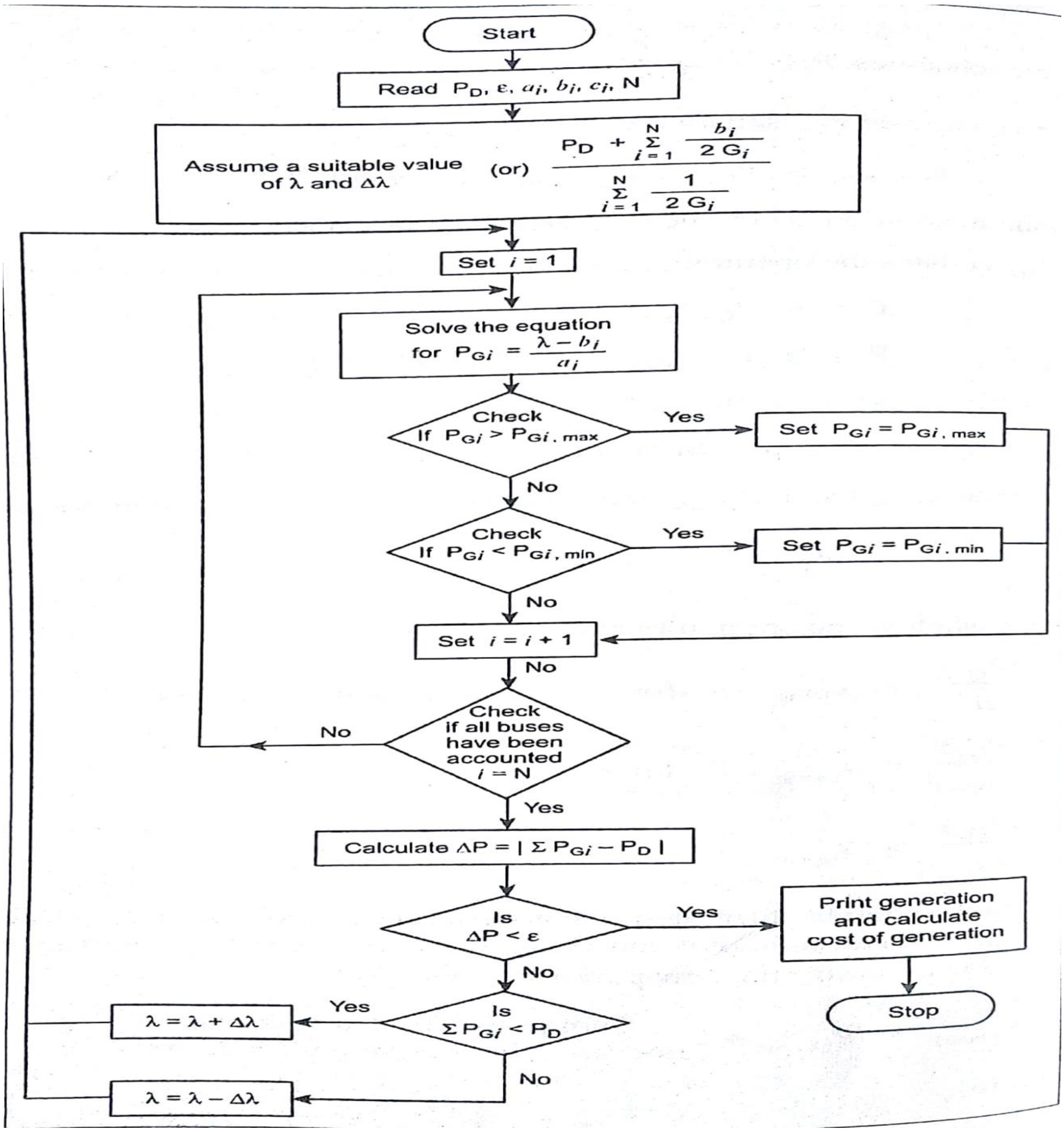
$$\mathbf{P_{Gi} = \alpha_i + \beta_i \lambda + \gamma_i \lambda^2}$$

$$\mathbf{PGi} = \frac{\lambda - bi}{2ai} \quad i=1,2,......N$$

- **Step 3:** if Computed $P_{G\,i}$ satisfy the limits,

$$PG_{\,i,min} \leq P_{G\,i} \leq PG_{\,i,max,} i=0,1,2.....N$$

  - Then the Optimum solution is obtained; otherwise go to the next step,



Flowchart for Economic Dispatch neglecting Losses

- **Step4:** if $PG_{\,i}$ violates the operating limits, then fix the generation at the respective limit.

$PG_i < P_{G\,i,min,}$ fix $P_{G\,i} = P_{Gi,\,min}$

$PG_i < P_{G\,i,\,max,}$ fix $P_{G\,i} = P_{Gi,\,max}$

- **Step 5:** Redistribute the remaining system load P_D ,

  $P_D = P_D$old - Sum of the fixed generations to the remaining units

- **Step 6:** Compute λ_{new} and $P_{D\,new}$ and compute the remaining generations using

$$\mathbf{PGi} = \frac{\lambda new - bi}{2ai}$$

- **Step7:** Check whether the optimality condition is satisfied, i.e.,

$$\frac{dFi(PGi)}{dPGi} = \lambda new \quad \text{for } PG_{i,\,min} \le P_{G\,i} \le PG_{i,\,max}$$

$$\frac{dFi(PGi)}{dPGi} \le \lambda new \quad \text{for } P_{G\,i} = P_{Gi,\,max}$$

$$\frac{dFi(PGi)}{dPGi} \ge \lambda new \quad \text{for } P_{G\,i} = P_{Gi,\,min}$$

➢ If condition satisfied then stop, otherwise release the generation schedule fixed at **PG $i_{,min}$ or PG $i_{,max}$** of those units are not satisfying optimality condition.

P_{Dnew1} = P_{Dnew} + {sum of the fixed generators not satisfying optimality condition} and go to step

DETERMINE PRIORITY LIST USING FULL LOAD AVERAGE PRODUCTION COST FOR THE DATA GIVEN.

Unit No.	Loading Limits		Fuel cost parameter			Fuel cost
	Min	Max	a_i	b_i	c_i	
1	100	400	0.006	7	600	1.1
2	50	300	0.01	8	400	1.2
3	150	500	0.008	6	500	1.0

Solution:

$$H_1 = 0.006\, P_{G1}^2 + 7\, P_{G1} + 600$$
$$H_2 = 0.01\, P_{G2}^2 + 8\, P_{G2} + 400$$
$$H_3 = 0.008\, P_{G3}^2 + 6\, P_{G3} + 500 \quad (3)$$

$$\text{FLAPC}_1 = K_1 \times \left.\frac{H_1(P_{G1})}{P_{G1}}\right|_{P_{G1} = P_{G1,max}}$$

$$= \frac{1.1\,[0.006 \times 400^2 + 7 \times 400 + 600]}{400} = \mathbf{11.99\ Rs./MWhr} \quad (2)$$

$$\text{FLAPC}_2 = K_2 \times \left.\frac{H_2(P_{G2})}{P_{G2}}\right|_{P_{G2} = P_{G2,max}}$$

$$= \frac{1.2\,[0.01 \times 300^2 + 8 \times 300 + 400]}{300} = \mathbf{14.8\ Rs./MWhr} \quad (2)$$

$$\text{FLAPC}_3 = K_3 \times \left.\frac{H_3(P_{G3})}{P_{G3}}\right|_{P_{G3} = P_{G3,max}}$$

$$= \frac{1.0\,[0.008 \times 500^2 + 6 \times 500 + 500]}{500} = \mathbf{11\ Rs./MWhr}$$

➢ **Priority Order: (Arrange FLAPC in ascending order)**

Unit	FLAPC	Min (MW)	Max (MW)

3	11	150	500
1	11.99	100	400
2	14.8	50	300

- **Unit Commitment:**

Combination	**Minimum MW from Combination**	**Maximum MW from Combination**
3 + 1 + 2	300	1200
3 + 1	250	900
3	150	500

DETERMINE THE ECONOMIC GENERATION SCHEDULES OF THREE GENERATING UNITS IN A POWER SYSTEM TO MEET THE SYSTEM LOAD OF 925 MW. THE OPERATING LIMIT AND COST FUNCTIONS IS GIVEN BELOW:

Operating limits $250\text{ MW} \le P_{G1} \le 450\text{ MW}$

$200\text{ MW} \le P_{G2} \le 350\text{ MW}$

$125\text{ MW} \le P_{G3} \le 225\text{ MW}$

Cost function is $F1\ (P_{G1}) = 0.0045\ P^2_{G1} + 5.2\ P_{G1} + 580$

$F_2\ (P_{G2}) = 0.0056\ P^2_{G2} + 4.5\ P_{G2} + 640$

$F_3\ (P_{G3}) = 0.0079\ P^2_{G3} + 5.8\ P_{G3} + 820$

☺ ***Solution : (i) Find initial value of λ :***

$$\lambda = \frac{P_D + \sum_{i=1}^{N} \frac{b_i}{2a_i}}{\sum_{i=1}^{N} \frac{1}{2a_i}} = \frac{925 + \frac{5.2}{2 \times 0.0045} + \frac{4.5}{2 \times 0.0056} + \frac{5.8}{2 \times 0.0079}}{\frac{1}{2 \times 0.0045} + \frac{1}{2 \times 0.0056} + \frac{1}{2 \times 0.0079}}$$

$$= \frac{925 + 1{,}346.6521}{263.688} = \frac{2271.6521}{263.688} = 8.6149$$

(2)

(ii) Find the generations using λ = 8.6149 :

$$\frac{dF_1(P_{G1})}{dP_{G1}} = \lambda_1 = 2 \times 0.0045\ P_{G1} + 5.2$$

$$\frac{dF_2(P_{G2})}{dP_{G2}} = \lambda_2 = 2 \times 0.0056\ P_{G2} + 4.5$$

$$\frac{dF_3(P_{G3})}{dP_{G3}} = \lambda_3 = 2 \times 0.0079\ P_{G3} + 5.8$$

$$P_{G1} = \frac{\lambda - 5.2}{2 \times 0.0045} = 379.433\text{ MW}$$

$$P_{G2} = \frac{\lambda - 4.5}{2 \times 0.0056} = 367.401\text{ MW}$$

$$P_{G3} = \frac{\lambda - 5.8}{2 \times 0.0079} = 178.158\text{ MW}$$

(3)

The solution satisfies $\sum_{i=1}^{N} P_{Gi} = 925$ MW. But generation schedules of unit 2 is not within the limit. Set unit 2 to its maximum output.

$$P_{G2} > P_{G2,\,max}$$
$$P_{G2} = P_{G2,\,max} = 350 \text{ MW},$$
$$\lambda_2 = 2 \times 0.0056 \times 350 + 4.5 = 8.42 < 8.6149$$

The incremental cost for unit 2 < λ, so limit 2 should be at its maximum.

$$P_{D,\,new} = P_D - P_{G2} = 925 - 350 \text{ MW} = 575 \text{ MW}$$

Now share the load $P_{G1} + P_{G3} = 575$ MW between units 1 and 3 using equal incremental cost rule.

$$\lambda_1 = \lambda_3$$
$$2 \times 0.0045\, P_{G1} + 5.2 = 2 \times 0.0079\, P_{G3} + 5.8$$
$$0.009\, P_{G1} - 0.0158\, P_{G3} = 0.6 \qquad \dots (1)$$
$$P_{G1} + P_{G3} = 575 \qquad \dots (2)$$

(4)

Multiplying equation (2) by 0.0158,

$$0.0158\, P_{G1} + 0.0158\, P_{G3} = 9.085 \qquad \dots (3)$$

Adding equation (1) and (3),

$$0.0248\, P_{G1} = 9.685$$
$$P_{G1} = 390.524 \text{ MW}$$
$$P_{G3} = 575 - 390.524 = 184.476 \text{ MW}$$
$$\lambda_{new} = 2 \times 0.0045 \times 390.524 + 5.2 = 8.7147$$
$$\text{Now } \lambda_1 = 8.7147 \text{ Rs / MWhr}$$
$$\lambda_2 = 8.42 \text{ Rs / MWhr}$$
$$\lambda_3 = 8.7147 \text{ Rs / MWhr}$$

$\lambda_2 < \lambda_{new}$ *i.e.*, we are fixing $P_{G2} = P_{G2,\,max}$.

The optimum schedule is

$$P_{G1} = 390.524 \text{ MW}$$
$$P_{G2} = 350 \text{ MW}$$
$$P_{G3} = 184.476 \text{ MW}$$

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT V - COMPUTER CONTROL OF POWER SYSTEMS

STATE ESTIMATION:

State estimation is the process of assigning a value to an unknown system state variable based on measurements from that system according to some criteria i.e., minimizing the sum of the squares of the differences between the estimated and true values of a function.

OBJECTIVES OF AUTOMATIC GENERATION CONTROL (AGC)

- To hold frequency at (or) very close to a specified nominal value
- To maintain the correct value of interchange power between control values
- To maintain each unit's generation at the most economic value

FUNCTIONS OF SCADA:

- Monitoring
- Supervisory control
- Data acquisition

STATES OF POWER SYSTEM:

- Normal State (**Secure State**)
- Alert State
- Emergency State
- Extremis State (**Serious Emergency State**)
- Restorative State

SOME EXAMPLES FOR CONTINGENCIES:

- **Single credible contingency:** Disconnection of generating unit, disconnection of transmission line, disconnection of transformer.
- **Critical single credible contingency** has severe impact on power system
- **Non-credible contingency:** Three phase electrical faults, multiple generating unit failures, double circuit transmission line failure, abnormal conditions caused by severe weather conditions / lightning / storm / equipment malfunction.

THREE CRITERIA IN STATISTICAL STATE ESTIMATION:

- Weighted least square criterion
- Maximum likelihood criterion
- Minimum variance criterion

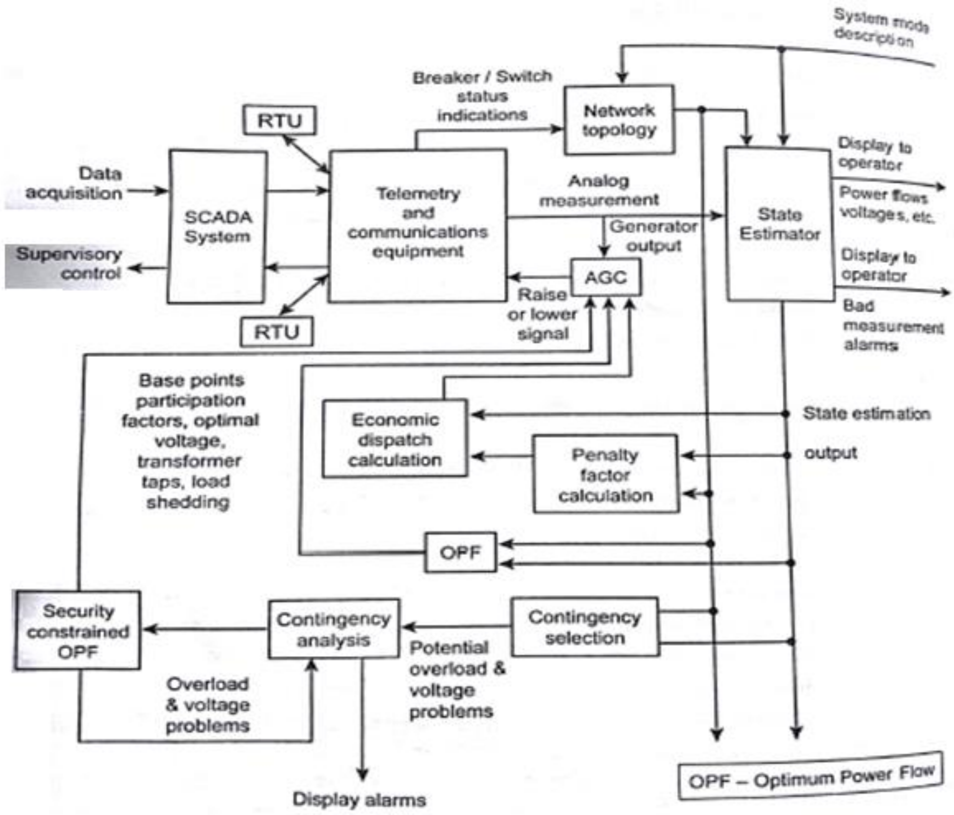
FOUR TYPES OF SCADA SYSTEMS AND ITS APPLICATION AREA:

Type 1: Small distribution systems, Small hydro stations, HVDC links.
Type 2: Medium sized power systems, power station HVDC link distribution systems
Type3: Regionalcontrol centre,distribution systems in large urban areas several hydro power station with cascade control
Type4: National and Regional control centres distributed systems in large urban areas, several hydro power station with cascade control

ENERGY CONTROL CENTRE (ECC):

Energy Control Centre (ECC) (or) System Control Centre (SCC):

- When power system increases in size – the number of substations, transformers, switchgear and so on – their operation and interaction become more complex.
- So it becomes **essential to monitor this information simultaneously for the total system** which is called as "***Energy Control Centre***".
- **System Control Centre: Energy Management (EM) is performed at control centre** called "***System Control Centre***".
- The **analog measurements of generator outputs** must be used directly by the **Automatic Generation Control** (**AGC**) program, whereas, all **other data will be processed** by the **state estimator** before being used by the programs. *(2)*



Energy Control Centre

REAL TIME OPERATIONS ARE IN TWO ASPECTS:

(a) Three Level Control:

1. Turbine-governor to adjust generation to balance changing load - *instantaneous control*

2. AGC (called Load Frequency Control (LFC) maintains frequency and net power interchange – action repeated at 2 – 6 sec. interval.
3. Economic Dispatch Control (EDC) distributes the load among the units such that fuel cost is minimum – executed at 5 – 10 minutes intervals.

(b) Primary Voltage Control:

1. Excitation controls regulate generator bus voltage
2. Transmission voltage control devices include SVC (Static VAR Compensators), shunt capacitors, transformer taps, etc.,

Automatic Generation Control (AGC):

The objectives of AGC are:

- To hold frequency at (or) very close to a specified nominal value
- To maintain the correct value of interchange power between control values
- To maintain each unit's generation at the most economic value

Energy Control Centre (ECC) Functions:

(1) System Monitoring:

- An energy control centrefulfills the function of coordinating their response of the system elements in both normal operationand emergency conditions.
- A more serious abnormality detected by the digital computermay cause suspension of normal control functions.
- In emergencies such as loss of a major generator (or) excess power demands by a neighboring utility on the tie lines, many alarms could be detectedand the system could enter an emergency state.

(2) Data Acquisition and Control:

- It provides operator and computer control systems with status and measurement information needed to supervise overall operations.
- Data acquisition and remote control is performed by computer systems called Supervisory Control and Data Acquisition (SCADA) System.
- A SCADA system consists of a master station and Remote Terminal Unit (RTU).

STATE ESTIMATION BY USING WEIGHTED LEAST SQUARE ESTIMATE (WLSE) METHOD.

Hence estimated system state $\hat{X}$ is more close with the more reliable measurements and less close with the less reliable measurements.

$$\text{State vector } [X] = [X_0] + [\Delta X]$$

$$\text{Substituting } X = (F[X])$$

$$(F[X]) = F([X_0] + [\Delta X]) = F[X_0] + [A]\,[\Delta x] \quad \dots (7.15)$$

[Neglecting higher powers of Δx of expansion]

(1)

Substituting F[X] from equation (7.15) in equation (7.14),

$$J = \{(F[X_0]) + [A]\,[\Delta X] - [Z]\}^T\,[W]\,\{(F[X_0]) + [A]\,[\Delta X] - [Z]\}$$

$$J = \{(F[X_0]) - [Z] + [A]\,[\Delta X]\}^T\,[W]\,\{(F[X_0] - [Z]) + [A]\,[\Delta X]\}$$

$$J = \{(F[X_0]) - [Z]\}^T\,[W]\,\{(F[X_0]) - [Z]\} + [\Delta X]^T\,[A]^T\,[W]\,[A]\,[\Delta X] + 2\,[A]^T\,[\Delta X]^T \cdot [W]\,\{(F[X_0]) - [Z]\} \quad \ldots (7.16)$$

If X is to be $\hat{X}$, to minimize J,

$$\left.\frac{\partial J}{\partial [\Delta X]}\right|_{[\Delta X] = [\Delta \hat{X}]} = 0$$

$$\frac{\partial J}{\partial [\Delta X]} = 2\,[A]^T\,[W]\,[A]\,[\Delta \hat{X}\,] + 2\,[A]^T\,[W]\,\{(F[X_0]) - [Z]\} = 0$$

$$\therefore 2\,[A]^T\,[W]\,[A]\,[\Delta \hat{X}\,] = -2\,[A]^T\,[W]\,\{(F[X_0]) - [Z]\}$$

$$[\Delta \hat{X}\,] = -\{[A]^T\,[W]\,[A]\}^{-1}\,[A]^T\,[W]\,\{(F[X_0]) - [Z]\}$$

$$[\Delta \hat{X}\,] = \{[A]^T\,[W]\,[A]\}^{-1}\,[A]^T\,[W]\,\{[Z] - (F[X_0])\} \quad \ldots (7.17)$$

where, $[X] = [X_0]$

(3)

Algorithm:

- Calculate (F[X]) and $[A] = \frac{\partial F}{\partial X}$ corresponding to $[X_0]$.
- Calculate $[\Delta \hat{X}\,]$ using the equation $[\Delta \hat{X}\,] = \{[A]^T\,[W]\,[A]\}^{-1}\,[A]^T\,[W]\,\{[Z] - (F[X_0])\}$
- If $[\Delta \hat{X}\,]$ elements are small in magnitude, then stop and $[X_0]$ is the system state $[\hat{X}\,]$.
- If $[\Delta \hat{X}\,]$ elements are not small, then update X_0, $[X_0]_{new} = [X_0]_{old} + [\Delta \hat{X}\,]$ and go to step 1.

ENERGY MANAGEMENT SYSTEM (EMS)

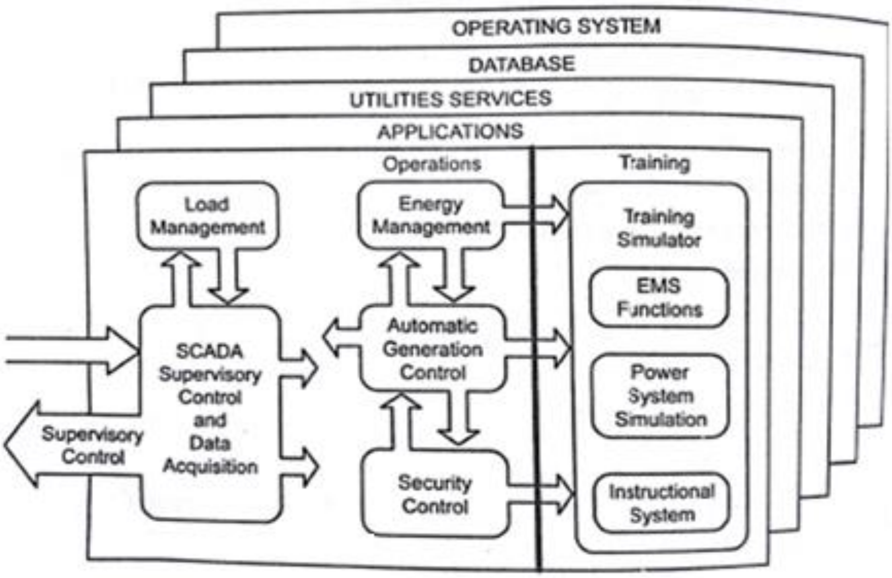
- Energy Management System (EMS)is the process of monitoring, coordinating and controlling the generation, transmission and distribution of electrical energy.
- It is performed at centres called 'System Control Centres (SCC)', by a computer system called Energy Management System (EMS).

Major Functions of EMS:

1. System Load forecasting – **Hourly energy, 1 to 7 days**
2. Unit commitment – **1 to 7 days**
3. Fuel scheduling to plants
4. Hydro-thermal scheduling - **upto 7 days**
5. MW interchange evaluation – **with neighboring system**
6. Transmission loss minimization

(3)

EMS consists of **energy management, AGC, security control, SCADA, load management.**



Energy Management System

LOAD MANAGEMENT:

- As the generator capacity has increased in prize and fuel shortage occurs on them, So many utilities are operating only during peak loads. This is called as "***Load Management***".

Functions of Load Management:

1. Data acquisition
2. Monitoring, sectionalizing switches and create circuit configuration
3. Feeder switch control and preparing distribution map
4. Preparation of switching orders
5. Customer meter reading
6. Load management – control customer load

Criterion: The objective is to minimize [J] the sum of the squares of the weighted deviations of the estimated measurements.

F[X] from the actual measurements [Z].

$$\therefore J = \{(F[X]) - [Z]\}^T \; [W]\{(F[X]) - [Z]\} \quad \ldots(7.14)$$

Unconstrained minimum of J is zero because of quadratic function.

Expanding the equation (7.14), we get,

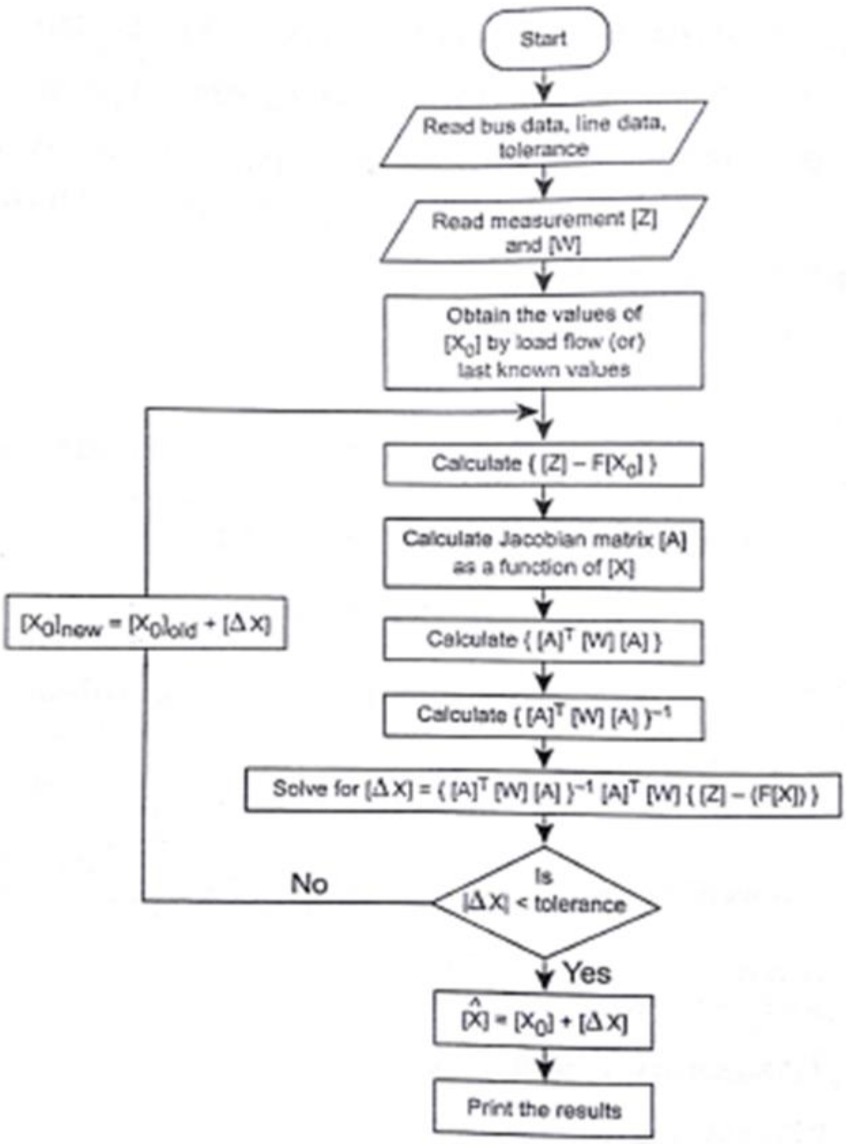
$$J = \sum_{i=1}^{n_s} W_i \, [(F_i[X]) - Z_i]^2$$

$$J \to 0, \quad \text{when } F_i[X] \to Z_i$$

As J is minimized, $F_i[X] - Z_i$ approaches zero,

$[F_i[X] - Z_i]^2$ approaches zero is determined by the values of W_i.

If W_i is large, $[F_i[X] - Z_i]^2$ will be small when J is minimized and vice versa.



Flow Chart

TYPICAL ENERGY CONTROL CENTRE FUNCTIONS.

Task of Energy Control Centre: Energy Control Centre can perform the following functions:

1. ***Load Forecasting:*** Load should be estimated in advance.

Forecast	Lead time	Application
Very short term	Few minutes to half an hour.	Real time control, Real time security evaluation.
Short term	Half an hour to a few hours	Allocation of spinning reserve, Unit commitment, maintenance scheduling.
Medium term	Few days to a few weeks.	Planning for seasonal peak-winter, summer.
Long term	Few months to a few years.	To plan the growth of the generation capacity.

2. ***Power System Planning:***

   - for generation
   - for transmission and distribution

(should aim at excess capacity than load)

3. ***Unit Commitment:*** The constraints are – spinning reserve, minimum up-time, minimum down-time, hydro constraints and fuel constraints.

4. ***Maintenance Scheduling:*** The planned maintenance outages of the generation equipment over a given future period.

5. ***Security Monitoring:*** The on-line process using real-time data for analyzing the effects of outages contingencies on the steady state performance of the system.

6. ***State Estimation:*** It is the process of estimating the state. When based on system monitoring data, it produces best estimates of the power system state

7. ***Economic Dispatch:*** It is to distribute the load among the generating units so as to minimize the total cost of the system.

8. ***LFC (Load Frequency Control):*** In interconnected systems with 2 or more independently controlled areas, in addition to control of frequency, generation within each area has to be controlled to maintain scheduled power interchange.

Energy Control Centre (ECC) Levels:

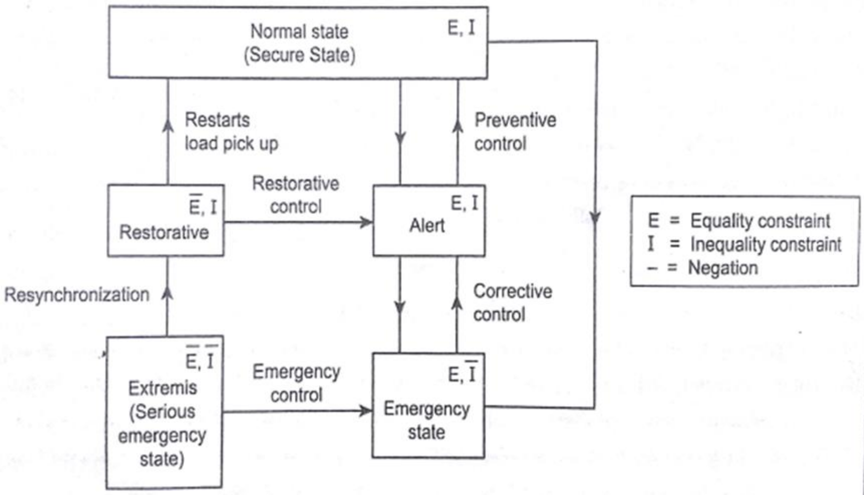
Level	System	Monitoring and Control
First level	Generating stations and sub-stations.	Local control center (Remote terminal unit)
Second level	Sub-transmission and transmission network.	Area load dispatch centre
Third level	Transmission system	State load dispatch centre
Fourth level (top level)	Interconnected power systems	Regional control center (System control center)

STATE TRANSITION DIAGRAM OF A POWER SYSTEM:

State Transition Diagram:

A power system may be operated in several different states. These are classified into five operating states. They are:

1. Normal State (**Secure State**)
2. Alert State
3. Emergency State
4. Extremis State (**Serious Emergency State**)
5. Restorative State



System States and Transition

Normal State (Secure State):

A system is said to be in **normal state**if both **load and operating constraints are satisfied.**It is one in which the total demand on the system is met by satisfying all the operating constraints. (**i.e., equality (E) and Inequality Constraints**).

Alert State:

A **normal state** of the system is said to be in **alert state** if one (or) more of the **postulatedcontingency states**, consists of the **constraint limits violated**.

Emergency State:

The system is said to be in **emergency state** if one (or) more **operating constraints are violated**, but the **load constraint is satisfied**.

Extremis State:

When the system is in **emergency state**, if **no proper corrective action is taken** in time, then it goes to either **serious emergency state (or) extremis state**.

Restorative State:

From this state, the **system may be brought back** either to **alert state** (or) **secure state**.

Control Strategies:

- To **achieve high power system security**, the control room should have ***data collection system*** and ***computerized power system analysis program software***, called "**Energy Management System**" (**EMS**).

Action by operator	Variables to be adjusted
Unit commitment	Generation on / off status
Economic dispatch	Generation MW output schedule
Generator bus voltage	Unit exciter setting
Network configuration	Substation CB open / close
Load shedding	Distribution feeder CB
On-load tap changing transformer	Tap position
Phase shifting transformer	Tap position
Tie-line system interchange	Interchange schedule

Alert State:

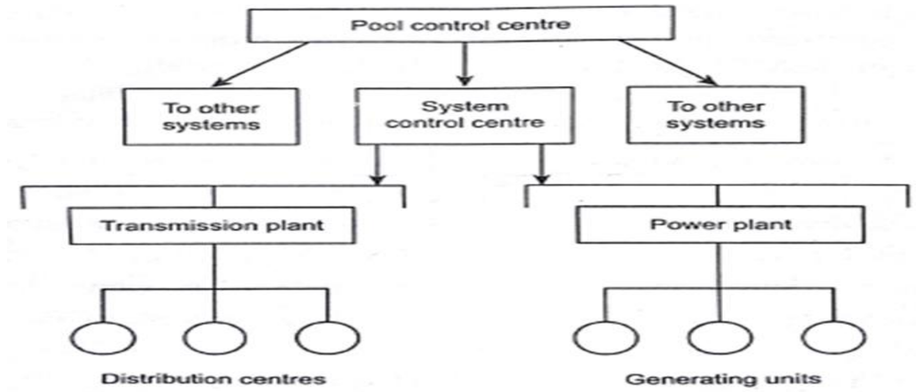
- When **severe disturbance occurs**, the system is**push to emergency.**
- **Preventive control** is needed **to restore adequatespinning reserve**, **generation shifting**, **tie-line rescheduling** and **voltage reduction.**

Extremis State:

- In this state, **control is to be done** for the **overall power system**, by **load shedding**.
- **Islanding power system** and the controls mentioned in emergency period.

Restorative State:

- **After rectified the problems in power system**, **restart the generator** and **run at synchronous speed** and **parallel operation of two (or) more areas** in the interconnected system.



Power System Control Hierarchy

SCADA SYSTEM FOR POWER SYSTEM:

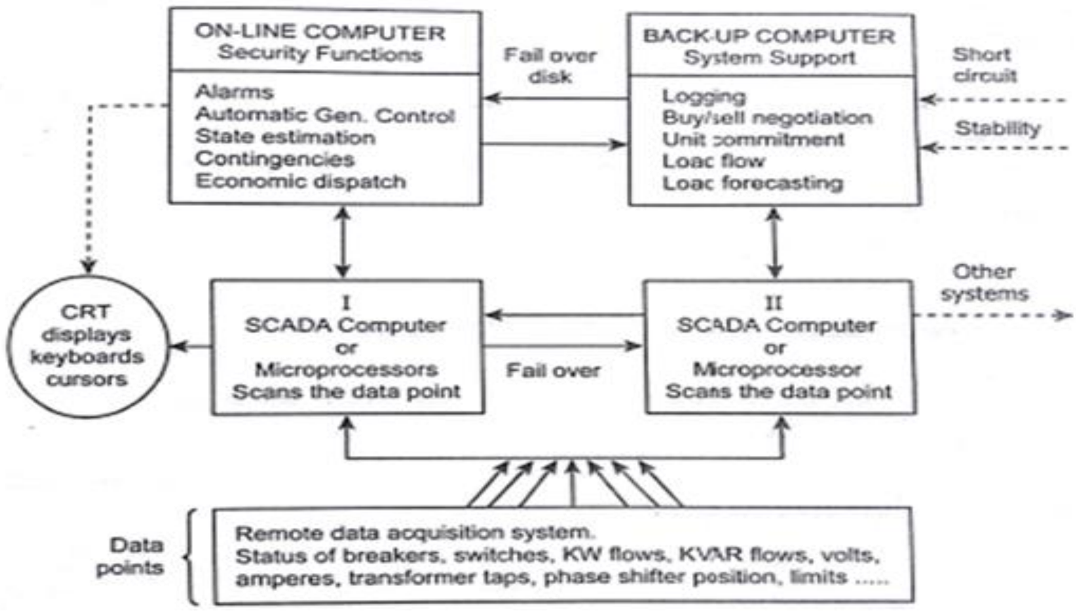
SCADA (Supervisory Control and Data Acquisition):

It consists of a **master station** and **RTU**'s linked by **communication channel**. The **hardware components** can be classified into:

1. **Process computer and associated hardware** at the**Energy Control Centre**.
2. **RTUs and the associated hardware** at the **remote stations**.
3. **Communication equipment** that links the **RTUs and process computers** at the **master station**.

System Hardware Configuration:

- The **supervisory control and data acquisition** system allows a few operators **to monitor** the **generation and HV transmission system.**



Digital Computer Control and Monitoring for Power System

- Usually **one computer**, the on-line units, is **monitoring and controlling the power system**. The **back-up computer** may be **executing off-line batch programs** such as **load forecasting (or) hydro-thermal allocation.**
- The **on-line computer periodically updates a disk memory** shared between the two computers.
- The **information used by the on-line computer** has a maximum age of update cycle (**typically 30 sec**.)
- The **microprocessors can transfer** data in and out of computer memory **without interrupting the central processing unit**. As a result of these precautions, for all critical hardware functions, there is often a guaranteed **99.8% (or) more availability**.
- The **most critical functions** have the **fastest scan cycle**. Typically, the **following categories are scanned every 2 seconds.**
  - All **status points** such as **switchgear position, substation loads** and **voltages, transformer tap positions** and **capacitor banks.**
  - **Tie-line flows** and interchanges schedules.
  - Generator loads, voltage, operating limits and boiler capacity.
  - Telemetry verification to detect failures and errors in the remote bilateral communication links between the digital computer and remote equipment.

<u>Components of SCADA:</u>

- ***Sensors:*****Analog and digital sensors** are used to interface the systems.
- ***Relays:***Relays are used to **sense the abnormal conditions** and protect the system.
- ***Remote Terminal Units (RTU):*****RTU's** are **microprocessors controlled electronic devices** which are used to **collect various datas** and **transmit to SCADA system.**
- ***Master Unit:*** **Master Unit** acts as a **central processor computer.**
- ***Communication Links:*** It is **used to linkRTU's** and **SCADA system**. **Satellite communication, microwave communication, fibre optic communication** may be used for communication purpose.

<u>Types of SCADA Systems and Area of Applications:</u>

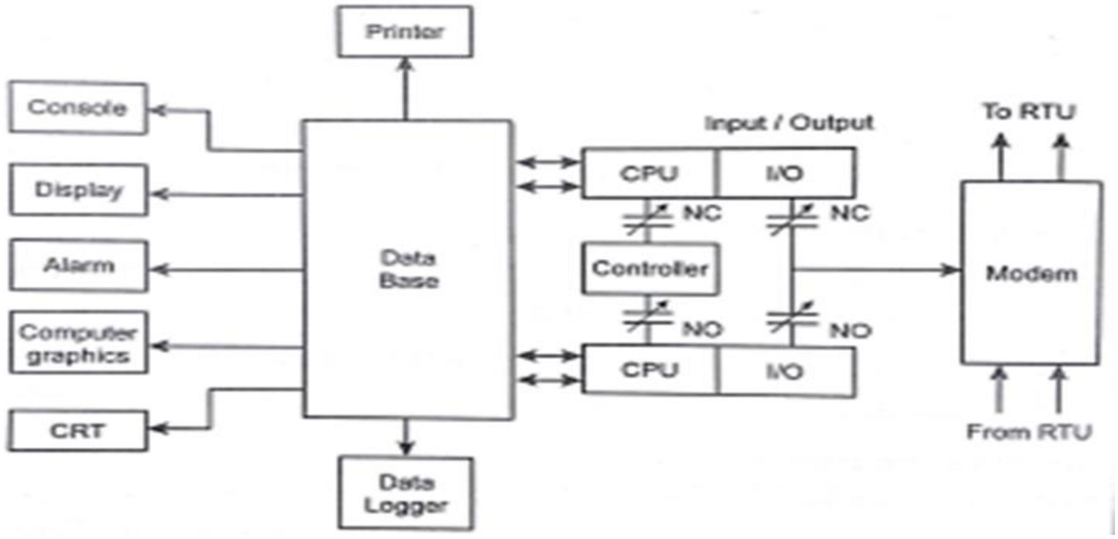
Type 1 : Small distribution systems (substation control center), Small hydro stations, HVDC links.

Type 2 : Medium sized power systems (plant control centre), power station HVDC link distribution systems.

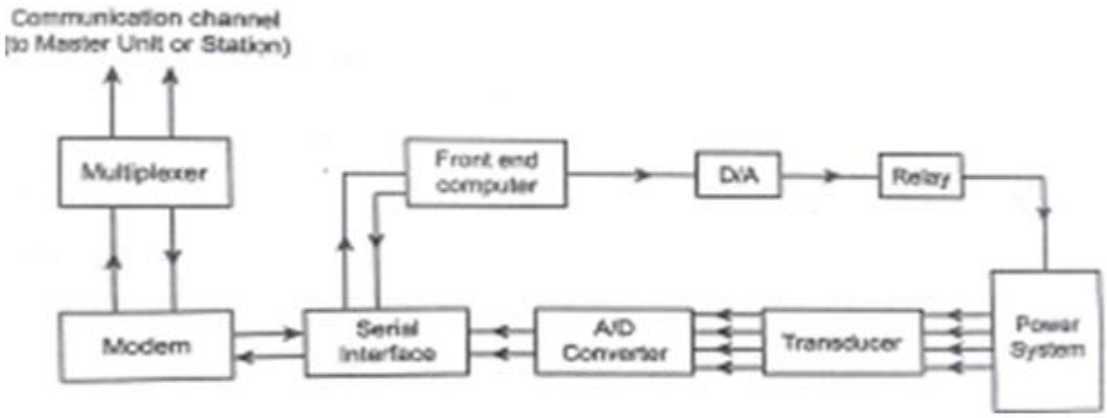
Type 3 : Regional control centre, distribution systems in large urban areas several hydro power station with cascade control.

Type 4 : National and Regional control centres distributed systems in large urban areas, several hydro power station with cascade control. *(2)*

<u>Master Station:</u>



Remote Terminal Units (RTU):



Functions of SCADA:

- Data Acquisition
- Information Display
- Remote terminal unit processing
- Economic modeling
- Remote start / stop
- Load shedding

HIERARCHICAL LEVELS USED IN EMS:

- System control centre.
- Area control centre.
- Remote terminal unit (RTU)

VARIOUS CONTROLS TO ENSURE SECURED OPERATION OF A POWER SYSTEM:

- Corrective action required to improve the load bus voltages
- Corrective action required to eliminate the overloads
- Load scheduling.