EE8702 - POWER SYSTEM OPERATION AND CONTROL

OBJECTIVES:

To impart knowledge on the following topics

- ⌚ Significance of power system operation and control.
- ⌚ Real power-frequency interaction and design of power-frequency controller.
- ⌚ Reactive power-voltage interaction and the control actions to be implemented for maintaining the voltage profile against varying system load.
- ⌚ Economic operation of power system.
- ⌚ SCADA and its application for real time operation and control of power systems

UNIT I PRELIMINARIES ON POWER SYSTEM OPERATION AND CONTROL

Power scenario in Indian grid – National and Regional load dispatching centers – requirements of good power system - necessity of voltage and frequency regulation – real power vs frequency and reactive power vs voltage control loops - system load variation, load curves and basic concepts of load dispatching - load forecasting - Basics of speed governing mechanisms and modeling - speed load characteristics - regulation of two generators in parallel.

UNIT II REAL POWER - FREQUENCY CONTROL

Load Frequency Control (LFC) of single area system-static and dynamic analysis of uncontrolled and controlled cases - LFC of two area system - tie line modeling – block diagram representation of two area system - static and dynamic analysis - tie line with frequency bias control – state variability model - integration of economic dispatch control with LFC.

UNIT III REACTIVE POWER – VOLTAGE CONTROL

Generation and absorption of reactive power - basics of reactive power control – Automatic Voltage Regulator (AVR) – brushless AC excitation system – block diagram representation of AVR loop - static and dynamic analysis – stability compensation – voltage drop in transmission line - methods of reactive power injection - tap changing transformer, SVC (TCR + TSC) and STATCOM for oltage control.

UNIT IV ECONOMIC OPERATION OF POWER SYSTEM

Statement of economic dispatch problem - input and output characteristics of thermal plant - incremental cost curve - optimal operation of thermal units without and with transmission losses (no derivation of transmission loss coefficients) - base point and participation factors method - statement of unit commitment (UC) problem - constraints on UC problem – solution of UC problem using priority list – special aspects of short term and long term hydrothermal problems.

UNIT V COMPUTER CONTROL OF POWER SYSTEMS

Need of computer control of power systems-concept of energy control centers and functions – PMU - system monitoring, data acquisition and controls - System hardware configurations - SCADA and EMS functions - state estimation problem – measurements and errors - weighted least square estimation - various operating states - state transition diagram.

OUTCOMES:

- Ability to understand the day-to-day operation of electric power system.
- Ability to analyze the control actions to be implemented on the system to meet the minute - to- minute variation of system demand.
- Ability to understand the significance of power system operation and control.
- Ability to acquire knowledge on real power-frequency interaction.
- Ability to understand the reactive power-voltage interaction.
- Ability to design SCADA and its application for real time operation.

TEXT BOOKS:

1. Olle.I.Elgerd, ‘Electric Energy Systems theory - An introduction’, McGraw Hill Education Pvt. Ltd., New Delhi, 34th reprint, 2010.
2. Allen. J. Wood and Bruce F. Wollen berg, ‘Power Generation, Operation and Control’, John Wiley & Sons, Inc., 2016.
3. Abhijit Chakrabarti and Sunita Halder, ‘Power System Analysis Operation and Control’, PHI learning Pvt. Ltd., New Delhi, Third Edition, 2010.

REFERENCES

1. Kothari D.P. and Nagrath I.J., ‘Power System Engineering’, Tata McGraw-Hill Education, Second Edition, 2008.
2. Hadi Saadat, ‘Power System Analysis’, McGraw Hill Education Pvt. Ltd., New Delhi, 21st reprint, 2010.
3. Kundur P., ‘Power System Stability and Control, McGraw Hill Education Pvt. Ltd., New Delhi, 10th reprint, 2010.

EE8702 - POWER SYSTEM OPERATION AND CONTROL

UNIT I

PRELIMINARIES ON POWER SYSTEM OPERATION AND CONTROL

Power scenario in Indian grid – National and Regional load dispatching centers – requirements of good power system - necessity of voltage and frequency regulation – real power vs frequency and reactive power vs voltage control loops - system load variation, load curves and basic concepts of load dispatching - load forecasting - Basics of speed governing mechanisms and modeling - speed load characteristics - regulation of two generators in parallel.

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Power Scenario in Indian grid

* India is the third-largest producer and second-largest consumer of electricity worldwide, with an installed power capacity of 401.01 GW as of April 30, 2022.

* Growing population along with increasing electrification and per capita usage will provide further impetus. Power consumption is estimated to reach 1894.7 TWh in 2022.

* Power is among the most crucial for the economic growth and welfare of nations.

* India's power sector is one of the most diversified in the world. Sources of power generation range from conventional sources such as coal, lignite, natural gas, oil, hydro and nuclear power, to viable non-conventional sources such as wind, solar, agricultural and domestic waste.

* India was ranked fourth in wind power, fifth in solar power and fourth in renewable power installed capacity, as of 2020.

Over 80% of India's energy needs are met by three fuels: coal, oil and solid biomass.

Installed capacity by source in India as on 20 july 2022.

→ Coal: (204,080 MW) (50.5%)

→ Lignite: 6,620 MW (1.6%)

→ Gas: 24,856 MW (6.2%)

→ Diesel: 510 MW (0.1%)

→ Hydro: 46,850 MW (11.6%).

→ Wind, Solar & Other RE: 114,065 MW (28.3%)

→ Nuclear: 6,780 MW (1.7%).

* The total installed power generation capacity is the sum of utility capacity, captive power capacity, and other non-utilities.

* The breakup of Renewable Energy sources (RES) is:

→ Solar Power (53,996.54 MW).

→ Wind Power (40,357.58 MW)

→ Bio mass (10,205.61 MW).

→ Small hydro (4,848.90 MW).

→ Waste-to-energy (476.75 MW)

Load Dispatch Center

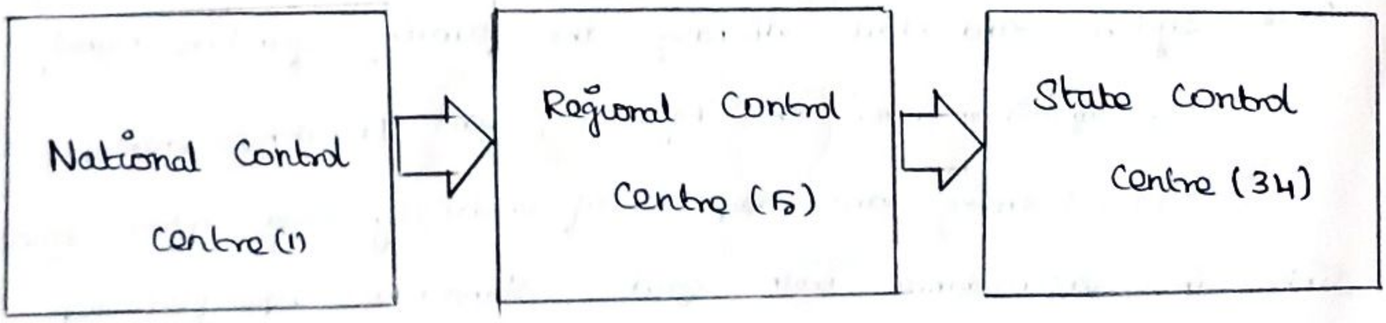
* Load dispatch center is a coordinating agency for state electricity boards for ensuring a mechanism for safe and secure grid operation.

* Load dispatch center is a important link between generation and transmission, which co-ordinates the power requirements of consumers of electricity.

* Power System Operation Corporation Limited (POSOCO) is a CPSE under the jurisdiction of Ministry of power, Government of India.

* It is responsible to monitor and ensure round the clock integrated operation of Indian Power system is a reliable, efficient and secure manner thus serving a mission critical activity.

* It consists of 5 Regional Load Despatch centres (RLDCs) and the National Load Despatch Centre (NLDC).



Load Despatch centres in India

National Load Despatch Center:

On 25 February 2009 the National Load Despatch centre (NLDC) was inaugurated by Sushilkumar Shinde (Former Union Minister of Power) and Shiela Dixit (Former Chief Minister, NCT of Delhi). National Load Despatch centre (NLDC) has been constituted as per Ministry of power (MOP) notification New Delhi dated 2 March 2005 and is the apex body to ensure integrated operation of the national power system.

Constitution:

There shall be a center at the national level to be known as National Load Despatch centre for optimum scheduling and despatch of electricity among the Regional Load Despatch Centres

National Load Despatch Centres shall be located at New Delhi with a back up at its center in Kolkata.

Functions:

The National Load Despatch Centre shall be the apex body to ensure integrated operation of the national Power system and shall discharge the following functions, namely:-

a) Supervision over the Regional Load Despatch centres;

b) Scheduling and despatch of electricity over inter-regional links in accordance with grid standards specified by the authority and grid code specified by Central commission in coordination with Regional Load Despatch Centres;

c) Coordination with Regional Load Despatch Centres for achieving maximum economy and efficiency in the operation of National Grid;

d) Monitoring of operations and grid security of the National Grid;

e) Supervision and control over the inter-regional links as may be required for ensuring stability of the power system under its control;

f) Coordination with Regional Load Despatch centres for the energy accounting of inter-regional exchange of power;

g) Coordination of trans-national exchange of power;

h) Providing operational feed back for national grid planning to the authority and the Central Trans-national exchange of power.

i) Dissemination of information relating to operations of transmission system in accordance with directions or regulations issued by Central Electricity Regulatory Commission and the Central Government from time to time.

j) Coordination with Regional Power Committees for regional outage schedule in the national perspective to ensure optimal utilisation of power resources.

Regional Load Despatch Center:

The five RLDCs oversee the interstate transmission for the following states:

* **Northern Regional Load Despatch Center (NRLDC):** Delhi, Haryana, Himachal Pradesh, Jammu and Kashmir, Ladakh, Punjab, Rajasthan, Uttar Pradesh, Uttarkhand.

* **Western Regional Load Despatch Center (WRLDC):** Maharashtra, Gujarat, Madhya Pradesh, Chattisgarh, Goa, Daman and Diu, Dadra and Nagar Haveli.

* **Eastern Regional Load Despatch Center (ERLDC):** Bihar, Jharkhand, Odisha, West Bengal, Sikkim.

* **Southern Regional Load Despatch Center (SRLDC):** Tamil Nadu, Karnataka, Kerala, Andhra Pradesh, Telangana, Pondicherry.

* **North-Eastern Regional Load Despatch Center (NERLDC):** Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Tripura.

Each RLDC maintains their own dedicated website where scheduling and despatch of power within their respective control areas are handled round the clock.

Economics of Generation

1) Load Curve

The Curve showing the variation of load on the power station with respect to time is known as load curve.

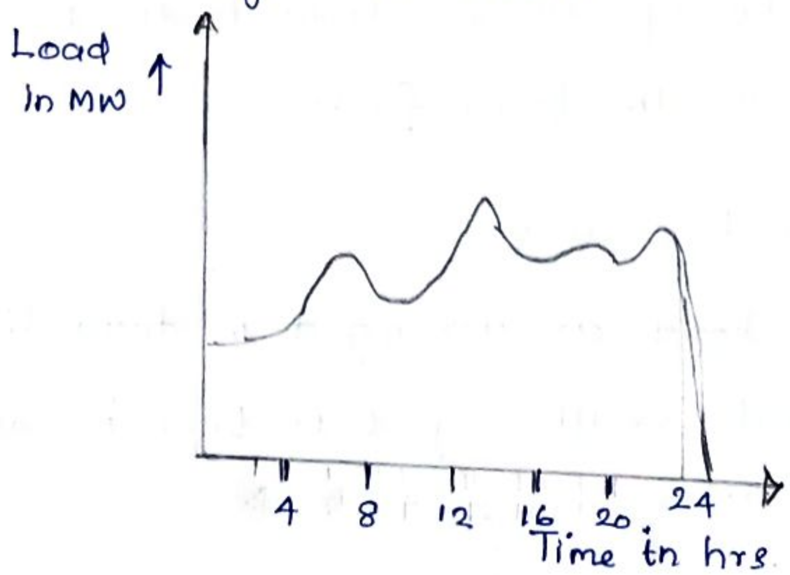
Load on the power system is not constant. It varies from time to time

Types of Load curve.

a) Daily load curve.
b) Monthly load curve
c) Yearly (or) Annual load curve.

a) Daily load curve

The curve showing the variation of load on a whole day (or) 24 hours with respect to time is called as daily load curve.



b) Monthly load curve

The Curve showing the Variation of load for a month (or) 30 × 24 hours with respect to time is called monthly load curve.

c) Yearly Load Curve (or) Annual load curve.

The curve showing the variation of load for a year (or) 365 × 24 hours with respect to time is called yearly load curve.

Load curve gives the following information

i) The area under the curve represents the total number of units generated in a day.

ii) The peak of the curve represents the maximum demand on the station.

iii) The area under the load curve divided by the number of hours, gives the average load on the power system.

iv) The ratio of average load to the maximum demand gives the load factor.

2) Load Duration Curve

The loads are arranged in descending order of magnitudes with respect to time is called Load duration curve.

ie) greater load on the left and lesser load on the right.

Important terms for deciding the type and Rating of Generating plant.

i) Connected load

The Sum of the continous rating of all the electrical equipment Connected to the Supply System is known as Connected load.

ii) Maximum demand

The greatest demand occur on the power System for a Short Interval of time is Called Maximum Demand.

iii) Demand factor

The ratio of actual Maximum demand on the System to the total rated load Connected to the System.

It is always less than unity

$$\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected Load}}$$

iv) Average load

The average loads (or) demands on the power Station is the average of loads occuring at Various events.

$$\text{Daily average load} = \frac{\text{No of units generated in day (kWhr)}}{\text{24 (No of hrs in a day)}}$$

$$\text{Monthly average load} = \frac{\text{No. of units generated in a month}}{30 \times 24 \text{ (No of hrs in a month)}}$$

$$\text{Annual average load} = \frac{\text{No of units generated in a year}}{365 \times 24 \text{ (No of hrs in a year)}}$$

v) Load factor

The ratio of average load to the Maximum demand during a certain period of time.

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum load}}.$$

If the plant is operated for 'T' hours

$$\text{Load factor} = \frac{\text{Average load} \times T}{\text{Maximum} \times T}$$

$T = 24$, for daily load curve

$T = 24 \times 7$, for weekly load curve

$T = 24 \times 365$, for Annual load curve.

vi) Diversity factor

The ratio of sum of the individual maximum demands of all the consumers to the Maximum demand of the power station is called the Diversity factor.

$$\text{Diversity factor} = \frac{\text{Sum of Individual Maximum Demand}}{\text{Maximum demand of power Station.}}$$

It is always greater than unity

If diversity factor is more, the cost of generation of Power is low.

vii) Coincidence factor

The reciprocal of diversity factor is called Coincidence factor.

viii) Capacity factor (or) plant factor

It is the ratio of the average load to the rated Capacity of the Power plant.

$$\text{Capacity factor} = \frac{\text{Average demand}}{\text{Rated Capacity of Power plant}}$$

$$= \frac{\text{Units (or) kWhr generated}}{\text{plant Capacity} \times \text{Number of hours.}}$$

ix) Utilisation factor

It is the ratio of Maximum demand to the rated Capacity of the Power plant.

$$\text{Utilisation factor} = \frac{\text{Maximum demand on the Power Station}}{\text{Rated Capacity of the power Station.}}$$

x) plant operating factor (or) Plant use factor.

It is defined as the ratio of the actual energy generated during a given period to the product of Capacity of plant and number of hours the plant has been actually operated during the period

$$\text{plant use factor} = \frac{\text{Total kWhr Generated}}{(\text{Rated capacity of the plant}) \times (\text{No of operating hours})}$$

xi) Reserve Capacity

It is the difference b/w the plant Capacity and Maximum demand.

Reserve Capacity = plant Capacity − Maximum Demand.

Problems

1) A generating station has the following daily load curve

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

Draw the load curve, load duration curve and find

(i) maximum demand

(ii) Units generated per day

(iii) Average Load

(iv) Load factor

Soln

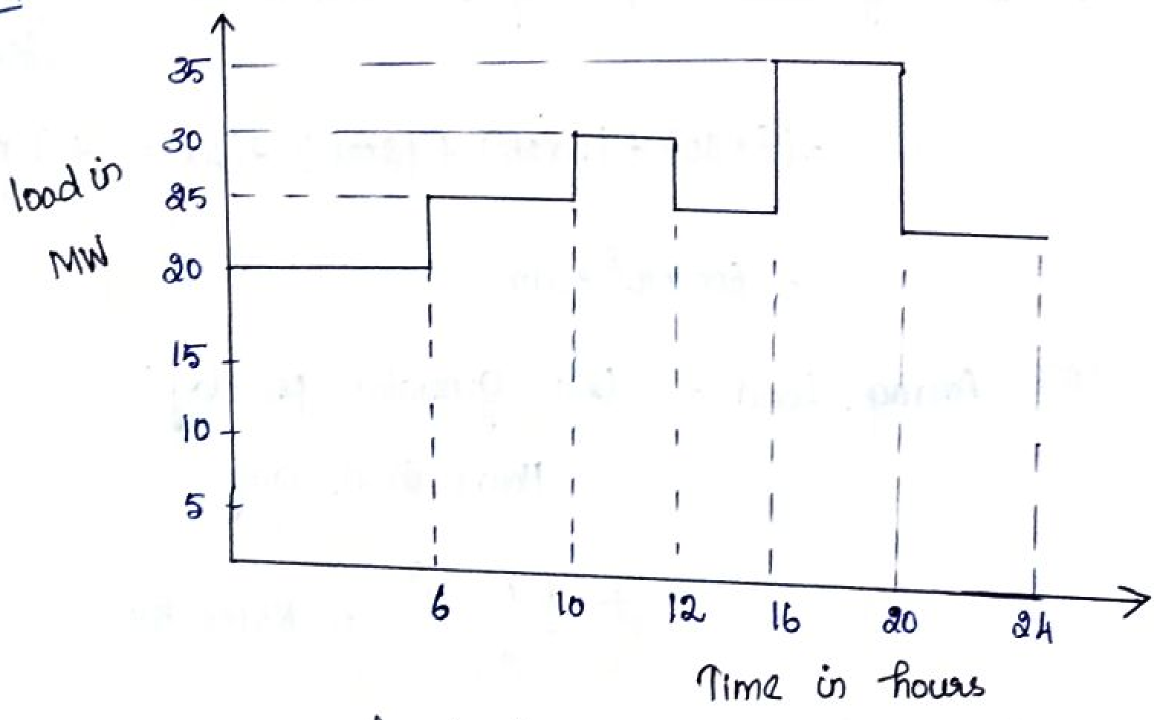


fig load curve

Load in MW	Duration (hours)	
35	4	0
30	2	6
25	8	14
20	10	24

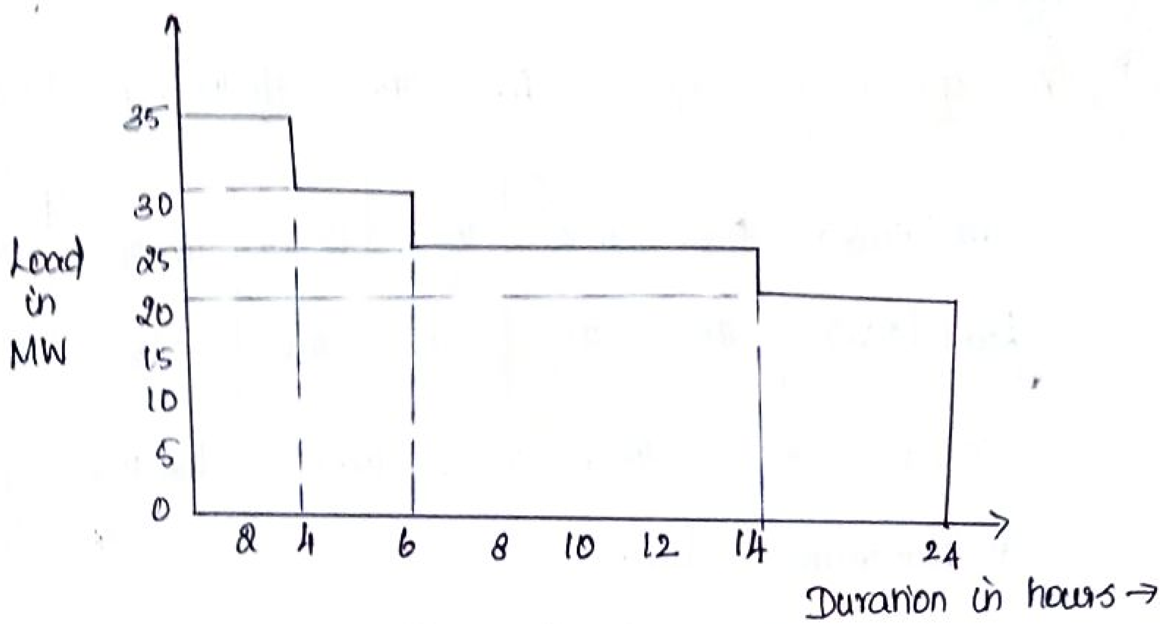


fig : Load duration curve

(i) Maximum demand = 35MW = 35×10^3 KW

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

$= (6 \times 20) + (4 \times 25) + (2 \times 30) + (4 \times 25) + (4 \times 35) + (4 \times 20)$

$= 600 \times 10^3$ KWhr

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

$= \frac{600 \times 10^3}{24} = 25000$ kW

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

$= \frac{25000}{35000} = 0.7143 = 71.43\%$

8) A generating station has a maximum demand of 35 MW. Load factor is 70%, Plant capacity factor is 60% and plant use factor is 75%. Find the reserve capacity and daily energy produced.

soln

Load factor $= \frac{70}{100} = 0.7$

Plant capacity factor $= \frac{60}{100} = 0.6$

maximum demand $= 35$ MW

$$\text{Load factor} = \frac{\text{Average demand}}{\text{maximum demand}}$$

Average demand = load factor x maximum demand

$= 0.7 \times 35 = 24.5$ MW

Reserve capacity = Plant capacity − maximum demand

$= 40.833 - 35$

$= 5.833$ MW

Plant use factor $= \frac{75}{100} = 0.75$

Total kwhr generated $= 0.75 \times 40.8 \times 24$

$= 734.99$ MWhr

3) A power station has to met the following demand.

Group A : 250 KW b/w 8.A.M and 6PM

Group B : 200 KW b/w 6 AM & 10 ~~P.M~~ AM

Group C : 100 KW b/w 6 AM & 10 ~~P.M~~ AM

Group D : 150 KW b/w 10 A.M & 6 PM & then b/w 6 PM & 6 AM

Draw the daily load curve and determine

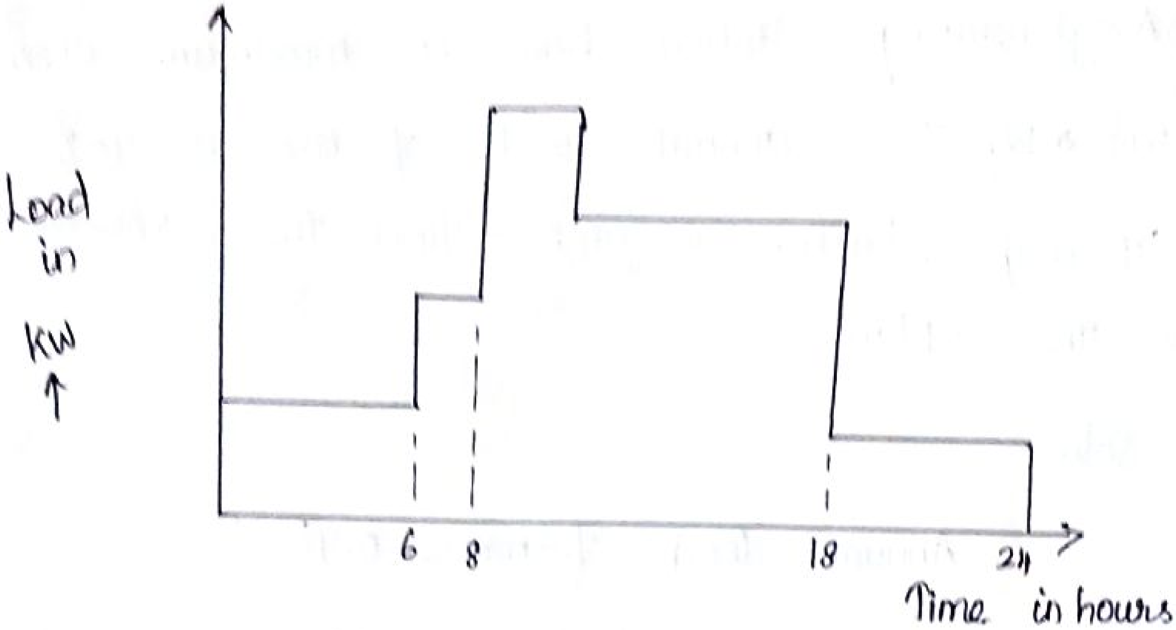
(a) diversity factor

(b) Units generated per day

(c) load factor

Soln

Time (hours) / Group	12-6 AM	6AM-8 AM	8AM to 10AM	10 Am-6PM	6PM-12PM
A			250 KW	250 KW	
B		200 KW	200 KW		
C		100 KW	100 KW		
D	150 KW			150 KW	150 KW
Total load on Power station	150 KW	300 KW	550 KW	400 KW	150 KW



(a) maximum demand = 550 kW

$$\text{diversity factor} = \frac{250 + 200 + 100 + 150}{550}$$

$$= 1.2727$$

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

$$= (6 \times 150) + (2 \times 300) + (2 \times 550) + (8 \times 400) + (6 \times 150)$$

$$= 6700 \text{ kWhr}$$

(c) $$\text{load factor} = \frac{\text{Average load}}{\text{maximum demand}}$$

$$\text{average load} = \frac{6700}{24} = 279.167$$

$$\text{Load factor} = \frac{279.167}{550}$$

$$= 0.5075 = 50.75\%$$

1) A generating station has a maximum demand of 500 MW. The annual load factor is 70% and capacity factor is 65%. Find the reserve capacity of the plant.

Soln

Annual load factor = 0.7

Capacity factor = 0.65

maximum demand = 500 MW

Energy generated per annum = 500 × 0.7 × 8760

= 3066 MWhr

$$\text{Capacity factor} = \frac{\text{Units generated per year}}{\text{Plant capacity} \times \text{hours}}$$

$$= \frac{3066 \times 10^3}{0.65 \times 8760}$$

= 538.46 MW

Reserve capacity = Plant capacity − maximum demand

= 538.46 − 500

= 38.46 MW

Q) A diesel station supplies the following loads to various consumers:

Industrial load - 1000 KW

Commercial Load - 750 KW

Domestic load - 500 KW

Domestic light - 500 KW.

If the maximum demand on the station is 2500 KW and the number of KWhr generated per year is 45×10^5, determine the diversity factor and annual load factor.

Solution:

Given, Maximum demand = 2500 KW.

Find, Diversity factor = $\dfrac{\text{Sum of individual maximum demands}}{\text{Max. demand of power station.}}$

Annual load Factor = $\dfrac{\text{Average load}}{\text{Maximum load.}}$

Diversity factor = $\dfrac{1000+750+500+500}{2500} = 1.1$

Average load = $\dfrac{\text{kwhr generated /year}}{\text{Hours in a year}} = \dfrac{45 \times 10^5}{24 \times 365}$

= 513.7 KW

Annual load Factor = $513.7/2500 = 0.20548$

= 20.548 %.

Result:

(i) Diversity Factor = 1.1

(ii) Annual Load Factor = 20.548 %

6) A power supply is having the following loads

Type of Load	Maximum demand (kW)	Diversity factor of group	Demand Factor
Domestic	10000	1.2	0.8
Commercial	30000	1.3	0.9
Industrial	50000	1.35	0.95

If the overall system diversity factor is 1.5, determine : a) the maximum demand

(b) Connected load of each type.

Solution :

(a) Maximum demand = $\frac{\text{Total Maximum demand}}{\text{System diversity factor}}$

Total maximum demand = 10000 + 30000 + 50000

= 90000

Maximum demand = $\frac{90000}{1.5}$ = 60000 kW.

(b) Connected Load of each type :

Domestic load :

Connected domestic Load = $\frac{\text{Maximum demand (domestic)}}{\text{Demand factor of domestic load}}$

Maximum demand of domestic load = Diversity factor × Maximum domestic demand

= 1.2 × 10000

= 12000 kW.

· Energy produced / day = 15 × 24

= 360 KWhr.

Maximum energy produced = $\frac{360}{0.72}$

= 500 MW hr.

Reverse capacity = Plant capacity − Maximum demand

= 30 − 25

= 5 MW //

Speed Governing Mechanism and modelling.

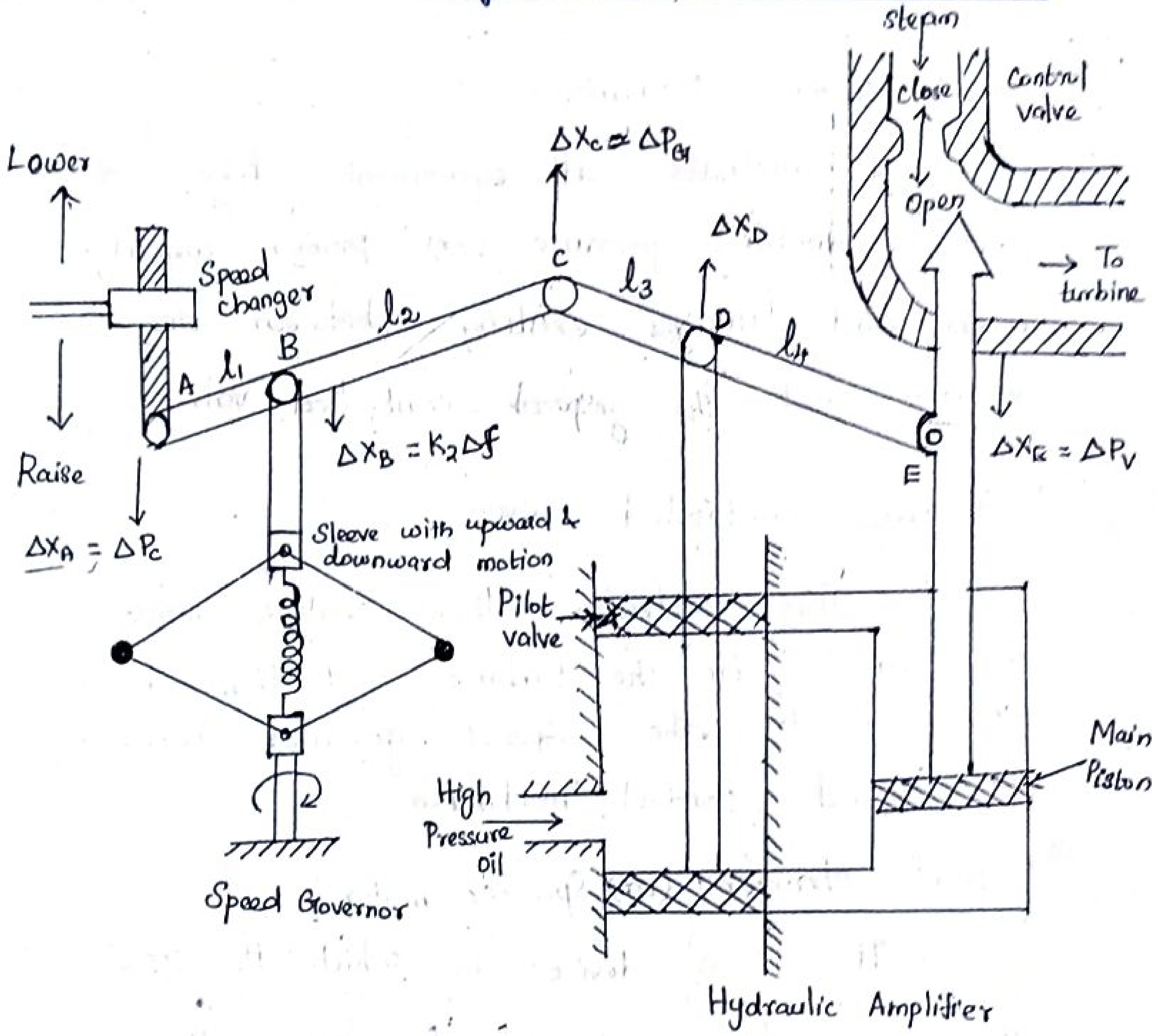


fig : Speed Governing system of the steam turbine.

The components of speed governing system are,

* Fly ball speed governor
* Speed changer
* Hydraulic Amplifier
* Linkage mechanism

Fly ball Speed governor :

It is a purely mechanical speed-sensitive device coupled directly to the hydraulic amplifier which adjusts the control valve opening via the linkage mechanism.

* As the load increases, speed of the turbine decreas and the speed changer gives raise command. So the fly ball move outwards and the point B moves downwards & the reverse happens with the increased speed.

Speed changer:

→ It makes it possible to restore the frequency to the initial value after the operation of the speed governors which has steady state characteristics.

→ A small downward movement of the linkage point A corresponds to an increase ΔP_c in the reference power setting.

Hydraulic Amplifier:

It consists of pilot valve & main piston.

→ With this arrangement, a low power pilot valve movement is converted to high power level movement of the oil-servomotor.

→ The input to the amplifier is the position X_D of 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 another rigid link pivoted at D.

→ The function of link mechanism is to control the steam valve (or) gate. We get the 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 the raise command and the fly balls move outwords and the point B move downwards 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. (ie) increases the flow of steam to the turbine. Thereby, increase the speed of the turbine & maintain the constant frequency.

Model of Speed Governor:

Nov/Dec 2011

Consider the steam is operating under steady state and delivering power P_G^0 from the generator at nominal frequency f^0.

Let X_S^0 = steam value setting.

* Let us assume the raise command ΔP_C to the speed changer, the point A be moved downwards by a small amount ΔX_A which causes the turbine power output to change.

$$\therefore \Delta X_A = K_C \Delta P_C .$$

Let us assume, + ⇒ downward direction (movement)

− ⇒ Upward direction (movement)

Movement of 'C':

(i) ΔX_A contributes $\left(-\frac{l_2}{l_1}\right) \Delta X_A = -k_1 \Delta X_A$

$= -k_1 K_C \Delta P_C$

(ii) Decrease in frequency Δf causes the fly balls to move outwards so that B moves downwards by a proportional amount $k_2 \Delta f$

$$\therefore \Delta X_C = -k_1 k_c \Delta P_c + k_2 \Delta f . \quad \text{——} (1)$$

Movement of D:

It is contributed by ΔX_C & ΔX_E. The movement ΔX_D is the amount by which the pilot valve opens, there by moving the main piston and opening the steam valve by ΔX_E.

$$\Delta X_D = \left(\frac{l_4}{l_3+l_4}\right) \Delta X_C + \left(\frac{l_3}{l_3+l_4}\right) \Delta X_E$$

$$\Delta X_D = k_3 \Delta X_C + k_4' \Delta X_E \quad \text{——— (2)}$$

Movement of E :

The volume of oil admitted to the cylinder is proportional to the line integral of ΔX_D.

$$\Delta X_E = k_5 \int_0^t -(\Delta X_D)\,dt \quad \text{——— (3)}$$

Taking laplace transform of (1), (2) & (3),

$$\Delta X_C(s) = -k_1 k_c \,\Delta P_c(s) + k_2 \,\Delta F(s) \quad \text{——— (4)}$$

$$\Delta X_D(s) = k_3 \,\Delta X_C(s) + k_4 \,\Delta X_E(s) \quad \text{——— (5)}$$

$$\Delta X_E(s) = -k_5 \cdot \frac{\Delta X_D(s)}{s} \quad \text{——— (6)}$$

sub (4) in (5).

$$\Delta X_D(s) = k_3 \left[-k_1 k_c \,\Delta P_c(s) + k_2 \,\Delta F(s)\right] + k_4 \,\Delta X_E(s) \quad \text{——— (7)}$$

sub (7) in (6),

$$\Delta X_E(s) = \frac{-k_5}{s}\left[k_3\left(-k_1 k_c \,\Delta P_c(s) + k_2 \,\Delta F(s)\right) + k_4 \,\Delta X_E(s)\right]$$

$$\Delta X_E(s) + \frac{k_5 k_4}{s} \Delta X_E(s) = \frac{-k_5}{s}\left[-k_3 k_1 k_c \,\Delta P_c(s) + k_2 k_3 \,\Delta F(s)\right]$$

$$\Delta X_E(s)\left[1+\frac{k_4 k_5}{s}\right] = -\frac{k_5}{s}\left[-k_1 k_3 k_c \,\Delta P_c(s) + k_2 k_3 \Delta F(s)\right]$$

$$\Delta X_E(s)\left[\frac{s+k_4 k_5}{s}\right] = \frac{+k_5}{s} \cdot k_1 k_3 k_c\left[\Delta P_c(s) - \frac{k_2}{k_1 k_c}\Delta F(s)\right]$$

$$\Delta X_E(s) = \frac{k_1 k_3 k_5 k_c}{(s+k_4 k_5)}\left[\Delta P_c(s) - \frac{k_2}{k_1 k_c}\Delta F(s)\right]$$

$$= \frac{k_1 k_3 k_5 k_c}{k_4 k_5\left(1+\frac{s}{k_4 k_5}\right)}\left[\Delta P_c(s) - \frac{k_2}{k_1 k_c}\Delta F(s)\right]$$

$$= \frac{k_1 k_3 k_c}{k_4}\left[\frac{\Delta P_c(s) - \frac{k_2}{k_1 k_c}\Delta F(s)}{1+\frac{s}{k_4 k_5}}\right]$$

Take $R = \frac{k_1 k_c}{k_2}$ ⇒ Speed regulation of the governor in Hz/MW.

and $k_G = \frac{k_1 k_3 k_c}{k_4}$ ⇒ Gain of speed governor.

$T_G = \frac{1}{k_4 k_5}$ ⇒ Time constant of speed governor.

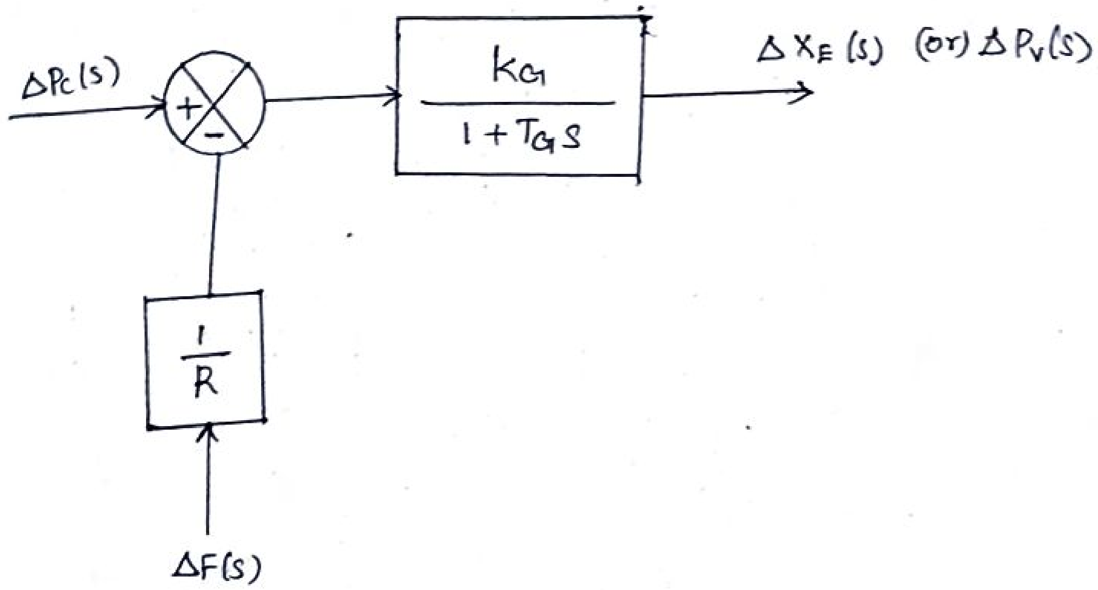
($T_G < 100$ ms)

$$\Delta X_E(s) = k_G\left[\frac{\Delta P_c(s) - \frac{1}{R}\Delta F(s)}{1+T_G s}\right]$$

$$\boxed{\Delta X_E(s) = \left[\Delta P_c(s) - \frac{1}{R}\Delta F(s)\right]\left(\frac{k_G}{1+T_G s}\right)}$$

The output of the generating unit at a given system frequency can be varied only by changing its 'load reference (or) control point' which is integrated with the speed governing system.

Block diagram of speed governor,



Turbine Model :

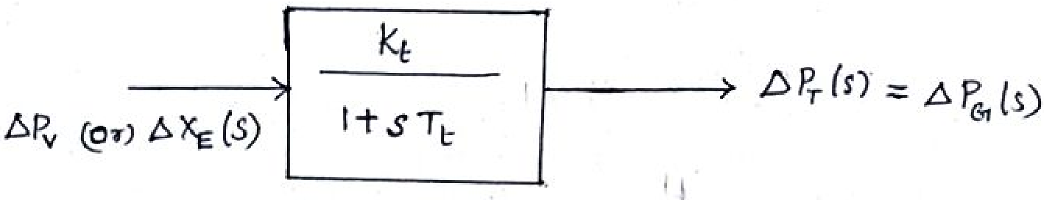
→ When a steam valve opening is increased, the power generation ΔP_G is also increased.

→ There is incremental increase in turbine power ΔP_T due to change in valve position ΔX_E, which will result in an increased generator power ΔP_G.

→ If the generator incremental loss is neglected then $\Delta P_T = \Delta P_G$.

⇒ The prime mover driving a generator unit may be steam turbine (or) a hydroturbine.

The model of a non-reheat turbine is,



⇒ the position of the valve that controls the emissio of steam into the turbine to the power output of the turbine

where T_t = Time constant of turbine

K_t = Gain Constant.

ΔP_V = Per unit change in valve position from nominal value.

Generator Load Model:

To develop the mathematical model of an isolated generator, which is only supplying local load and is not supplying power to another area, suppose there is a real load change of ΔP_D.

→ Due to the action of the turbine controllers, the generator increases its output by an amount ΔP_G.

* The net surplus power $(\Delta P_G - \Delta P_D)$ will be absorbed by the system in two ways.

(1) By increasing the kinetic energy in the rotor at the rate $\frac{d}{dt}(W_{K.E})$

(2) As the frequency changes, the motor load changes being sensitive to speed.

(i) By increasing the kinetic energy in the rotor at the rate $\frac{d}{dt}(W_{K.E})$ (or) ΔP_G.

$$W^{0}_{K.E} = H \times P_r \quad \text{kWsec.}$$

where H = Inertia constant $= \dfrac{\text{stored energy in MJ}}{\text{Rating in MVA}}$.

$$W^{0}_{K.E} = \frac{1}{2} J \omega_0^2 \Rightarrow \boxed{W^{0}_{K.E} \propto f_0^2} \quad \text{------- (8)}$$

$$W_{K.E} \propto (f_0 + \Delta f)^2 \quad \text{------- (9)}$$

$$\frac{W_{K.E}}{W^{0}_{K.E}} = \frac{(f_0 + \Delta f)^2}{f_0^2}$$

$$W_{K.E} = W^{0}_{K.E}\left(\frac{f_0 + \Delta f}{f_0}\right)^2 = W^{0}_{K.E}\left(1 + \frac{\Delta f}{f_0}\right)^2$$

$$= W^{0}_{K.E}\left[1 + 2\frac{\Delta f}{f_0} + \left(\frac{\Delta f}{f_0}\right)^2\right]$$

Neglecting second order term,

$$W_{K.E} = W^{0}_{K.E}\left[1 + 2\frac{\Delta f}{f_0}\right]$$

Rate of change of kinetic Energy $\Big\}$ $$\frac{dW_{K.E}}{dt} = W^{0}_{K.E}\left[0 + \frac{2}{f_0}\frac{d(\Delta f)}{dt}\right]$$

$$\frac{dW_{K.E}}{dt} = \frac{2W^{0}_{K.E}}{f_0}\frac{d(\Delta f)}{dt} \quad \text{------- (10)}$$

sub $W^{0}_{K.E}$ in (10), i.e, $W^{0}_{KE} = HP_r$.

$$\boxed{\frac{dW_{K.E}}{dt} = \frac{2HP_r}{f_0} \cdot \frac{d(\Delta f)}{dt}} \quad \text{------- (11)}$$

$$\boxed{\Delta P_G = \frac{2HP_r}{f_0}\frac{d(\Delta f)}{dt}}$$

2) As the frequency changes, the motor load changes being sensitive to speed. $[\Delta F(s)]$

Rate of change of load w.r.to frequency } $\frac{\partial P_D}{\partial f} = B$.

where B = Damping co-efficient in MW/Hz

Value of damping co-efficient is positive for motor load

For the generator, $\frac{\partial P_D}{\partial f} = -B$.

$$\partial P_D = -B\,\partial f$$

$$\Delta P_D = -B\,\Delta f. \quad \text{------ (12)}$$

The net surplus power, (power balance equation)

$$\Delta P_G - \Delta P_D = \frac{2HP_r}{f_0}\frac{d}{dt}(\Delta f) + B\Delta f \quad \text{---- (13)}$$

To find p.u value, $\div$ing the above equation by P_r

$$\Delta P_{G\,p.u} - \Delta P_{D\,p.u} = \frac{2H}{f_0}\frac{d}{dt}(\Delta f) + B_{p.u}\,\Delta f.$$

Taking Laplace transform,

$$\Delta P_G(s) - \Delta P_D(s) = \frac{2H}{f_0}\cdot s\,\Delta F(s) + B\,\Delta F(s)$$

$$\Delta P_G(s) - \Delta P_D(s) = \Delta F(s)\left[\frac{2Hs}{f_0} + B\right]$$

$$\Delta F(s) = \frac{\Delta P_G(s) - \Delta P_D(s)}{\left(\frac{2Hs}{f_0} + B\right)}$$

$$= \frac{\Delta P_G(s) - \Delta P_D(s)}{B\left[1 + \frac{2Hs}{Bf_0}\right]}$$

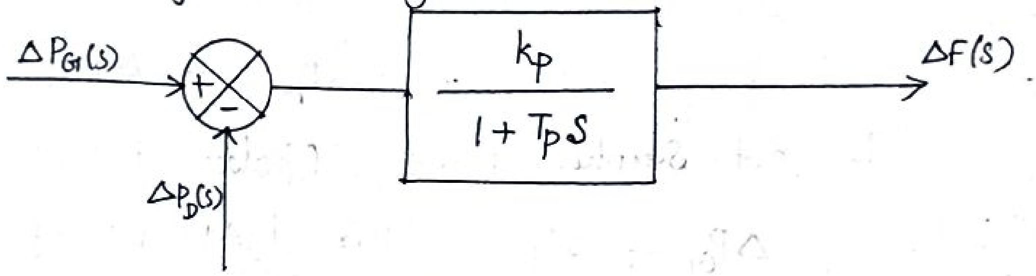
Take $1/B = k_p$ = Power system gain

$$\frac{2H}{Bf_0} = T_p = \text{Power system time constant.}$$

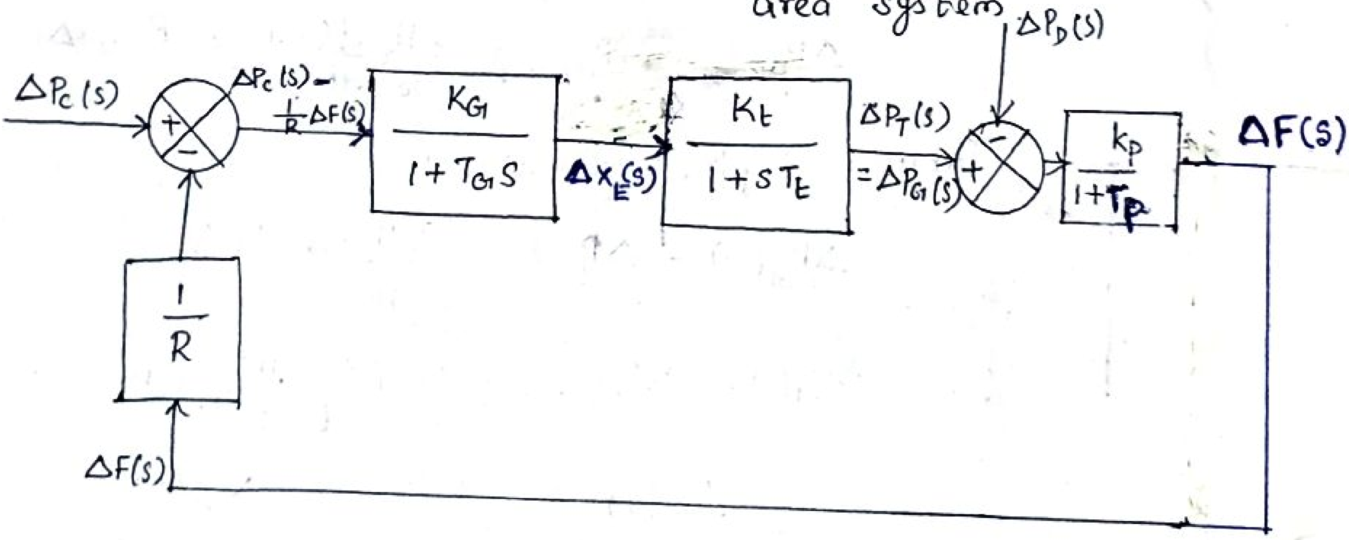
$$\Delta F(s) = \frac{\Delta P_G(s) - \Delta P_D(s)}{\left(\frac{1 + T_p s}{k_p}\right)}$$

$$\boxed{\Delta F(s) = \left[\Delta P_G(s) - \Delta P_D(s)\right]\left(\frac{k_p}{1 + T_p s}\right)}$$

Block diagram of generator model is



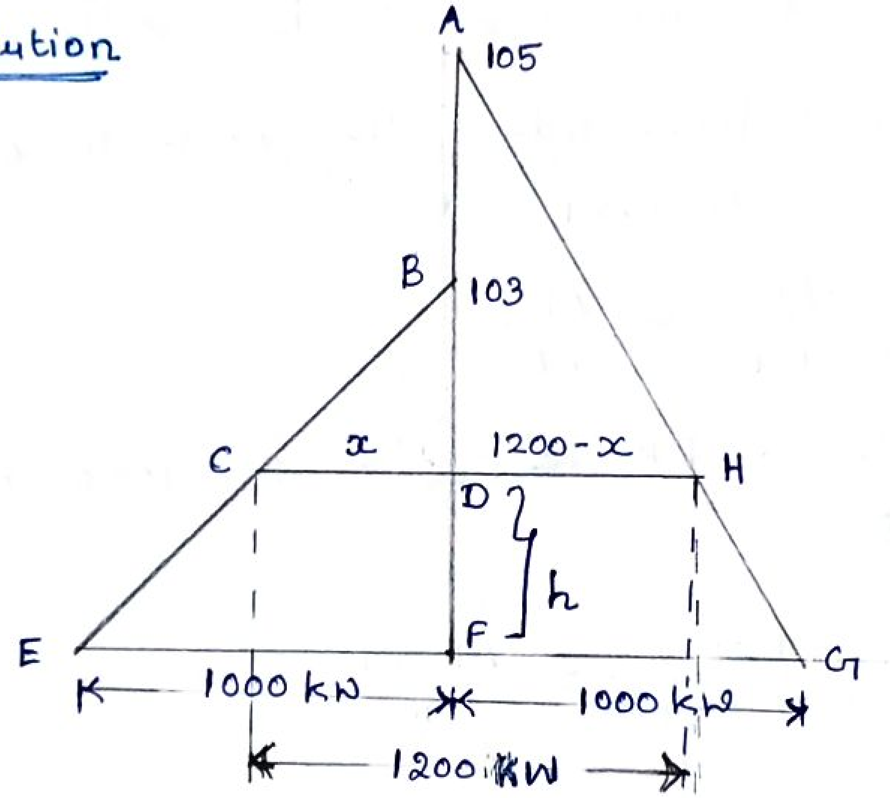
Model of Load frequency control of a single area system



⇒ Combining the governor moder, turbine model, and generator load model, we get the complete block diagram of LFC [Load frequency control) of an isolated power system

Two 100 kW alternators operate in parallel. The speed regulation of first alternator is 100% to 103% from full load to no load and that of other 100% to 105%. How will the two alternators share a load of 1200 kW and at what load will one machine cease to ~~supply~~ supply any portion of the load.

Solution



i) From the left hand side of the figure, the Δ BCD and Δ BFE are similar

$$\frac{CD}{EF} = \frac{BD}{BF}$$

where $CD = x$, $EF = 1000$, $BD = BF - DE$, $BF = 3$

$$\frac{x}{1000} = \frac{BF - DF}{3}$$

where $BF = 3$, $DF = h$

$$\frac{x}{1000} = \frac{3-h}{3}$$

$$3x = 1000(3-h)$$

$$x = \frac{1000}{3}(3-h)$$

$$x = 333.333(3-h)$$

$$x = 1000 - 333.333h \rightarrow (1)$$

From right hand side of the figure, the ΔADH and ΔAFG are similiar

$$\frac{DH}{FG} = \frac{AD}{AF}$$

Where $DH = 1200 - x$, $FG = 1000$, $AD = AF - DF$, $AF = 5$

$$\frac{1200-x}{1000} = \frac{AF-DF}{5}$$

where $AF = 5$, $DF = h$

$$\frac{1200-x}{1000} = \frac{5-h}{5}$$

$$1200 - x = 1000\left(\frac{5-h}{5}\right)$$

$$1200 - x = \frac{1000}{5}(5-h)$$

$$1200 - x = 200(5-h)$$

$$1200 - x = 1000 - 200h$$

$$-x = 1000 - 200h - 1200$$

$$-x = -200 - 200h$$

$$x = 200 - 200h \rightarrow (2)$$

Equating Equations (1) and (2)

$$1000 - 333.333h = 200 - 200h$$

$$-333.333h - 200h = 200 - 1000$$

$$-533.333h = -800$$

$$h = \frac{-800}{-533.333}$$

$$h = 1.5$$

From Equations (1) or (2)

Equation (1) becomes

$$x = 1000 - (333.333 \times 1.5)$$

$$x = 500$$

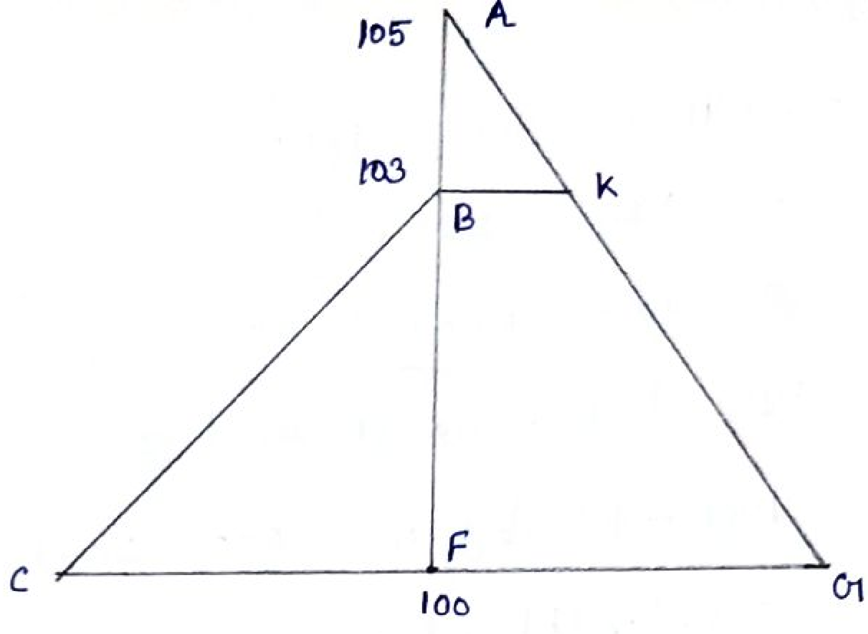
Let x be the load shared by gnr 1 and 1200-x be the load shared by gnr 2.

Therefore

Load shared by gnr 1 is $= x = \underline{\underline{500}}$ kW

Load shared by gnr 2 is $= 1200 - x = \underline{\underline{700}}$ kW

ii) If we assume, the machine 1 is cease to supply any load, the line CH in figure 1 shifted to point B



$$\frac{BK}{FG} = \frac{AB}{AF}$$

Where ~~BK~~ $FG = 1000$, $AB = 2$, $AF = 5$

$AB = 105 - 103 = 2$

$$\frac{BK}{1000} = \frac{2}{5}$$

$$BK = 1000 \times \frac{2}{5}$$

$$BK = 200 \times 2$$

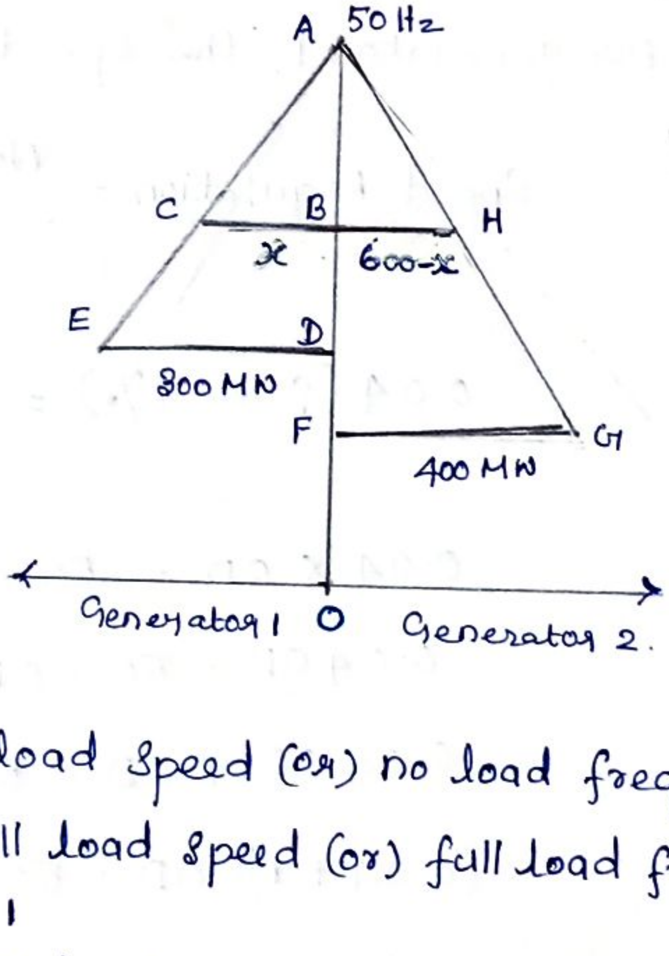
$$BK = 400$$

Let BK is Load shared by gns 2, when machine 1 stops to sharing the load.

Therefore, the Amount of load shared by one machine out of 1200 kW load is 400 kW

Two synchronous generators operating in parallel. Their capacities are 300 MW and 400 MW. The drop characteristics of their governors are 4% and 5% from noload to full load. Assuming that the generators are operating at 50 Hz at no load, how would be a load of 600 MW shared between them. What will be the system frequency at this load? Assume free governor action?

Solution



OA → no load speed (or) no load frequency

OD → full load speed (or) full load frequency of Generator 1

OF → full load speed (or) full load frequency of Generator 2

From the left hand side, the Δ ABC and Δ ADE are similiar

$$\frac{CB}{ED} = \frac{AB}{AD}$$

where $CB = x$, $ED = 300$, $AB = OA - OB$, $AD = OA - OD$

$$\frac{x}{300} = \frac{OA - OB}{OA - OD}$$

where $OA = 50$, $OB = f$

$$\frac{x}{300} = \frac{50 - f}{50 - OD} \rightarrow (1)$$

For generator 1, the speed Regulation is given by

$$\text{Speed Regulation} = \frac{\text{No load speed} - \text{full load speed}}{\text{full load speed}}$$

$$0.04 \text{ (given } 4\%) = \frac{50 - OD}{OD}$$

$$0.04 \times OD = 50 - OD$$

$$0.04\,OD = 50 - OD$$

$$0.04\,OD + OD = 50$$

$$(0.04 + 1)\,OD = 50$$

$$1.04\,OD = 50$$

$$OD = \frac{50}{1.04}$$

$$\boxed{OD = 48.077 \text{ Hz}}$$

Substitute OD in equation ①

$$\frac{x}{300} = \frac{50-f}{50-48.077}$$

$$\frac{x}{300} = \frac{50-f}{1.923}$$

$$1.923x = 300(50-f)$$

$$x = \frac{300}{1.923}(50-f)$$

$$x = 156.006(50-f)$$

$$x = 7800.312 - 156.006f \rightarrow ②$$

From the right hand side of the figure, the ΔABH and ΔAFG are similiar

$$\frac{BH}{FG} = \frac{AB}{AF}$$

where $BH = 600 - x$, $FG = 400$, $AB = OA - OB$

$AF = OA - OF$

$$\frac{600-x}{400} = \frac{OA-OB}{OA-OF}$$

where $OA = 50$, $OB = f$

$$\frac{600-x}{400} = \frac{50-f}{50-OF} \rightarrow ③$$

For generator 2, the speed Regulation is given by

$$\text{Speed Regulation} = \frac{\text{No load speed} - \text{full load speed}}{\text{full load speed}}$$

$$0.05 = \frac{50 - OF}{OF}$$

$$0.05\,OF = 50 - OF$$

$$0.05\,OF + OF = 50$$

$$(0.05 + 1)\,OF = 50$$

$$1.05\,OF = 50$$

$$OF = \frac{50}{1.05}$$

$$\boxed{OF = 47.619\ Hz}$$

Substitute OF in eq ③

$$\frac{600 - x}{400} = \frac{50 - f}{50 - 47.619}$$

$$\frac{600 - x}{400} = \frac{50 - f}{2.381}$$

$$(600 - x)\,2.381 = 400(50 - f)$$

$$1428.6 - 2.381x = 20000 - 400f$$

$$-2.381x = 20000 - 400f - 1428.6$$

$$-2.381x = 18571.4 - 400f$$

$$-x = \frac{18571.4 - 400f}{2.381}$$

$$-x = \frac{18571.4}{2.381} - \frac{400f}{2.381}$$

$$-x = 7799.832 - 167.997f$$

$$x = -7799.832 + 167.997f \rightarrow (4)$$

Equating the equations (2) and (4)

$$7800.312 - 156.006f = -7799.832 + 167.997f$$

$$-156.006f - 167.997f = -7799.832 - 7800.312$$

$$-324.003f = -15600.144$$

$$f = \frac{-15600.144}{-324.003}$$

$$\boxed{f = 48.148 \text{ Hz}}$$

When gnr 1 and 2 sharing the load 600 MW, the system frequency is 48.148 Hz

Substitute f in equation (2) or (4)

In equation (2)

$$x = 7800.312 - (156.006 \times 48.148)$$

$$x = 288.912$$

Let x be load shared by the Generator 1 and 600-x be the load shared by the Generator 2 is taken in the figure.

Therefore

Load Shared by Generator 1 is x = 288.912 MW

Load Shared by Generator 2 is $600 - x$ = 600 - 288.

EE8702 - POWER SYSTEM OPERATION AND CONTROL

UNIT II

REAL POWER - FREQUENCY CONTROL

Load Frequency Control (LFC) of single area system-static and dynamic analysis of uncontrolled and controlled cases - LFC of two area system - tie line modeling – block diagram representation of two area system - static and dynamic analysis - tie line with frequency bias control – state variability model - integration of economic dispatch control with LFC.

Prepared by

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V V College of Engineering

Single area power system - Load frequency control

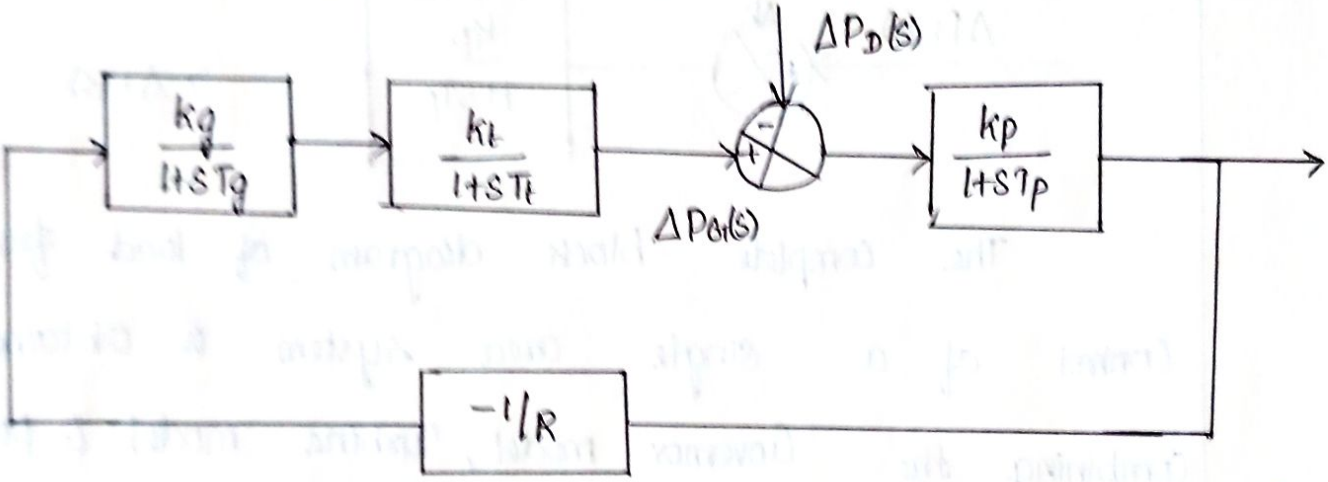
→ Static Analysis

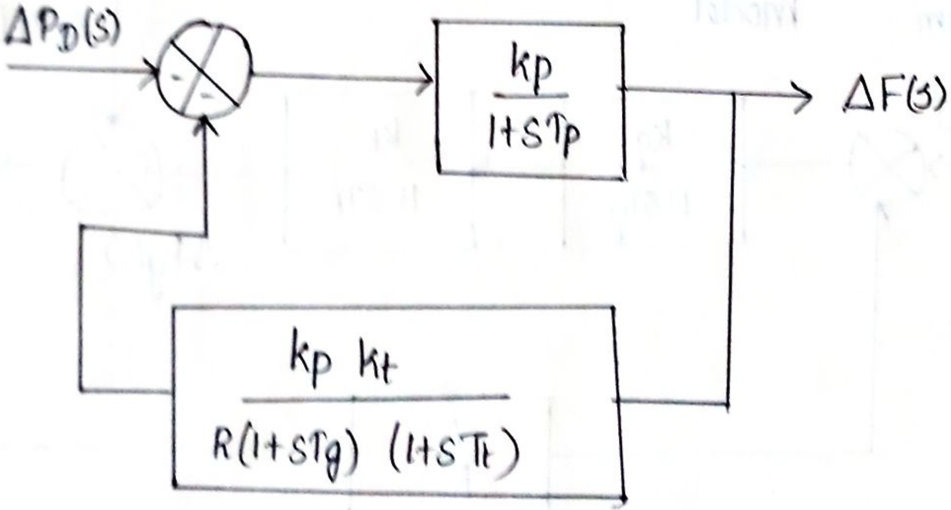
→ Dynamic Analysis

Static Analysis

(1) Uncontrolled Case

Consider the load frequency block dgm and $\Delta P_c = 0$.





The Closed loop T.F

$$T.F = \frac{G(s)}{1 + G(s)H(s)}$$

$$\Delta F(s) = \frac{k_p}{(1+sT_p) + \frac{k_p k_g k_t}{R(1+sT_g)(1+sT_t)}} \times [-\Delta P_D(s)]$$

For a small change in step i/p

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

Applying final value theorem

$$\Delta F_{static} = \lim_{s \to 0} s . \Delta F(s)$$

$$\Delta F_{static} = \frac{-k_p}{1 + \frac{k_p k_g k_t}{R}} \times \Delta P_D$$

Take $k_g . k_t = 1$

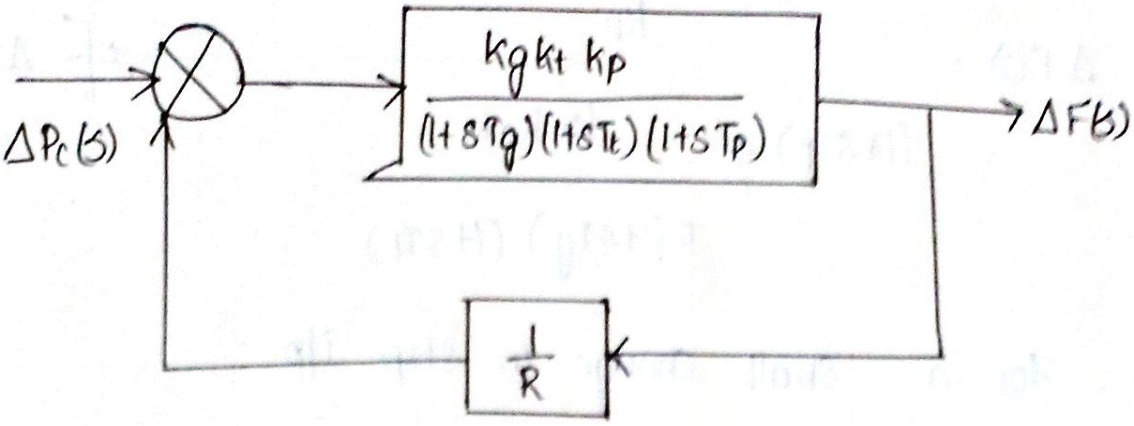
$$\Delta F_{static} = \frac{-k_p}{1 + \frac{k_p}{R}} \Delta P_D$$

$$\boxed{\Delta F_{static} = \frac{-\Delta P_D}{D + 1/R} = \frac{-\Delta P_D}{\beta}}$$

(II) controlled case.

Consider LFC block diagram with

$\Delta P_D = 0$



$$\Delta F(s) = \frac{K_g K_t K_p}{(1+sT_g)(1+sT_t)(1+sT_p) + \frac{K_g K_t K_p}{R}} \times \Delta P_c(s)$$

For a step change ΔP_c.

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

Applying final value theorem,

$$\Delta F_{static} = \lim_{s \to 0} s . \Delta F(s)$$

$$= \frac{K_g K_p K_t}{1 + \frac{K_g K_p K_t}{R}} \times \Delta P_c$$

Take $K_g K_t = 1$

$$\Delta F_{static} = \frac{K_p}{1 + \frac{K_p}{R}} \times \Delta P_c$$

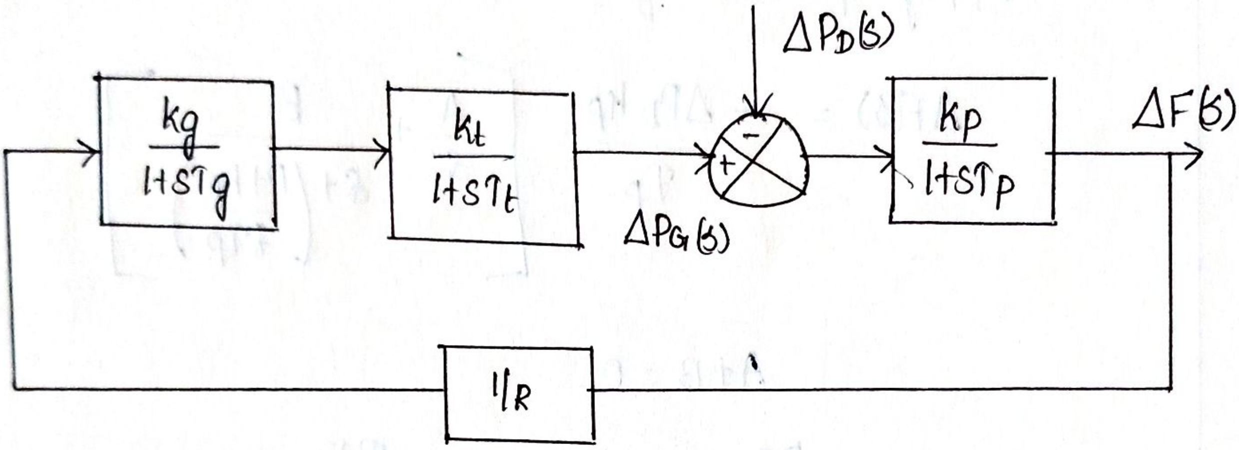
$$\boxed{\Delta F_{static} = \frac{\Delta P_c}{D + 1/R} = \frac{\Delta P_c}{\beta}}$$

Dynamic Analysis

(i) Uncontrolled case

Consider LFC block diagram with

$\Delta P_c = 0$



for approximate analysis

$$k_g k_t = 1$$

$$T_g = T_t = 0.$$

block diagram reduced to

$$\Delta F(s) = \frac{k_p}{1 + sT_p + \frac{k_p}{R}} \left[-\Delta P_D(s) \right]$$

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

$$\Delta F(s) = \frac{k_p}{1 + sT_p + \frac{k_p}{R}} \left(- \frac{\Delta P_D}{s} \right)$$

$$= \frac{-\Delta P_D \cdot k_p}{T_p \cdot s \left(s + \frac{R+k_p}{R T_p}\right)}$$

Apply partial fraction

$$\Delta F(s) = \frac{-\Delta P_D k_p}{T_p} \left[\frac{A}{s} + \frac{B}{s + \left(\frac{R+k_p}{R T_p}\right)} \right]$$

$$A + B = 0.$$

$$A = \frac{R T_p}{R+k_p} \qquad B = \frac{-R T_p}{R+k_p}$$

By taking Inverse laplace Transform

$$\Delta f(t) = -\frac{\Delta P_D k_p R}{R+k_p} \left\{ 1 - e^{-\left(\frac{R+k_p}{R T_p}\right)t} \right\}$$

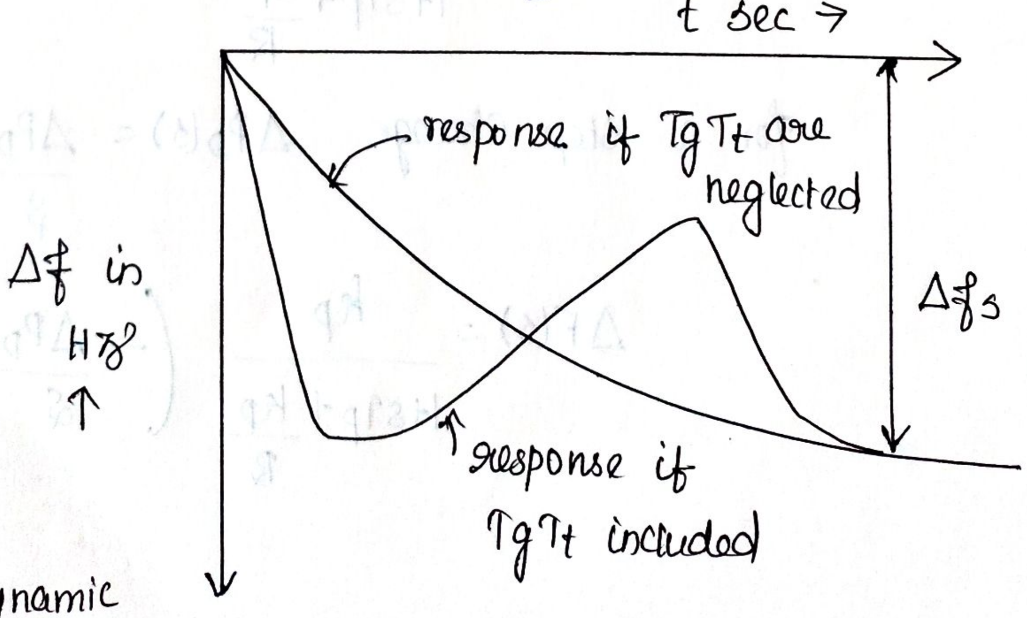
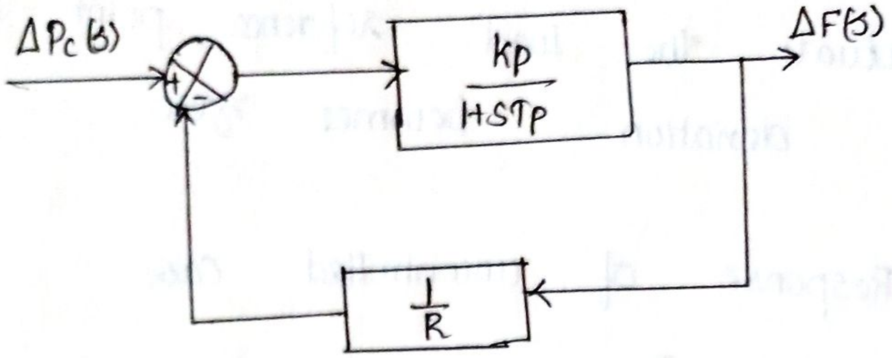


fig Dynamic response

(ii) Controlled case

Assume that $k_g k_t = 1$, $T_g = T_t = 0$.



$$\Delta F(s) = \frac{k_p}{1+sT_p + \frac{k_p}{R}} \Delta P_c(s)$$

For a step change, $\Delta P_c(s) = \frac{\Delta P_c}{s}$

$$\Delta F(s) = \frac{k_p \Delta P_c}{T_p s \left(s + \frac{R+k_p}{RT_p}\right)}$$

Apply partial fraction,

$$\Delta F(s) = \frac{k_p \Delta P_c}{T_p} \left[\frac{A}{s} + \frac{B}{s + \frac{R+k_p}{RT_p}} \right]$$

comparing coefficients, $A + B = 0$

$$A = \frac{RT_p}{R+k_p} \qquad B = \frac{-RT_p}{R+k_p}$$

Taking inverse laplace Transform

$$\Delta f(t) = \frac{\Delta P_c k_p R}{R+k_p} \left[1 - e^{-\left(\frac{R+k_p}{RT_p}\right)t} \right]$$

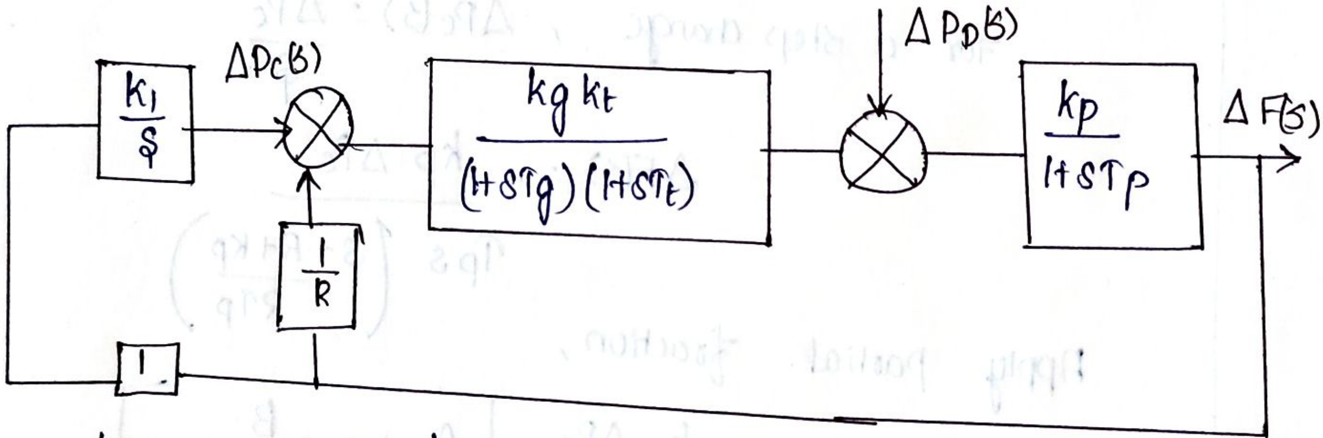
LFC of a single area system with integral controller

The purpose of the integral controller (IC) is to actuate the load reference point until the frequency deviation becomes zero.

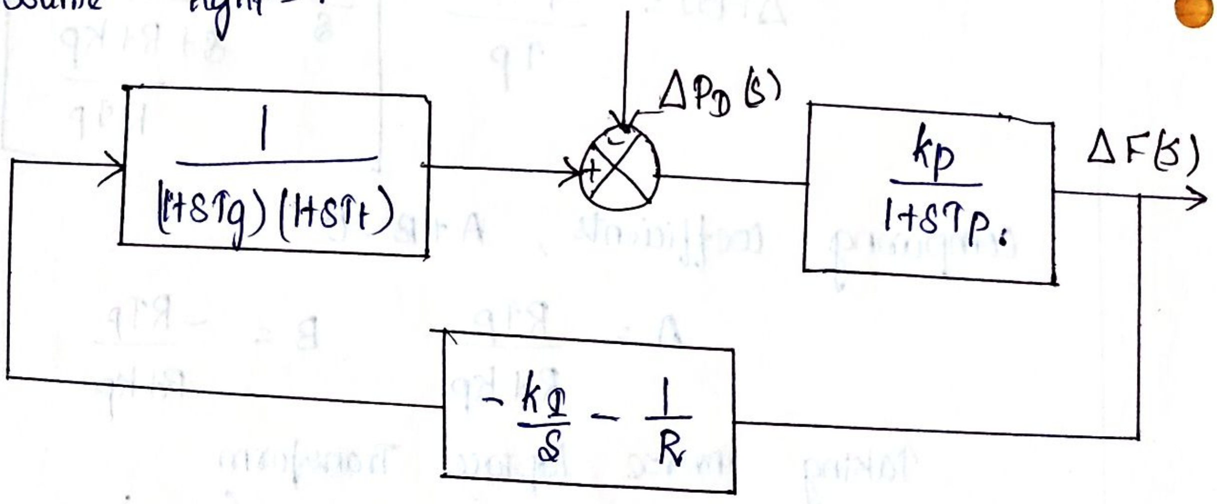
Static Response of uncontrolled case

Assume that $\Delta P_c = 0$

The reduced block diagram is shown



Assume $k_g k_t = 1$



$$\Delta P_c = -k_I \int \Delta F \cdot dt$$

Taking laplace Transform

$$\Delta P_c(s) = -\frac{k_I}{s}\,\Delta F(s)$$

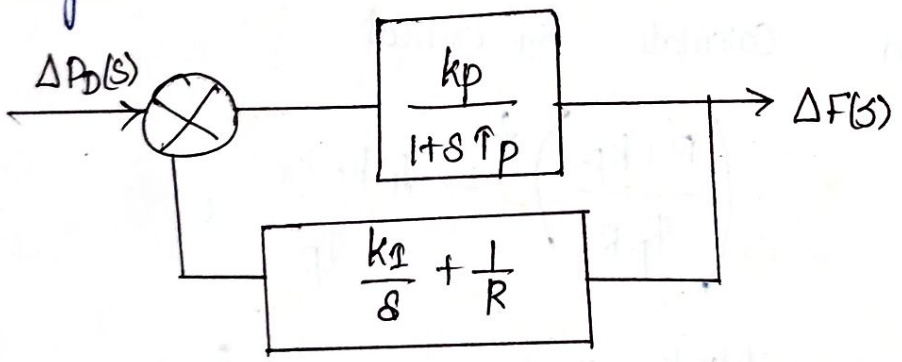
for a step change $\Delta P_D(s) = \frac{\Delta P_D}{s}$

$$\Delta F(s) = \frac{k_p}{(1+sT_p) + \left(\frac{k_I}{s} + \frac{1}{R}\right) \times \frac{k_p}{(1+sT_g)(1+sT_t)}}\;\frac{\Delta P_D}{s}$$

$$\Delta F_{static} = \lim_{s \to 0} s \cdot \Delta F(s) = 0.$$

Dynamic Analysis of uncontrolled case

Assume $k_g k_t = 1$ and $T_g = T_t = 0$. Then the block diagram reduced to



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

$$\Delta F(s) = \frac{-k_p}{(1+sT_p) + k_p\left(\frac{k_I}{s} + \frac{1}{R}\right)} \times \frac{\Delta P_D}{s}$$

$$= \frac{-k_p \cdot R\,\Delta P_D}{T_p \cdot R s^2 + s(R + k_p) + k_p k_I R}$$

$$\Delta F(s) = \frac{-k_p \, \Delta P_D . R}{T_p R \left[s^2 + s\left(\frac{R+k_p}{R T_p}\right) + \frac{k_p k_I}{T_p} \right]}$$

For calculating the poles

$$s^2 + s\left(\frac{R+k_p}{R T_p}\right) + \frac{k_p k_I}{T_p} = 0$$

$$s = \frac{-\frac{R+k_p}{R T_p} \pm \sqrt{\left(\frac{R+k_p}{R T_p}\right)^2 - 4\frac{k_p k_I}{T_p}}}{2}$$

The two roots are equal for a critical case

and Calculate k_I critical

$$\left(\frac{R+k_p}{T_p R}\right)^2 - 4\frac{k_p k_I}{T_p} = 0$$

$$\frac{4 k_p k_{I \, critical}}{T_p} = \left(\frac{R+k_p}{T_p R}\right)^2$$

$$k_{I \, critical} = \frac{(R+k_p)^2}{4 k_p T_p R^2}$$

$$= \frac{R^2 + 2 k_p R + k_p^2}{4 k_p T_p R^2}$$

$$K_{I\,critical} = \frac{1}{4 K_P T_P}\left[1 + \frac{K_P}{R}\right]^2$$

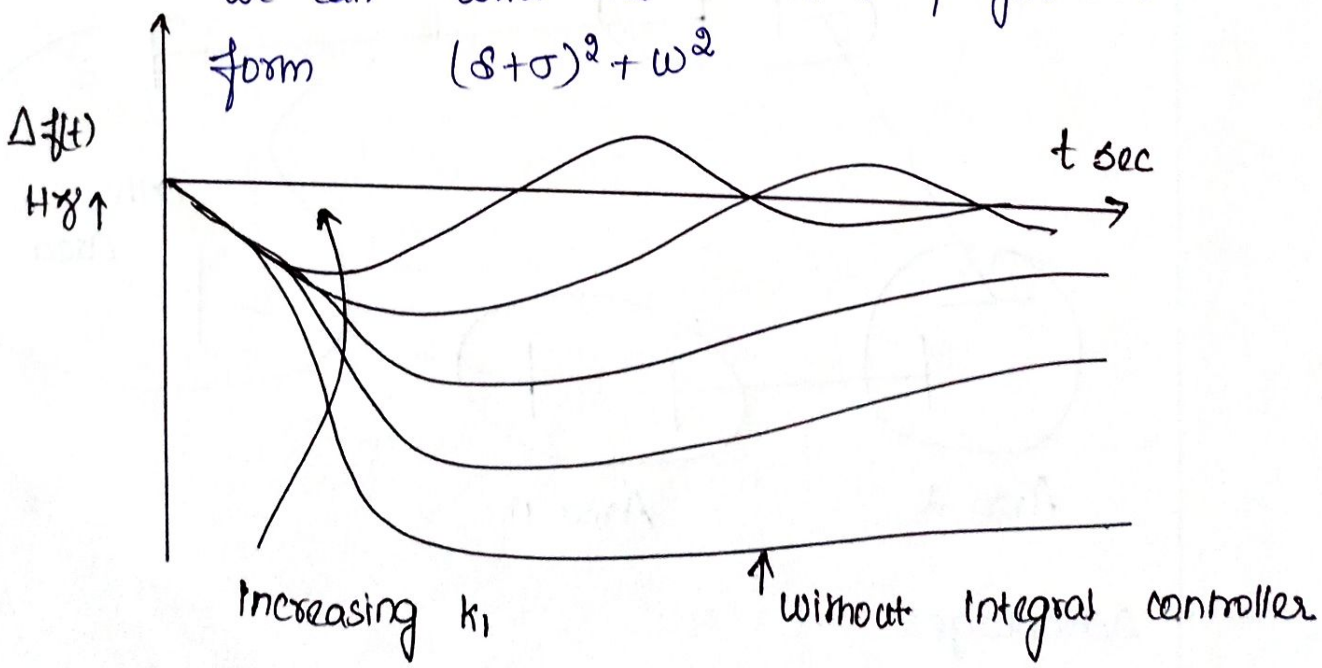
Sub $K_P = \frac{1}{D}$ and $T_P = \frac{2H}{D f_0}$ then

$$K_{I\,critical} = \frac{f_0}{8H}\left(D + \frac{1}{R}\right)^2$$

Time response $\Delta f(t)$ is obtained after taking Inverse laplace Transform

$$s^2 + s\left(\frac{R + K_P}{R T_P}\right) + \frac{K_P K_I}{T_P}$$

We can write the dominal polynomial in the form $(s+\sigma)^2 + \omega^2$



Two Area Load Frequency Control Modelling

For better Load frequency Control, the large power system Can be divided into number of load frequency Control areas.

This load frequency Control areas are interconnected by means of tie lines. This tie line transport Power in or out of a area as per the inter area power Contracts.

Location of tie line in LFC Model

The incremental Power Balance Equation is

$$\Delta P_{G1} - \Delta P_{D1} = \frac{2H_1}{f^0} \frac{d}{dt} \Delta f_1 + B_1 \Delta f_1 + \Delta P_{tie,1}$$

$$\Delta P_{G1} - \Delta P_{D1} - \Delta P_{tie,1} = \frac{2H_1}{f^0} \frac{d}{dt} \Delta f_1 + B_1 \Delta f_1$$

All quanties other than frequency are in P.U

Taking Laplace Transform

$$\Delta P_{G1}(s) - \Delta P_{D1}(s) - \Delta P_{tie,1}(s) = \frac{2H_1 s}{f^0} \Delta F_1(s) + B_1 \Delta F_1(s)$$

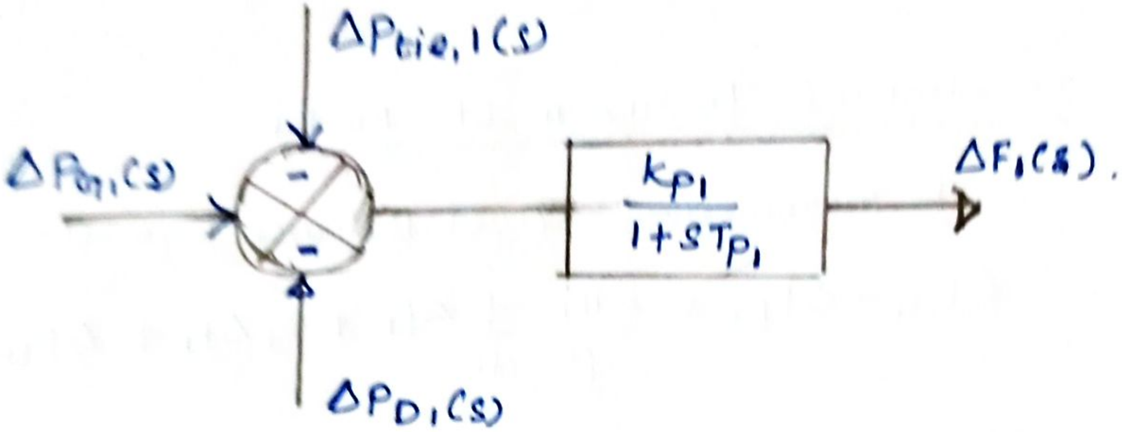
$$\Delta P_{G1}(s) - \Delta P_{D1}(s) - \Delta P_{tie,1}(s) = \Delta F_1(s) \left[\frac{2H_1 s}{f^0} + B_1 \right]$$

$$\Delta F_1(s) = \frac{\Delta P_{G1}(s) - \Delta P_{D1}(s) - \Delta P_{tie,1}(s)}{\frac{s 2H_1}{f^0} + B_1}$$

$$\Delta F_1(s) = \frac{\Delta P_{G1}(s) - \Delta P_{D1}(s) - \Delta P_{tie,1}(s)}{B_1\left(1 + s\frac{2H_1}{f^0 B_1}\right)}$$

$$\Delta F_1(s) = \frac{K_{P1}}{1+sT_{P1}}\left[\Delta P_{G1}(s) - \Delta P_{D1}(s) - \Delta P_{tie,1}(s)\right]$$

where $K_{P1} = \frac{1}{B_1}$, $T_{P1} = \frac{2H_1}{f^0 B_1}$



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$$\Delta F_2(s) = \frac{K_{P2}}{1+sT_{P2}}\left[\Delta P_{G2}(s) - \Delta P_{D2}(s) - \Delta P_{tie,2}(s)\right]$$

Modeling of tie line

Power transported out of area 1 is given by

$$P_{tie,1} = \frac{|V_1||V_2|}{X_{12}} \sin(\delta_1^0 - \delta_2^0)$$

For an Incremental Change in tie line Power

$$\Delta P_{tie,1} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1^0 - \delta_2^0)\left(\frac{\partial \delta_1^0}{\partial \delta_{12}} - \frac{\partial \delta_2^0}{\partial \delta_{12}}\right)$$

$$\Delta P_{tie,1} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1^\circ - \delta_2^\circ)(\Delta\delta_1 - \Delta\delta_2)$$

$$\Delta P_{tie,1}(p.u) = \frac{|V_1||V_2|}{X_{12} \cdot P_{r1}} \cos(\delta_1^\circ - \delta_2^\circ)(\Delta\delta_1 - \Delta\delta_2).$$

$$\Delta P_{tie,1}(p.u) = T_{12}(\Delta\delta_1 - \Delta\delta_2).$$

where

$$T_{12} = \frac{|V_1||V_2|}{X_{21} P_{r1}} \cos(\delta_1^\circ - \delta_2^\circ). \rightarrow (1)$$

$$\omega = 2\pi f, \quad f = \frac{\omega}{2\pi}$$

$$f = \frac{1}{2\pi} \frac{d\delta}{dt}$$

$$f = \frac{1}{2\pi} \Delta\delta.$$

$$\Delta f = \frac{1}{2\pi} \frac{\partial}{\partial t} \Delta\delta$$

$$\int \Delta f \, dt = \frac{1}{2\pi} \int \frac{\partial}{\partial t} \Delta\delta \, dt$$

$$\int \Delta f \, dt = \frac{1}{2\pi} \Delta\delta$$

$$\Delta\delta = 2\pi \int \Delta f \, dt$$

$$\therefore \quad \Delta\delta_1 = 2\pi \int \Delta f_1 \, dt$$

$$\Delta\delta_2 = 2\pi \int \Delta f_2 \, dt.$$

$$\Delta P_{tie,1}(p.u) = T_{12}\left[2\pi\int \Delta f_1\,dt - 2\pi\int \Delta f_2\,dt\right]$$

$$\Delta P_{tie,1}(p.u) = 2\pi T_{12}\left[\int \Delta f_1\,dt - \int \Delta f_2\,dt\right]$$

Taking Laplace transform

$$\Delta P_{tie,1}(s) = 2\pi T_{12}\left[\frac{\Delta F_1(s)}{s} - \frac{\Delta F_2(s)}{s}\right]$$

$$\boxed{\Delta P_{tie,1}(s) = \frac{2\pi T_{12}}{s}\left[\Delta F_1(s) - \Delta F_2(s)\right]} \rightarrow (2)$$

lly

$$\Delta P_{tie,2}(s) = \frac{2\pi T_{21}}{s}\left[\Delta F_2(s) - \Delta F_1(s)\right]$$

$$\Delta P_{tie,2}(s) = -\frac{2\pi T_{21}}{s}\left[\Delta F_1(s) - \Delta F_2(s)\right]$$

From Equation (1), we can write

$$T_{21} = \frac{|V_2||V_1|}{X_{21} P_{r2}} \cos(\delta_2^\circ - \delta_1^\circ)$$

$$T_{21} = \frac{|V_1||V_2|}{X_{12} P_{r2}} \cos(\delta_1^\circ - \delta_2^\circ) \times \frac{P_{r1}}{P_{r1}}$$

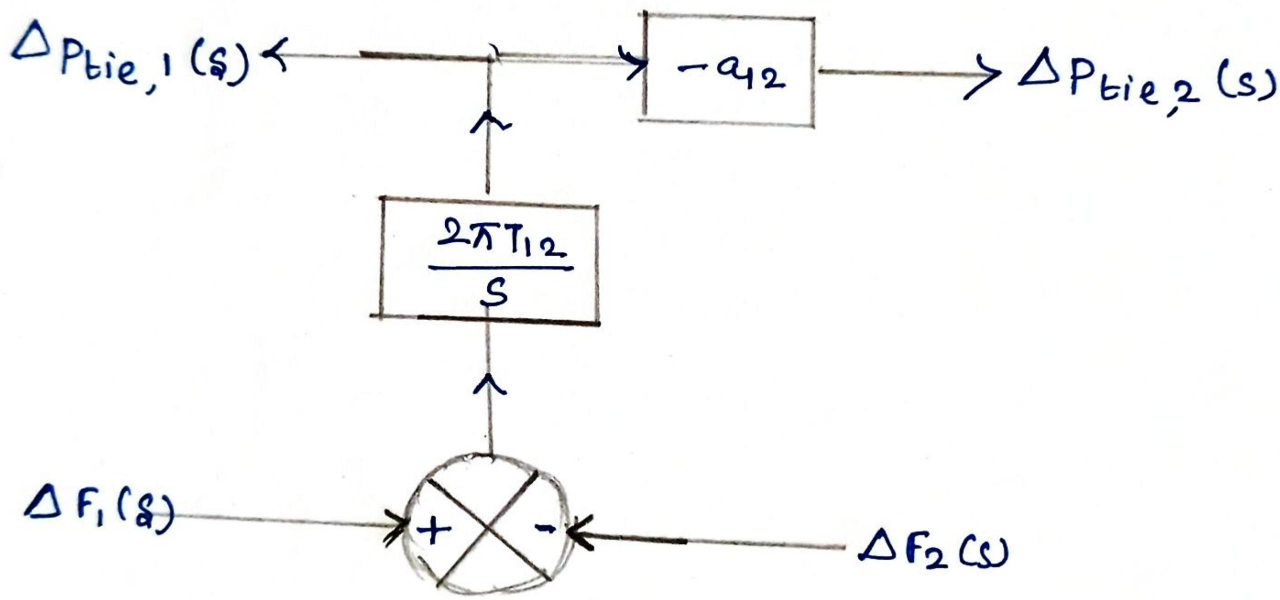
$$T_{21} = \frac{|V_1||V_2|}{X_{12} P_{r1}} \cos(\delta_1^\circ - \delta_2^\circ) \times \frac{P_{r1}}{P_{r2}}$$

$$T_{21} = \frac{|V_1||V_2|}{X_{12} P_{r1}} \cos(\delta_1^\circ - \delta_2^\circ) \times a_{12}$$

$$T_{21} = T_{12} a_{12}$$

$$\Delta P_{tie,2}(s) = -\frac{2\pi T_{12} a_{12}}{s} \left[\Delta F_1(s) - \Delta F_2(s)\right] \rightarrow (3)$$

Refering the equations (2) and (3), we can develop the Block diagram representation of tie line is



Static Analysis of Two area system for Uncontrolled case

Assume that $\Delta P_{C1} = \Delta P_{C2} = 0$

The frequency deviation is,

$$\Delta F_{1\,static} = \Delta F_{2\,static} = \Delta F_{static}$$

In steady state,

$$\Delta P_{G1\,static} = -\frac{1}{R_1}\Delta F_{static}$$

$$\Delta P_{G2\,static} = -\frac{1}{R_2}\Delta F_{static}$$

$$\left[\Delta P_{G1} - \Delta P_{D1} - \Delta P_{tie1}\right]\left[\frac{1/D_1}{1+\frac{2HS}{f_0 D_1}}\right] = \Delta F_{static}$$

$$= D\,\Delta F_{static} + \frac{2H}{f_0}\cdot\frac{d}{dt}\Delta F_{static}$$

Put $\frac{d}{dt}\Delta F_{static} = 0$ for area1 then,

$$\Delta P_{G1} - \Delta P_{D1} - \Delta P_{tie1} = D_1\Delta F_{static}$$

$$\Delta P_{tie1} = \Delta P_{G1} - \Delta P_{D1} - D\Delta F_{static} \quad \rightarrow (1)$$

similarly for area 2,

$$\Delta P_{G2} - \Delta P_{D1} = D_2\Delta F_{static} + \Delta P_{tie2}$$

$$= D_2\Delta F_{static} - a_{12}\left[\Delta P_{G1} - \Delta P_{D1} - D_1\Delta F_{static}\right] \quad \rightarrow (2)$$

$$\Delta F_{static}\left[-\frac{1}{R_2} - D_2 - \frac{a_{12}}{R_1} - a_{12} D_1\right] = a_{12}\,\Delta P_{D1} + \Delta P_{D2}$$

$$\Delta P_{tie1} = -\Delta F_{static}\left[D + \frac{1}{R_1}\right] - \Delta P_{D1}$$

Let $B_1 = D_1 + \frac{1}{R_1}$ and $B_2 = D_2 + \frac{1}{R_2}$

Then,

$$\Delta P_{tie1}, \frac{B_1\,\Delta P_{D2} - B_2\,\Delta P_{D1}}{B_2 + a_{12} B_1}$$

$$\Delta F_{static} = -\left[\frac{\Delta P_{D2} + a_{12}\,\Delta P_{D1}}{B_2 + a_{12} B_1}\right]$$

For identical areas,

$$B_1 = B_2 = B$$

$$R_1 = R_2 = R$$

$$D_1 = D_2 = D.$$

If step load changes occur only at area 1

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

$$\Delta F_{static} = -\frac{\Delta P_{D1}}{2B}$$

$$\Delta P_{tie1} = -\frac{\Delta P_{D1}}{2}$$

Dynamic Response of uncontrolled case of two area system

Assume that two areas are identical and time constants of generators and turbines are negligible as compared to power systems.

$$T_{p1} >> T_{g1} ; T_{t1} \quad T_{p2} >> T_{g2}, T_{t2}$$

$$\Delta P_{c1} = \Delta P_{c2} = 0.$$

$$\Delta f_1(s) = \frac{-k_{p1}}{1+sT_p}\left[\frac{\Delta f_1(s)}{R_1} + \Delta P_{D1}(s) + \Delta P_{tie,1}(s)\right]$$

$$\Delta f_2(s) = \frac{-k_{p2}}{1+sT_p}\left[\frac{\Delta f_2(s)}{R_2} + \Delta P_{D2}(s) + \Delta P_{tie2}(s)\right]$$

$$\Delta P_{tie1}(s) = \frac{2\pi T_{12}}{s}\left[\Delta f_1(s) - \Delta f_2(s)\right]$$

For identical areas,

$$\Delta P_{tie1} = -\Delta P_{tie2}$$

$$a_{12} = 1$$

$$R_1 = R_2 = R$$

$$D_1 = D_2 = D$$

$$k_{p1} = k_{p2} = k_1$$

$$\Delta f_1(s)\left[1 + \frac{k_p}{R(1+sT_p)}\right] = \frac{-k_p}{1+sT_p}\left[\Delta P_{D1}(s) + \Delta P_{tie1}(s)\right]$$

$$\Delta f_1(s) = \frac{-K_p R}{sRT_p + R + K_p}\left[\Delta P_{D1}(s) + \Delta P_{tie\,1}(s)\right]$$

$$\Delta f_2(s) = \frac{-K_p R}{sRT_p + R + K_p}\left[\Delta P_{D2}(s) - \Delta P_{tie\,1}(s)\right]$$

Sub $\Delta f_1(s)$ and $\Delta f_2(s)$

$$K_p = \frac{1}{D}$$

$$\Delta P_{tie\,1}(s) = \frac{-2\pi T_{12}\left[\Delta P_{D1}(s) - \Delta P_{D2}(s)\right]}{T_p D\left[s^2 + s\left(\frac{R + 1/D}{T_p R}\right) + \frac{4\pi T_{12}}{T_p D}\right]}$$

$$T_p = \frac{2H}{Df_0} \text{ sec}$$

$$s^2 + 2\alpha s + \omega^2 = (s+\alpha)^2 + \omega^2 - \alpha^2$$

$$\alpha = \frac{f_0}{4H}\left(D + \frac{1}{R}\right)$$

$$\omega^2 = \frac{2\pi T_{12} f_0}{H}$$

$$s_{12} = \frac{-2\alpha \pm \sqrt{(2\alpha)^2 - 4\omega^2}}{2}$$

$$= -\alpha \pm \sqrt{\alpha^2 - \omega^2}$$

case (i)

If $\alpha = \omega$ then the system will be critically damped and the roots are $s_{12} = -\omega$

case (ii)

If $\alpha > \omega$,

$$s_{12} = -\alpha \pm \sqrt{\alpha^2 - \omega^2}$$

case (iii)

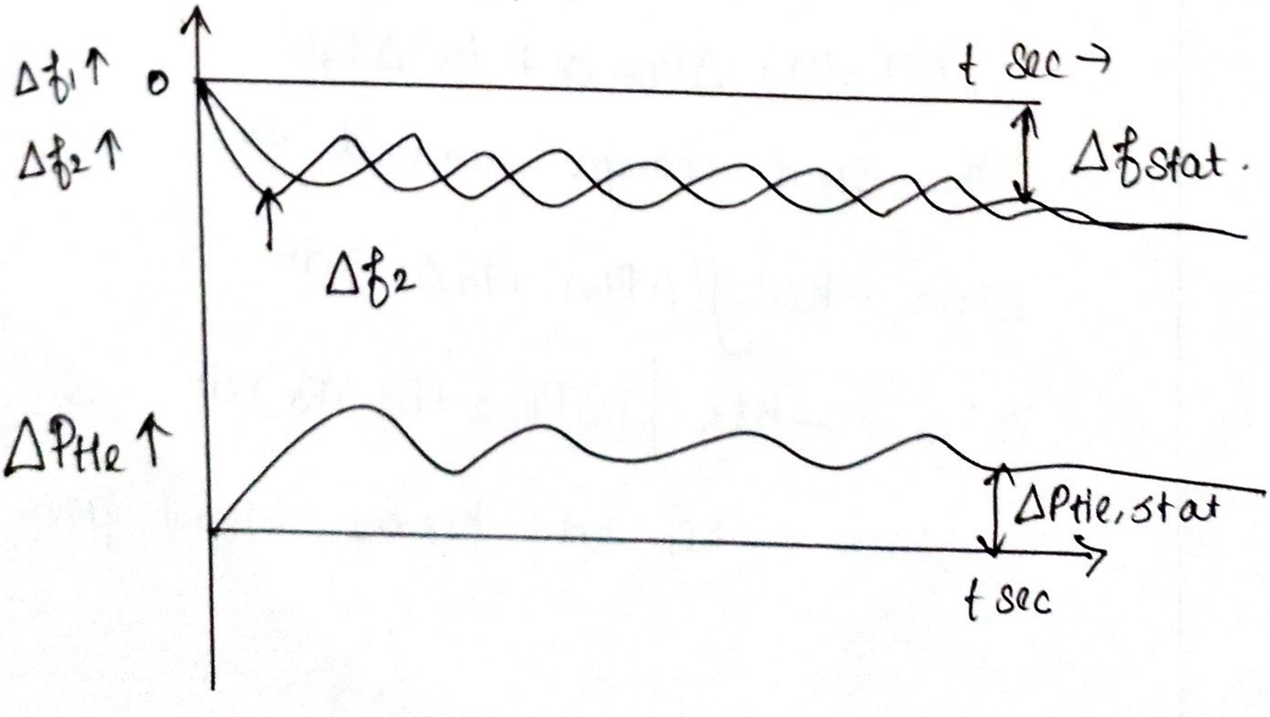
If $\alpha < \omega$, system will be overlapped.

$$s_{12} = -\alpha \pm j\sqrt{\omega^2 - \alpha^2}$$

$$\omega_d = \sqrt{\omega^2 - \alpha^2}$$

$$= \sqrt{\frac{2\pi f_0 T_{12}}{H} - \left[\frac{f_0}{4H}\left(D + \frac{1}{R}\right)^2\right]}$$

$$D = 0, \ \alpha = \frac{f_0}{4HR}$$



Tie line with frequency Bias control of two area System

In two area power system, each area must absorbs its own loads.

In two area power system, the area 1 is responsible for frequency reset and the area 2 is responsible for tie line power,

$$ACE_1 \simeq \Delta F_1$$

$$ACE_2 \simeq \Delta P_{tie\,2}$$

$$ACE_1 = \Delta P_{tie1} + b_1 \Delta F_1 \rightarrow (1)$$

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

where b_1 and b_2 are area frequency bias,

In laplace transform,

$$ACE_1(s) = \Delta P_{tie\,1}(s) + b_2 \Delta F_1(s)$$

$$ACE_2(s) = \Delta P_{tie1}(s) + b_2 \Delta F_2(s)$$

The speed changer commands are,

$$\Delta P_{c1} = -K_{I1} \int (\Delta P_{tie1} + b_1 \Delta F_1)\, dt$$

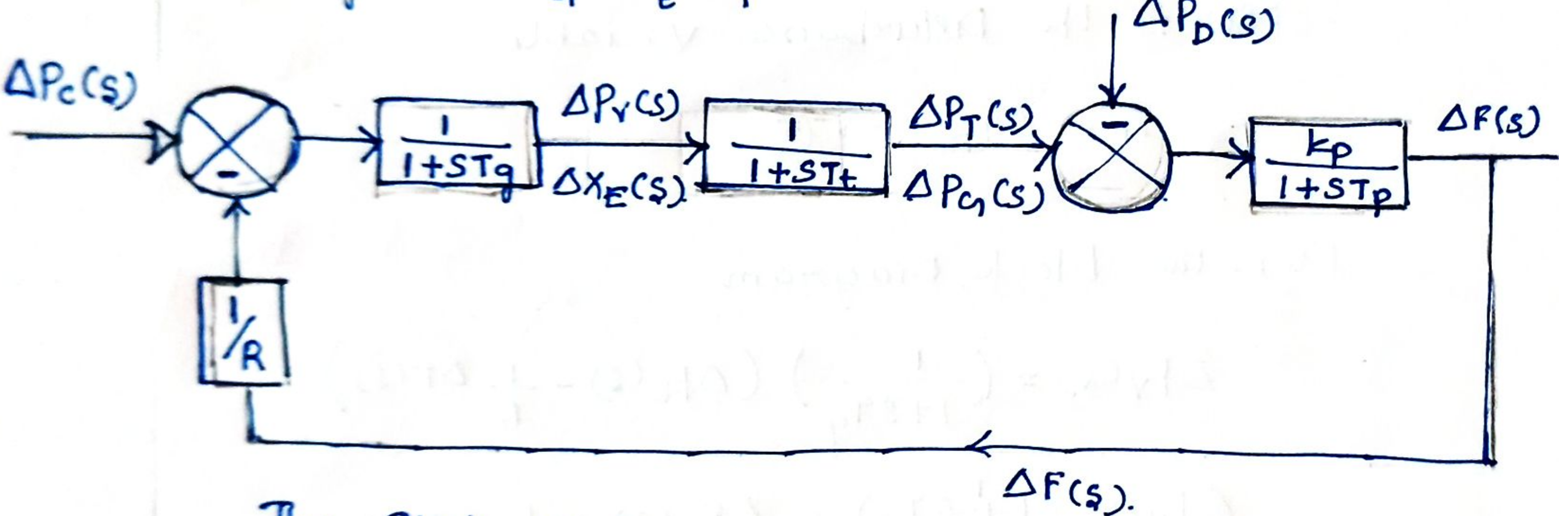
$$\Delta P_{c2} = -K_{I2} \int (\Delta P_{tie\,2} + b_2 \Delta F_2)\, dt$$

Where K_{I1} and K_{I2} are integral gains

State variable model of Load frequency Control

Optimum Linear Regulator (OLR) design results in a Controller that minimizes both transient variable oscillations and Control effects. OLR design is based upon the availablity of a dynamic System model is Called State Variable model.

Consider the LFC model of Single area, with assumption $k_g = k_t = 1$



The State Variable of a System is defined as

$$\dot{x}(t) = A\,x(t) + B\,u(t) + p(t) \rightarrow (1)$$

$x(t)$ is the State Variables of the LFC, they are ΔP_v, ΔP_T and Δf. Therefore the State Variables

$$\left.\begin{aligned} x_1 &= \Delta P_V \\ x_2 &= \Delta P_T \\ x_3 &= \Delta f \end{aligned}\right\} \quad (2)$$

$\dot{x}(t)$ is the derivate of the State Variables.

$$\left.\begin{aligned} \dot{x}_1 &= \frac{d(\Delta P_v)}{dt} \\ \dot{x}_2 &= \frac{d(\Delta P_T)}{dt} \\ \dot{x}_3 &= \frac{d(\Delta f)}{dt} \end{aligned}\right\} \quad (3)$$

u(t) is the Control Variable

$$u = \Delta P_c \rightarrow (4)$$

P(t) is the Disturbance variable

$$P = \Delta P_D \rightarrow (5)$$

From the Block Diagram

$$\Delta P_v(s) = \left(\frac{1}{1+sT_g}\right)\left(\Delta P_c(s) - \frac{1}{R}\Delta F(s)\right)$$

$$\Delta P_v(s)(1+sT_g) = \Delta P_c(s) - \frac{1}{R}\Delta F(s).$$

$$\Delta P_v(s) + sT_g\,\Delta P_v(s) = \Delta P_c(s) - \frac{1}{R}\Delta F(s)$$

$$sT_g\,\Delta P_v(s) = \Delta P_c(s) - \frac{1}{R}\Delta F(s) - \Delta P_v(s)$$

$$s\,\Delta P_v(s) = \frac{\Delta P_c(s)}{T_g} - \frac{1}{RT_g}\Delta F(s) - \frac{\Delta P_v(s)}{T_g}$$

Taking Inverse Laplace

$$\frac{d}{dt}(\Delta P_v) = \frac{\Delta P_c}{T_g} - \frac{\Delta f}{RT_g} - \frac{\Delta P_v}{T_g}$$

From Equations (2), (3), (4) and (5)

$$\dot{x}_1 = \frac{u}{T_g} - \frac{x_3}{RT_g} - \frac{x_1}{T_g} \rightarrow ⑥$$

$$\Delta P_T(s) = \left(\frac{1}{1+sT_t}\right)\Delta P_V(s)$$

$$\Delta P_T(s)[1+sT_t) = \Delta P_V(s)$$

$$\Delta P_T(s) + sT_t\,\Delta P_T(s) = \Delta P_V(s)$$

$$sT_t\,\Delta P_T(s) = \Delta P_V(s) - \Delta P_T(s)$$

$$\therefore\ s\Delta P_T(s) = \frac{\Delta P_V(s)}{T_t} - \frac{\Delta P_T(s)}{T_t}$$

Taking Inverse Laplace transform

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

From Equations ②, ③, ④ and ⑤

$$\dot{x}_2 = \frac{x_1}{T_t} - \frac{x_2}{T_t} \rightarrow ⑦$$

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

$$\Delta F(s)[1+sT_p] = k_p\Delta P_T(s) - k_p\Delta P_D(s)$$

$$\Delta F(s) + sT_p\,\Delta F(s) = k_p\Delta P_T(s) - k_p\Delta P_D(s)$$

$$sT_p\,\Delta F(s) = k_p\Delta P_T(s) - k_p\Delta P_D(s)$$

$$s\Delta F(s) = \frac{k_p}{T_p}\Delta P_T(s) - \frac{k_p}{T_p}\Delta P_D(s)$$

Taking Inverse Laplace transform

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

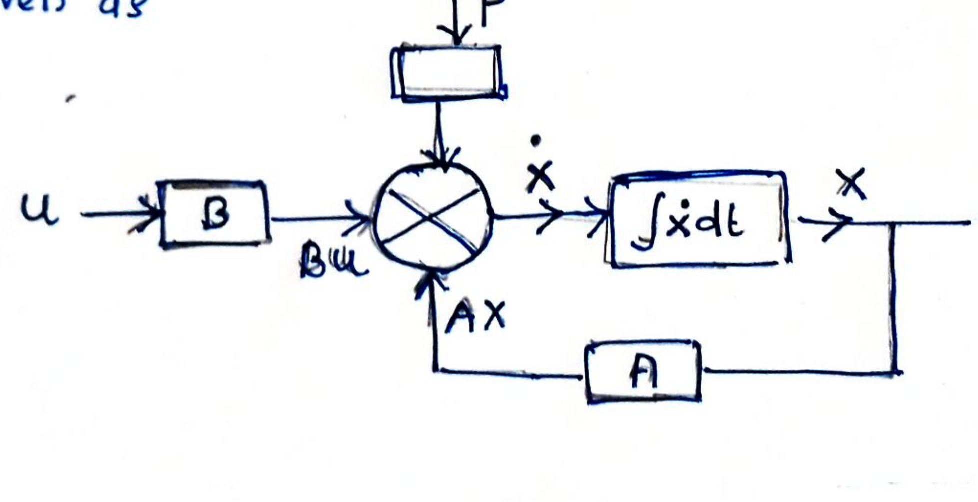
From Equations ②, ③, ④ and ⑤

$$\dot{x}_3 = \frac{k_p}{T_p}x_2 - \frac{k_p}{T_p}P \rightarrow ⑧$$

From Equations ⑥, ④ and ⑧, we can form the State Variable Equation of LFC model as

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix} = \begin{bmatrix}-1/T_g & 0 & -1/RT_g\\ 1/T_t & -1/T_t & 0\\ 0 & k_p/T_p & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}1/T_g\\ 0\\ 0\end{bmatrix}u + \begin{bmatrix}0\\ 0\\ -\frac{k_p}{T_p}\end{bmatrix}P$$

The block diagram of State variable model is given as



STATE VARIABLE MODEL OF TWO AREA SYSTEM:

Consider the block diagram of two area system,

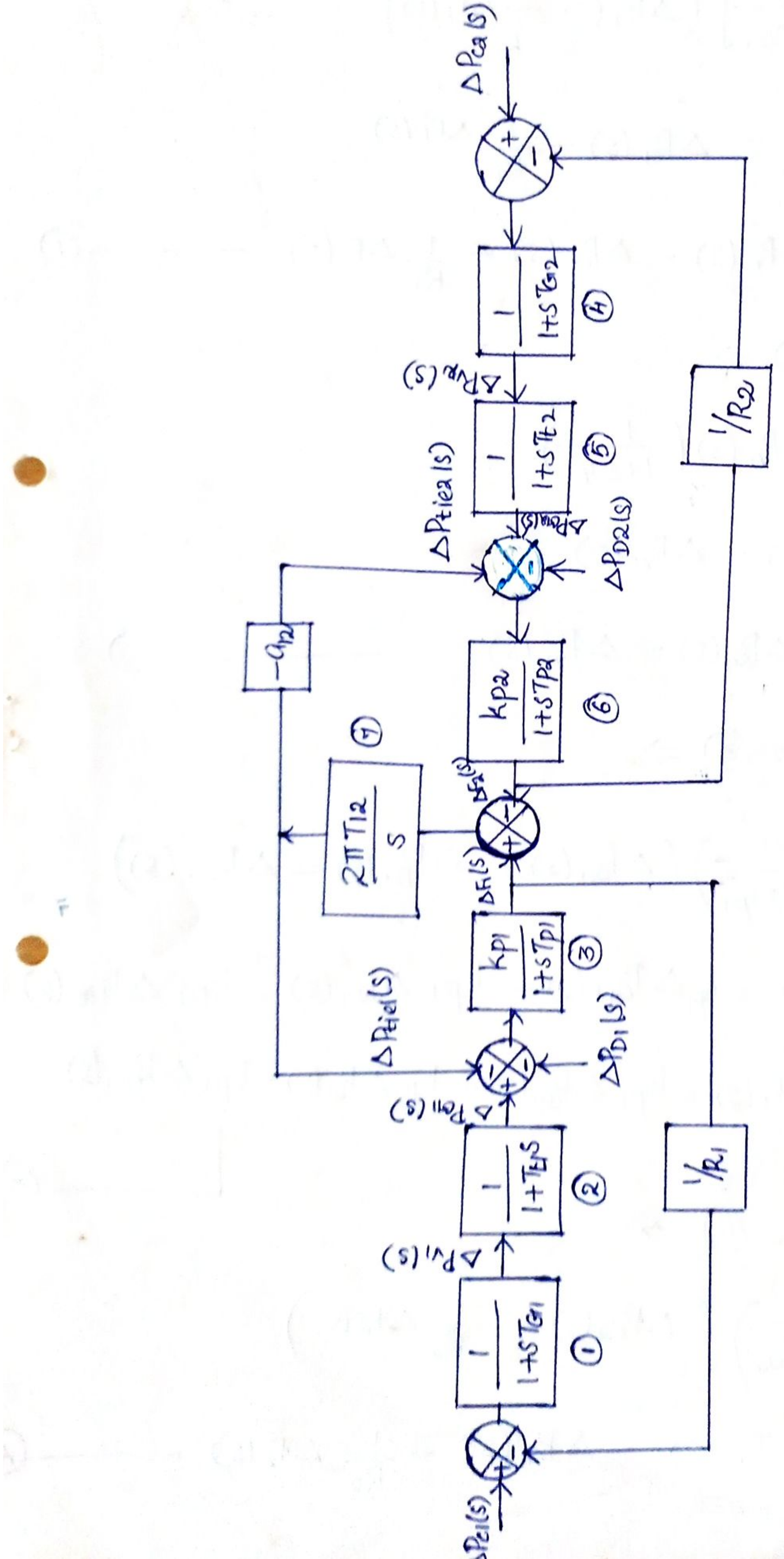


Fig: Block diagram of two area system.

From the block ① ⇒

$$\Delta P_{V1}(s) = \left[\frac{1}{1+sT_{G1}}\right]\left(\Delta P_{C1}(s) - \frac{1}{R_1}\Delta f_1(s)\right)$$

$$(1+sT_{G1})\,\Delta P_{V1}(s) = \Delta P_{C1}(s) - \frac{1}{R_1}\Delta f_1(s)$$

$$\Delta P_{V1}(s) + sT_{G1}\,\Delta P_{V1}(s) = \Delta P_{C1}(s) - \frac{1}{R_1}\Delta f_1(s) \quad \text{——— ①}$$

From the block ② ⇒

$$\Delta P_{G1}(s) = \Delta P_{V1}(s)\left(\frac{1}{1+sT_{t1}}\right)$$

$$(1+sT_{t1})\,\Delta P_{G1}(s) = \Delta P_{V1}(s)$$

$$\Delta P_{G1}(s) + sT_{t1}\,\Delta P_{G1}(s) = \Delta P_{V1}(s) \quad \text{——— ②}$$

From the block ③ ⇒

$$\Delta f_1(s) = \left(\frac{k_{p1}}{1+sT_{p1}}\right)\left(\Delta P_{G1}(s) - \Delta P_{D1}(s) - \Delta P_{tie1}(s)\right)$$

$$\Delta f_1(s)\,(1+sT_{p1}) = k_{p1}\Delta P_{G1}(s) - k_{p1}\Delta P_{D1}(s) - k_{p1}\Delta P_{tie1}(s)$$

$$\Delta f_1(s) + sT_{p1}\,\Delta f_1(s) = k_{p1}\Delta P_{G1}(s) - k_{p1}\Delta P_{D1}(s) - k_{p1}\Delta P_{tie1}(s) \quad \text{——— ③}$$

From the block ④ ⇒

$$\Delta P_{V2}(s) = \left(\frac{1}{1+sT_{G2}}\right)\left(\Delta P_{C2}(s) - \frac{1}{R_2}\Delta f_2(s)\right)$$

$$\Delta P_{V2}(s) + sT_{G2}\,\Delta P_{V2}(s) = \Delta P_{C2}(s) - \frac{1}{R_2}\Delta f_2(s) \quad \text{——— ④}$$

From the block ⑤ ⇒

$$\Delta P_{G2}(s) = \left(\frac{1}{1+sT_{t2}}\right) \Delta P_{V2}(s)$$

$$\Delta P_{G2}(s) + s\,T_{t2}\,\Delta P_{G2}(s) = \Delta P_{V2}(s) \qquad \text{—— ⑤}$$

From the block ⑥ ⇒

$$\Delta F_2(s) = \left(\frac{k_{p2}}{1+sT_{p2}}\right)\left(\Delta P_{G2}(s) - \Delta P_{D2}(s) - \Delta P_{tie2}(s)\right)$$

$$\Delta P_{tie2}(s) = -a_{12}\,\Delta P_{tie1}(s).$$

$$\Delta F_2(s) = \left(\frac{k_{p2}}{1+sT_{p2}}\right)\left(\Delta P_{G2}(s) - \Delta P_{D2}(s) + a_{12}\,\Delta P_{tie1}(s)\right)$$

$$\Delta F_2(s) + sT_{p2}\,\Delta F_2(s) = k_{p2}\,\Delta P_{G2}(s) - k_{p2}\,\Delta P_{D2}(s) + k_{p2}a_{12}\,\Delta P_{tie1}(s) \qquad \text{—— ⑥}$$

From the block ⑦ ⇒

$$\Delta P_{tie1}(s) = \left(\frac{2\pi T_{12}}{s}\right)\left[\Delta F_1(s) - \Delta F_2(s)\right]$$

$$s\,\Delta P_{tie1}(s) = 2\pi T_{12}\,\Delta F_1(s) - 2\pi T_{12}\,\Delta F_2(s) \qquad \text{—— ⑦}$$

Taking inverse laplace transform of ①, ②, ③, ④, ⑤, ⑥ and ⑦,

$$① \Rightarrow T_{G1}\frac{d\,\Delta P_{V1}}{dt} = \Delta P_{C1} - \frac{1}{R_1}\Delta f_1 - \Delta P_{V1}$$

$$\frac{d}{dt}\Delta P_{V1} = \frac{1}{T_{G1}}\Delta P_{C1} - \frac{1}{R_1 T_{G1}}\Delta f_1 - \frac{1}{T_{G1}}\Delta P_{V1} \qquad \text{—— ⑧}$$

Thus second order area is designed

(2) $\Rightarrow T_{t1} \dfrac{d}{dt} \Delta P_{G11} = \Delta P_{V1} - \Delta P_{G11}$

$$\frac{d}{dt}\Delta P_{G11} = \frac{1}{T_{t1}}\Delta P_{V1} - \frac{1}{T_{t1}}\Delta P_{G1} \quad \text{——— (9)}$$

(3) $\Rightarrow T_{P1} \dfrac{d}{dt}\Delta f_1 = k_{P1}\Delta P_{G1} - k_{P1}\Delta P_{D1} - k_{P1}\Delta P_{tie1} - \Delta f_1$

$$\frac{d}{dt}\Delta f_1 = \frac{k_{P1}}{T_{P1}}\Delta P_{G1} - \frac{k_{P1}}{T_{P1}}\Delta P_{D1} - \frac{k_{P1}}{T_{P1}}\Delta P_{tie1} - \frac{1}{T_{P1}}\Delta f_1 \quad \text{——— (10)}$$

(4) $\Rightarrow T_{G2} \dfrac{d}{dt}\Delta P_{V2} = \Delta P_{C2} - \dfrac{1}{R_2}\Delta f_2 - \Delta P_{V2}$

$$\frac{d}{dt}\Delta P_{V2} = \frac{1}{T_{G2}}\Delta P_{C2} - \frac{1}{R_2 T_{G2}}\Delta f_2 - \frac{1}{T_{G2}}\Delta P_{V2} \quad \text{——— (11)}$$

(5) $\Rightarrow T_{t2} \dfrac{d}{dt}\Delta P_{G2} = \Delta P_{V2} - \Delta P_{G2}$

$$\frac{d}{dt}\Delta P_{G2} = \frac{1}{T_{t2}}\Delta P_{V2} - \frac{1}{T_{t2}}\Delta P_{G2} \quad \text{——— (12)}$$

(6) $\Rightarrow T_{P2} \dfrac{d}{dt}\Delta f_2 = k_{P2}\Delta P_{G2} - k_{P2}\Delta P_{D2} + k_{P2} a_{12}\Delta P_{tie1} - \Delta f_2$

$$\frac{d}{dt}\Delta f_2 = \frac{k_{P2}}{T_{P2}}\Delta P_{G2} - \frac{k_{P2}}{T_{P2}}\Delta P_{D2} + \frac{k_{P2} a_{12}}{T_{P2}}\Delta P_{tie1} - \frac{1}{T_{P2}}\Delta f_2 \quad \text{——— (13)}$$

(7) $\Rightarrow$

$$\frac{d}{dt}\Delta P_{tie1} = 2\pi T_{12}\Delta f_1 - 2\pi T_{12}\Delta f_2 \quad \text{——— (14)}$$

The state equation is,

$$\dot{x}(t) = A x(t) + B u(t) + W p(t).$$

$\dot{x}(t) = \dfrac{d}{dt}x(t)$, $x(t)$ = state variable

$u(t)$ = control variable

$p(t)$ = disturbance inputs.

Assume the state variables,

$x_1 = \Delta P_{V1}$; $x_2 = \Delta P_{G1}$; $x_3 = \Delta f_1$; $x_4 = \Delta P_{V2}$

$x_5 = \Delta P_{G2}$; $x_6 = \Delta f_2$; $x_7 = \Delta P_{tie1}$

Control inputs, $u_1 = \Delta P_{C1}$

$u_2 = \Delta P_{C2}$

Disturbance inputs, $P_1 = \Delta P_{D1}$

$P_2 = \Delta P_{D2}$

$\dot{x}_1 = \frac{d}{dt}\Delta P_{V1}$; $\dot{x}_2 = \frac{d}{dt}\Delta P_{G12}$; $\dot{x}_3 = \frac{d}{dt}\Delta f_1$; $\dot{x}_4 = \frac{d}{dt}\Delta P_{V2}$

$\dot{x}_5 = \frac{d}{dt}\Delta P_{G2}$; $\dot{x}_6 = \frac{d}{dt}\Delta f_2$; $\dot{x}_7 = \frac{d}{dt}\Delta P_{tie1}$

(8) $\Rightarrow$ $$\dot{x}_1 = \frac{1}{T_{G1}}u_1 - \frac{1}{R_1 T_{G1}}x_3 - \frac{1}{T_{G1}}x_1 \quad \text{——— (15)}$$

(9) $\Rightarrow$ $$\dot{x}_2 = \frac{1}{T_{t1}}x_1 - \frac{1}{T_{t1}}x_2 \quad \text{——— (16)}$$

(10) $\Rightarrow$ $$\dot{x}_3 = \frac{k_{p1}}{T_{p1}}x_2 - \frac{k_{p1}}{T_{p1}}P_1 - \frac{k_{p1}}{T_{p1}}x_7 - \frac{1}{T_{p1}}x_3 \quad \text{——— (17)}$$

(11) $\Rightarrow$ $$\dot{x}_4 = \frac{1}{T_{G2}}u_2 - \frac{1}{R_2 T_{G2}}x_6 - \frac{1}{T_{G2}}x_4 \quad \text{——— (18)}$$

(12) $\Rightarrow$ $$\dot{x}_5 = \frac{1}{T_{t2}}x_4 - \frac{1}{T_{t2}}x_5 \quad \text{——— (19)}$$

(13) $\Rightarrow$ $$\dot{x}_6 = \frac{k_{p2}}{T_{p2}}x_5 - \frac{k_{p2}}{T_{p2}}P_2 + \frac{k_{p2}a_{12}}{T_{p2}}x_7 - \frac{1}{T_{p2}}x_6 \quad \text{——— (20)}$$

(14) $\Rightarrow$ $$\dot{x}_7 = 2\pi T_{12}x_3 - 2\pi T_{12}x_6 \quad \text{——— (21)}$$

$$
\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \\ \dot{x}_7 \end{bmatrix}
=
\begin{bmatrix}
-\frac{1}{T_{G1}} & 0 & -\frac{1}{R_1 T_{G1}} & 0 & 0 & 0 & 0 \\
\frac{1}{T_{t1}} & -\frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{k_{p1}}{T_{p1}} & -\frac{1}{T_{p1}} & 0 & 0 & 0 & -\frac{k_{p1}}{T_{p1}} \\
0 & 0 & 0 & -\frac{1}{T_{G2}} & 0 & -\frac{1}{R_2 T_{G2}} & 0 \\
0 & 0 & 0 & \frac{1}{T_{t2}} & -\frac{1}{T_{t2}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{k_{p2}}{T_{p2}} & -\frac{1}{T_{p2}} & \frac{k_{p2} a_{12}}{T_{p2}} \\
0 & 0 & 2\pi T_{12} & 0 & 0 & -2\pi T_{12} & 0
\end{bmatrix}
\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{bmatrix}
$$

$$
+
\begin{bmatrix}
\frac{1}{T_{G1}} & 0 \\
0 & 0 \\
0 & 0 \\
0 & \frac{1}{T_{G2}} \\
0 & 0 \\
0 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix} u_1 \\ u_2 \end{bmatrix}
+
\begin{bmatrix}
0 & 0 \\
0 & 0 \\
-\frac{k_{p1}}{T_{p1}} & 0 \\
0 & 0 \\
0 & 0 \\
0 & -\frac{k_{p2}}{T_{p2}} \\
0 & 0
\end{bmatrix}
\begin{bmatrix} P_1 \\ P_2 \end{bmatrix}
$$

EE8702 - POWER SYSTEM OPERATION AND CONTROL

UNIT III

REACTIVE POWER – VOLTAGE CONTROL

Generation and absorption of reactive power - basics of reactive power control – Automatic Voltage Regulator (AVR) – brushless AC excitation system – block diagram representation of AVR loop - static and dynamic analysis – stability compensation – voltage drop in transmission line - methods of reactive power injection - tap changing transformer, SVC (TCR + TSC) and STATCOM for oltage control.

Prepared by

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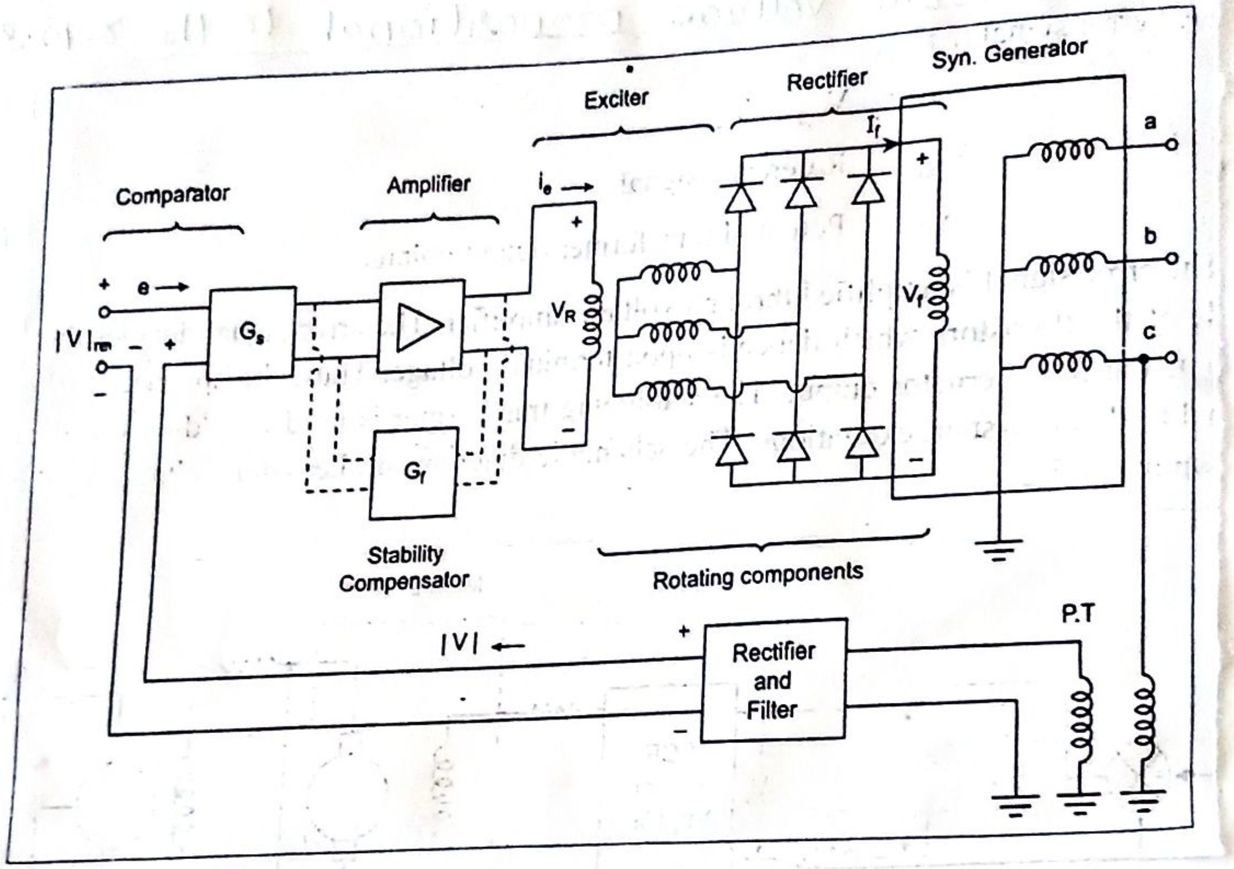
Modelling of Automatic Voltage Regulator



Schematic diagram of Brushless Automatic Voltage Regulator

Let us we assume that generator terminal voltage $|V|$ has been decreased. This results in an increased error voltage (e) which in turn, causes increased values of V_R, i_e, V_f and i_f. The increased i_f increases the generator flux, resulting ~~the~~ to raise magnitude of the terminal voltage to the required level.

Using the potential transformer, the terminal voltage of the generator is stepped down to the value required for control signal and then rectified to get D.C Voltage proportional to the r.m.s Value of terminal voltage.

From the Diagram, the modelling of AVR includes

i) Comparator
ii) Amplifier
iii) Exciter
iv) Generator

i) Comparator

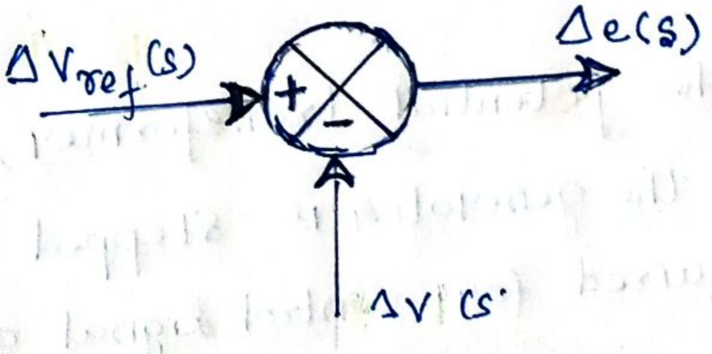
The Comparator Compares the measured signal $|V|$ against the reference DC signal $|V_{ref}|$. The difference between these two signals produce an error voltage 'V_e' called error signal

The error signal $\Delta e = \Delta|V_{ref}| - \Delta|V|$

Taking Laplace Transform

$$\Delta e(s) = \Delta V_{ref}(s) - \Delta V(s).$$

The model of Camparator is



2, Amplifier

The amplifier amplifies the input error signal

$$\Delta V_R \propto \Delta e$$

$$\Delta V_R = K_A \Delta e$$

Where $K_A \rightarrow$ Amplifier Gain

$\Delta V_R \rightarrow$ Output voltage of a Amplifier

Taking Laplace transform

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

Amplifier transfer function

$$\frac{\Delta V_R(s)}{\Delta e(s)} = K_A$$

In reality, the amplifier will have a time delay that can be represented by a time constant 'T_A'

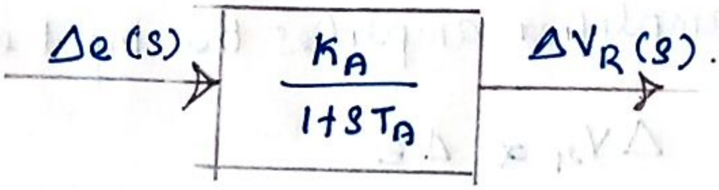
Therefore the modified Amplifer transfer function

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

$$\Delta V_R(s) = \frac{K_A}{1+sT_A} \Delta e(s).$$

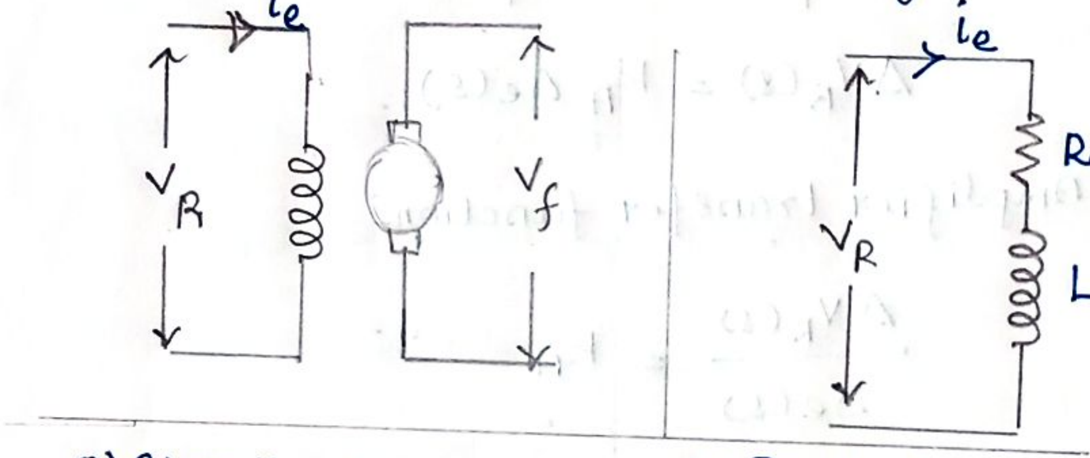
Typical value of K_A are in the range of 10 to 400 and for T_A is 0.02 to 0.1 seconds.

The model of Amplifier is



iii) Exciter

The purpose of the exciter is to supply field current to the rotor field of the synchronous gnr.



a) Circuit of an Exciter   b) Equivalent circuit for field winding of an Exciter

Let R_e be the exciter field Resistance

L_e be the exciter field Inductance.

From the equivalent circuit

$$\Delta V_R = R_e \Delta i_e + L_e \frac{d}{dt}(\Delta i_e) \rightarrow (1)$$

and

$$\Delta V_f \propto \Delta i_e$$

$$\Delta V_f = K_1 \Delta i_e \rightarrow (2)$$

Taking Laplace transform

① ⇒

$$\Delta V_R(s) = R_e \Delta i_e(s) + L_e s \Delta i_e(s)$$

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

② ⇒

$$\Delta V_F(s) = k_1 \Delta i_e(s)$$

The exciter transfer function is

$$\frac{V_F(s)}{V_R(s)} = \frac{k_1 \Delta i_e(s)}{\Delta i_e(s) [R_e + L_e s]}$$

$$\frac{V_F(s)}{V_R(s)} = \frac{k_1}{R_e + L_e s}$$

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

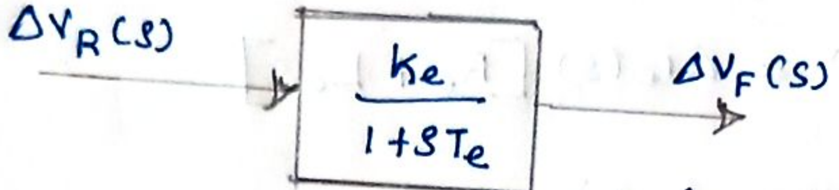
$$\frac{V_F(s)}{V_R(s)} = \frac{k_1 / R_e}{1 + \frac{L_e}{R_e} s}$$

where $k_e = k_1 / R_e$ and $T_e = L_e / R_e$

$$\therefore \quad \frac{V_F(s)}{V_R(s)} = \frac{k_e}{1 + s T_e}.$$

$$V_F(s) = \frac{k_e}{1 + s T_e} V_R(s)$$

The model of



iv) Synchronous Generator

Synchronous generator generators 3ϕ AC power at its terminals. The terminal voltage of the gnr is maintained constant during its varying load, with the help of Excitation systems.

The terminal voltage (V) of the generator equals to difference b/w induced emf (E) and drop across the armature (V_{drop})

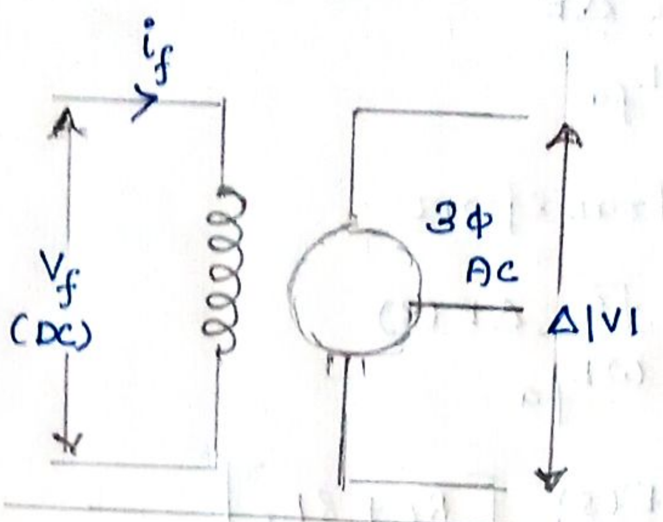
$$\Delta V = \Delta E - V_{drop}$$

At no load, the drop can be neglected the

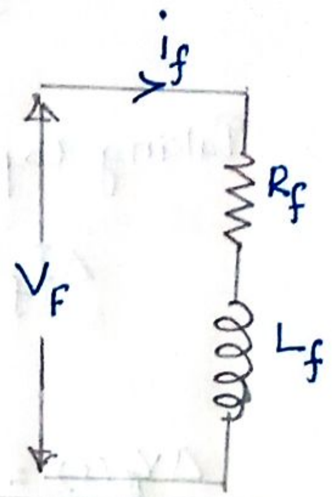
$$\Delta V = \Delta E$$

Taking Laplace transform

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



a) Circuit diagram of a Synchronous generator



b) Equivalent circuit for field winding of a Synchronous generator

From the equivalent circuit

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

Taking Laplace Transform

$$\Delta V_F(s) = R_f \Delta I_f(s) + sL_f \Delta I_f(s)$$

$$\Delta V_F(s) = \Delta i_f(s)\,[R_f + sL_f]$$

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

L_{fa} → mutual Inductance between rotor field and Stator Armature

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

$$I_f = \frac{\sqrt{2}\,E_{f\,Rms}}{\omega L_{fa}} = \frac{\sqrt{2}\,E}{\omega L_{fa}}$$

$$\therefore \quad \Delta I_f = \frac{\sqrt{2}\,\Delta E}{\omega L_{fa}}$$

Taking Laplace Transform

$$\Delta I_f(s) = \frac{\sqrt{2}}{\omega L_{fa}} \Delta E(s)$$

$$\Delta V_F(s) = \frac{\sqrt{2}\,\Delta E(s)}{\omega L_{fa}} \left[R_f + sL_f\right]$$

Transfer function of generator is

$$\frac{\Delta V(s)}{\Delta V_F(s)} = \frac{\Delta E(s)}{\frac{\sqrt{2}\,\Delta E(s)}{\omega L_{fa}} \left[R_f + sL_f\right]}$$

$$\frac{\Delta V(s)}{\Delta V_F(s)} = \frac{\Delta E(s)}{\frac{\sqrt{2}}{\omega L_{fa}} \Delta E(s)\, R_f \left[1 + s\frac{L_f}{R_f}\right]}$$

$$\frac{\Delta V(s)}{\Delta V_F(s)} = \frac{1}{\frac{\sqrt{2} R_f}{\omega L_{fa}} \left[1 + s\frac{L_f}{R_f}\right]}$$

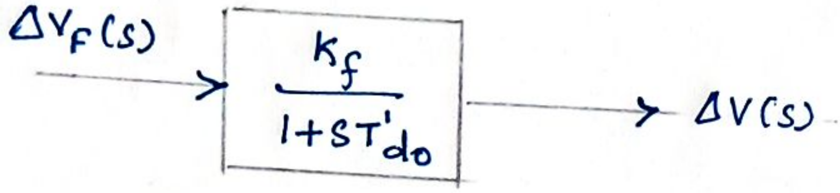
$$\frac{\Delta V(s)}{\Delta V_F(s)} = \frac{K_f}{1 + sT'_{do}}$$

where $K_f = \frac{1}{\sqrt{2} R_f / \omega L_{fa}} = \frac{\omega L_{fa}}{\sqrt{2} R_f}$

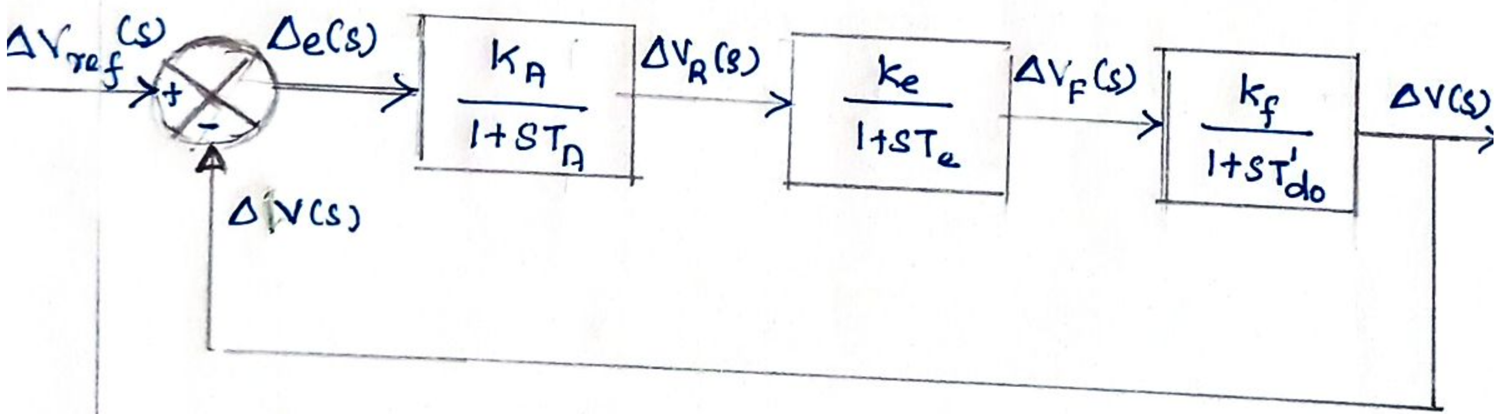
$T'_{do} = \frac{L_f}{R_f} \Rightarrow$ open circuit direct axis time constant

$$\Delta V(s) = \frac{K_f}{1+sT'_{do}} \cdot \Delta V_f(s).$$

The model of Synchronous generator is



combining all the individual Blocks, we get the Closed loop model of AVR



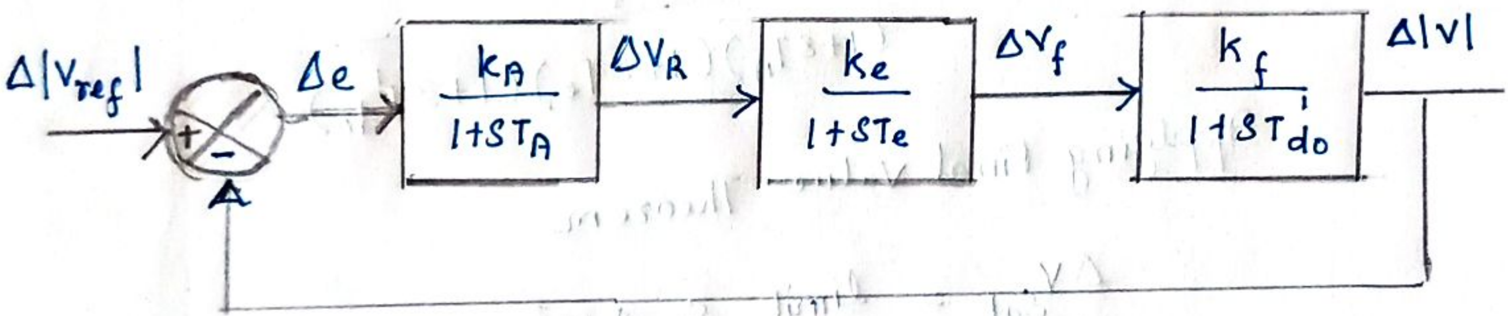
Static Analysis of AVR loop.

* The automatic voltage regulator must regulate the terminal voltage $|V|$ with in the required accuracy limit.

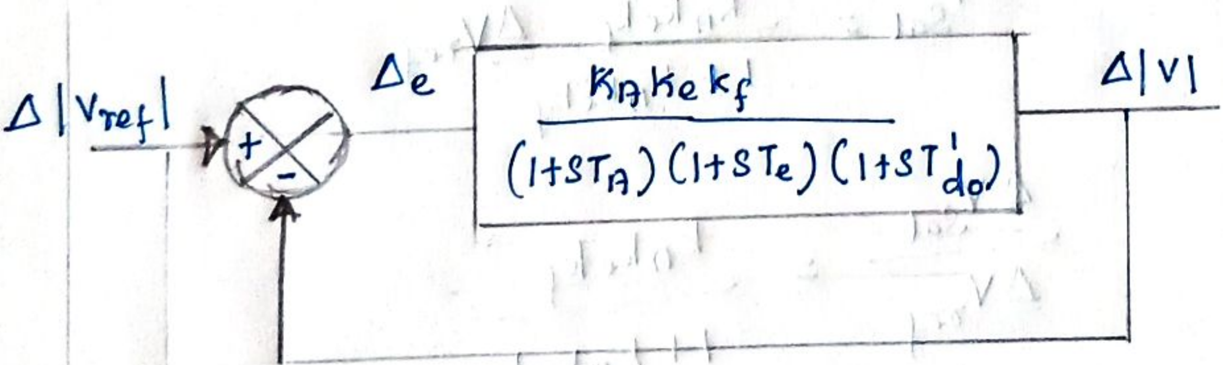
* It must have sufficient speed Response

* It must be stable

The block diagram of AVR Loop is



Initial error $\Delta e_0 = \Delta|V_{ref_0}| - \Delta|V_0|$



The Closed loop transfer function is

$$\frac{\Delta V(s)}{\Delta V_{ref}(s)} = \frac{\dfrac{k_A k_e k_f}{(1+sT_A)(1+sT_e)(1+sT'_{do})}}{1 + \dfrac{k_A k_e k_f}{(1+sT_A)(1+sT_e)(1+sT'_{do})}}$$

$$\Delta V(s) = \frac{\frac{k_A k_e k_f}{(1+sT_A)(1+sT_e)(1+sT'_{do})} \times \Delta V_{ref}(s)}{1 + \frac{k_A k_e k_f}{(1+sT_A)(1+sT_e)(1+sT'_{do})}}$$

$$\Delta V_{ref}(s) = \frac{\Delta V_{ref}}{s}.$$

$$\Delta V(s) = \frac{\frac{k_A k_e k_f}{(1+sT_A)(1+sT_e)(1+sT'_{do})} \times \frac{\Delta V_{ref}}{s}}{1 + \frac{k_A k_e k_f}{(1+sT_A)(1+sT_e)(1+sT'_{do})}}$$

Applying Final Value Theorem

$$\Delta V_{sat} = \lim_{s \to 0} s \cdot \Delta V(s)$$

$$\Delta V_{sat} = \frac{k_A k_e k_f \; \Delta V_{ref}}{1 + k_A k_e k_f}$$

$$\frac{\Delta V_{sat}}{\Delta V_{ref}} = \frac{k_A k_e k_f}{1 + k_A k_e k_f}$$

$$\frac{\Delta V_{sat}}{\Delta V_{ref}} = \frac{k}{1+k}, \text{ where } k = k_A k_e k_f.$$

To find k

Let us assume that Δe_o must be some percentage P of reference voltage ΔV_{refo}

$$\therefore \quad \Delta e_o < \frac{P}{100} \Delta V_{refo}$$

From the Block diagram

$$\Delta e_o = \Delta V_{refo} - \Delta V_o \quad \text{and}$$

$$\frac{\Delta V_o}{\Delta V_{refo}} = \frac{G(s)}{1+G(s)H(s)} = \frac{G(s)}{1+G(s)}$$

$$\Delta V_o = \frac{G(s)}{1+G(s)} \Delta V_{refo}$$

where $G(s) = \dfrac{k_A k_e k_f}{(1+sT_A)(1+sT_e)(1+sT'_{do})}$

$$\Delta e_o = \Delta V_{refo} - \frac{G(s)}{1+G(s)} \Delta V_{refo}$$

$$\Delta e_o = \Delta V_{refo} \left[1 - \frac{G(s)}{1+G(s)}\right]$$

$$\Delta e_o = \Delta V_{refo} \left[\frac{1+G(s)-G(s)}{1+G(s)}\right]$$

$$\Delta e_o = \Delta V_{refo} \left[\frac{1}{1+G(s)}\right]$$

For Static Analysis, $s = 0$

$$\Delta e_o = \Delta V_{ref_o}\left[\frac{1}{1+\lim_{s\to 0} G(s)}\right]$$

Position Error Constant K_p is given as $\lim_{s\to 0} G(s)$

$$\lim_{s\to 0} G(s) = k_A k_e k_f = K$$

$$\therefore \Delta e_o = \Delta V_{ref_o}\left[\frac{1}{1+K}\right]$$

$$\Delta V_{ref_o}\left[\frac{1}{1+K}\right] < \frac{P}{100}\Delta V_{ref_o}$$

$$\frac{1}{1+K} < \frac{P}{100}$$

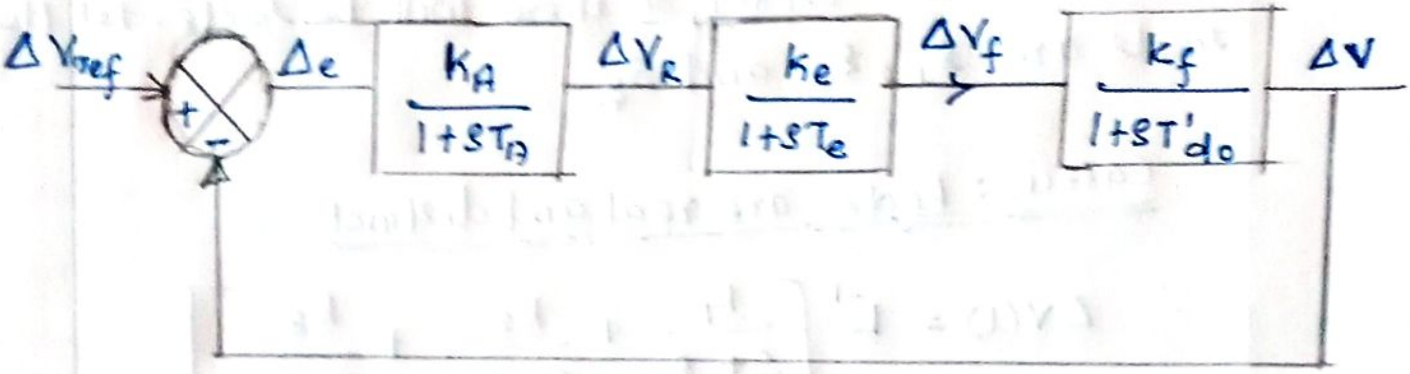
$$1+K > \frac{100}{P}$$

$$100 > \frac{100}{P} - 1$$

If Δe_o is less than 1%, then K must exceed 99%.

Dynamic Analysis of AVR Loop

The block diagram of AVR loop is



The closed loop transfer function is

$$\frac{\Delta V(s)}{\Delta V_{ref}(s)} = \frac{\dfrac{K_A K_e K_f}{(1+sT_A)(1+sT_e)(1+sT'_{do})}}{1 + \dfrac{K_A K_e K_f}{(1+sT_A)(1+sT_e)(1+sT'_{do})}}$$

$$\frac{\Delta V(s)}{\Delta V_{ref}(s)} = \frac{G(s)}{1 + G(s)H(s)}$$

where

$$G(s) = \frac{K_A K_e K_f}{(1+sT_A)(1+sT_e)(1+sT'_{do})}$$

$$H(s) = 1$$

$$\Delta V(s) = \frac{G(s)}{1+G(s)} \times \Delta V_{ref}(s)$$

Taking Inverse Laplace Transform

$$\Delta V(t) = L^{-1}(\Delta V(s))$$

The dynamic response depends upon the eigen Values (or) Closed loop poles, which are obtained from the Characteristic Equation $1 + G(s) = 0$

$G(s)$ is 3rd order, so there will be roots. Let the roots are s_1, s_2 and s_3.

Case(i): Roots are real and distinct

$$\Delta V(t) = L^{-1}\left[\frac{k_1}{s - s_1} + \frac{k_2}{s - s_2} + \frac{k_3}{s - s_3}\right]$$

The Dynamic Response is

$$\Delta V(t) = k_1 e^{-s_1 t} + k_2 e^{-s_2 t} + k_3 e^{-s_3 t}$$

Case ii): Two roots are complex Conjuate

The Dynamic Response is

$$\Delta V(t) = A e^{\sigma t} \sin(\omega t + \beta)$$

For AVR loop to be stable, the transient components vanishes with time.

The AVR loop is to be stable, when the poles are located in left hand of s plane.

When the poles are closer to the $j\omega$ axis, the response is more dominant it becomes.

Generation and Absorption of Reactive Power

Synchronous Generator

Synchronous generators can generate (or) absorb Reactive power. Reactive Power (Q) is supplied by synchronous generator depending upon the short circuit ratio (SCR)

$$SCR = \frac{1}{X_s}$$

where $X_s \rightarrow$ Synchronous Reactance.

An overexcited synchronous machine operating on noload condition generates reactive power.

An underexcited synchronous machine absorbs reactive power.

Shunt Capacitors

It offers cheapest mean of reactive power supply.

Shunt Reactors

It offers the cheapest mean of Reactive Power absorption and these are connected in the transmission line during light load condition.

Transformers

Transformer always absorb reactive power regardless of their loading.

At no load : Shunt magnetising reactance effect is predominant

At full load : Series leakage inductance effect is predominant

P.U reactance, $X_p = \frac{\text{Actual } X}{\text{Base value}} = \frac{\text{Actual } X}{V/I}$

Actual $X = X_T \cdot \frac{V}{I} = X_T \cdot \frac{kV}{I} \times 1000$

$I_{ph} = \frac{kVA}{\sqrt{3}\, kV}$

$X = X_T \times \frac{kV}{kVA} \times \sqrt{3}\, kV \times 1000$

$X = \sqrt{3}\, X_T \frac{(kV)^2}{kVA} \times 1000$

Reactive power loss or absorbed Q_T

$Q_T = 3\,|I|^2 \times \sqrt{3}\, X_T \frac{(kV)^2}{kVA} \times 1000$

$= 3 \left(\frac{kVA}{\sqrt{3}\, kV}\right)^2 \sqrt{3}\, X_T \left(\frac{kV}{kVA}\right)^2 \times 1000$

$Q_T = \frac{\sqrt{3}(kVA)^2}{3\, kV^2} \sqrt{3}\, X_T \frac{kV^2}{kVA^2} \times 1000$

$Q_T = \sqrt{3}\, kVA\, X_T\, 1000$ VAR

$Q_T = \sqrt{3}\, kVA\, X_T$ kVAR

Where

I - Current in amps flowing through the tfr

X - Transformer reactance / phase.

Cables

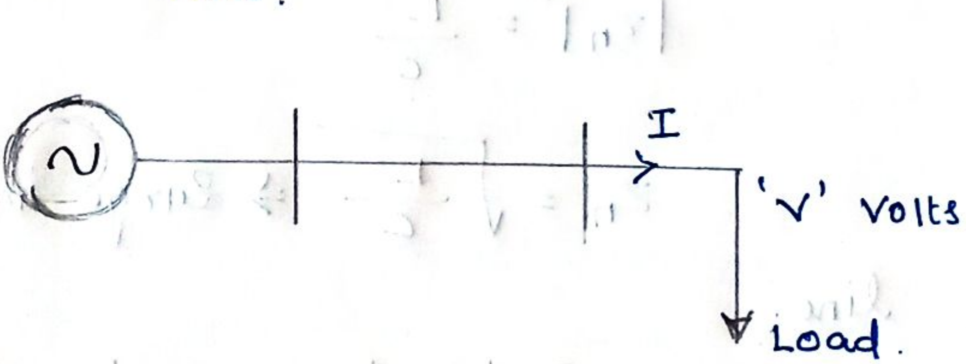
Cables generate more reactive power than transmission lines because the cables have high capacitance.

Overhead lines

Transmission lines are considered as generating KVAR in their shunt capacitance and consuming KVAR in their series Inductance.

The inductive KVAR varies with the line current whereas, the capacitive KVAR varies with the system potential.

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



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

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

Due to the capacitance of the line, the reactive Power generated by the line will be

$$\Delta Q_c = \frac{|V|^2}{X_c} = \frac{|V|^2}{1/\omega C} = |V|^2 \omega C$$

Case (i) : If $\Delta Q_L = \Delta Q_c$

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

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

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

$$Z_n = \frac{V}{I}$$

$$|Z_n|^2 = \frac{L}{C}$$

$Z_n = \sqrt{\frac{L}{C}}$ ⇒ Surge impedance of the line.

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

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

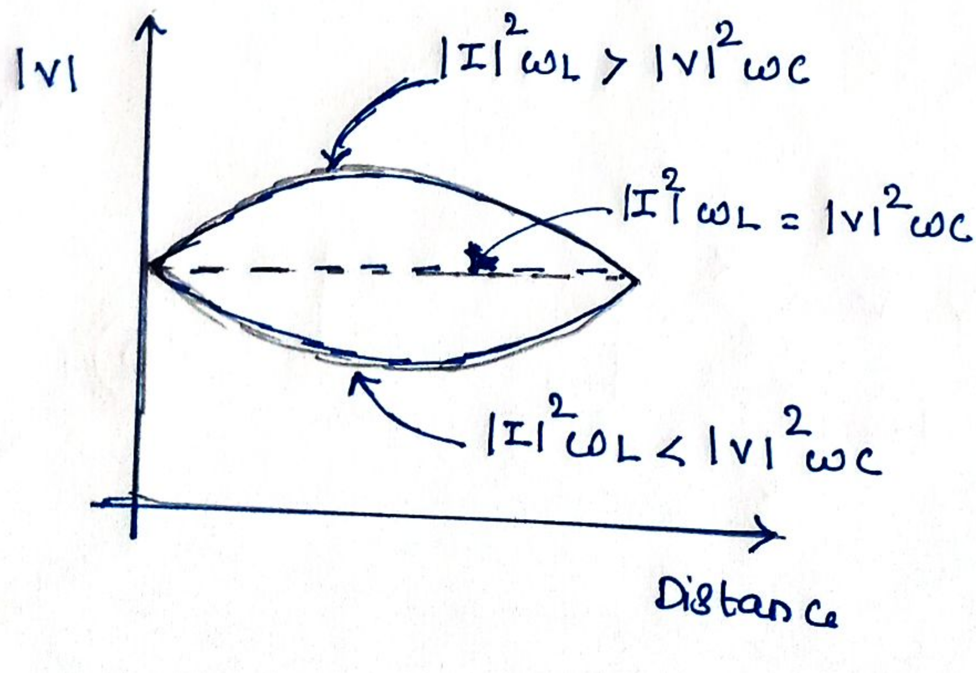
At $\delta = 90°$, $P_{max} = \frac{|E||V|}{X}$

By varying $X, \delta, |V|$, we can get the control power transfer.

Case ii : $\Delta Q_L > \Delta Q_C$

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

Here the line is loaded below Z_n (ie) light loaded condition. The net effect of the line will be absorbed reactive power.



Case iii : $\Delta Q_L < \Delta Q_C$

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

Here the line is loaded above Z_n ie) Heavy load condition. The net effect of the line will be generation of Reactive power.

Load

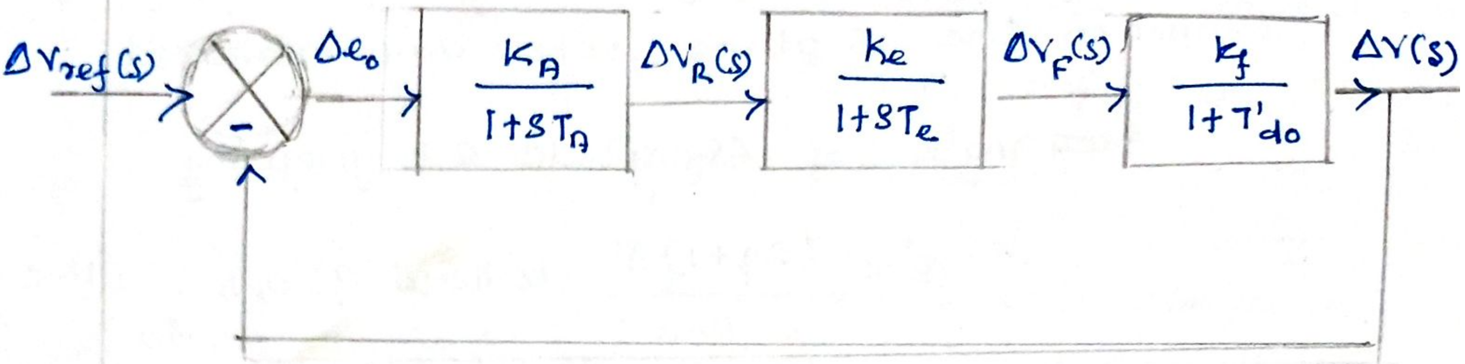
Loads absorbs Reactive power. Load change occurs depending on the day, session and weather conditions.

Both active and reactive power of the composite loads vary with the magnitudes of voltages.

Loads operating at low power factor gives voltage drop in the line and is uneconomical. So the Industrial consumers improve the power factor using shunt capacitors.

Stability Compensation

The block diagram of AVR loop is



The open loop transfer function of AVR Loop is given by

$$\frac{\Delta V(s)}{\Delta V_{ref}(s)} = \frac{K_A K_e K_f}{(1+sT_A)(1+sT_e)(1+sT'_{do})}$$

Number of zeros = 0

Number of poles = 3. They are $\frac{-1}{T_A}$, $\frac{-1}{T_e}$ and $\frac{-1}{T'_{do}}$

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

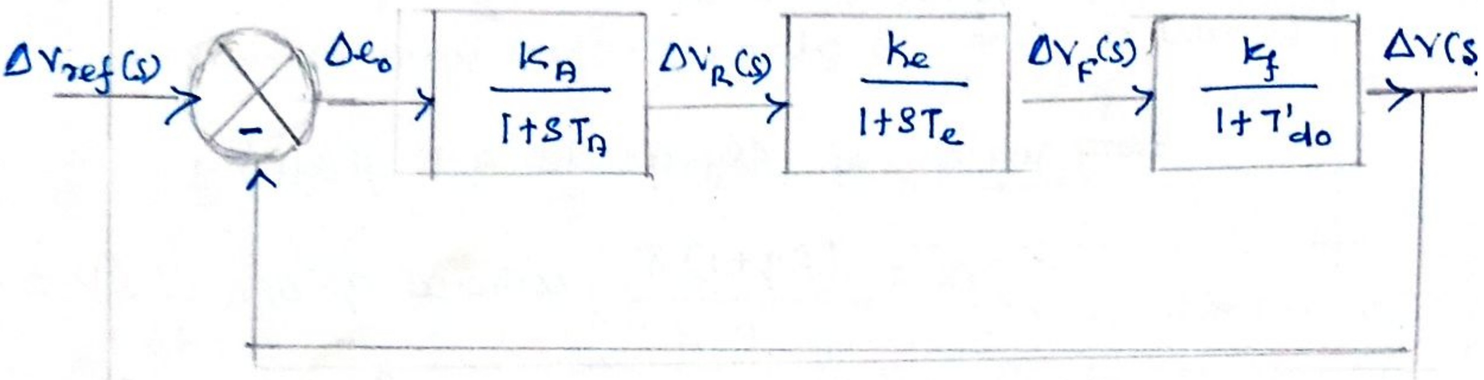
No: of Root Locus (N) = 3

N = P, if P > Z

N = Z, if P < Z.

Stability Compensation

The block diagram of AVR loop is



The open loop transfer function of AVR Loop is given by

$$\frac{\Delta V(s)}{\Delta V_{ref}(s)} = \frac{K_A K_e K_f}{(1+sT_A)(1+sT_e)(1+sT'_{do})}$$

Number of zeros = 0

Number of poles = 3. They are $\frac{-1}{T_A}$, $\frac{-1}{T_e}$ and $\frac{-1}{T'_{do}}$

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

No: of Root Locus (N) = 3

N = P, if P > Z

N = Z, if P < Z.

Root locus path exists on a point on the real axis, If there is odd number of placed on the righthand side of this point.

Asymptode angle gives the direction of the poles travel on the s plane, when gain increased.

∴ Angle of Asymptode α is given by

$$\alpha^\circ = \frac{(2q+1)\pi}{P-Z}, \text{ where } q = 0, 1, \ldots (P-Z-1)$$

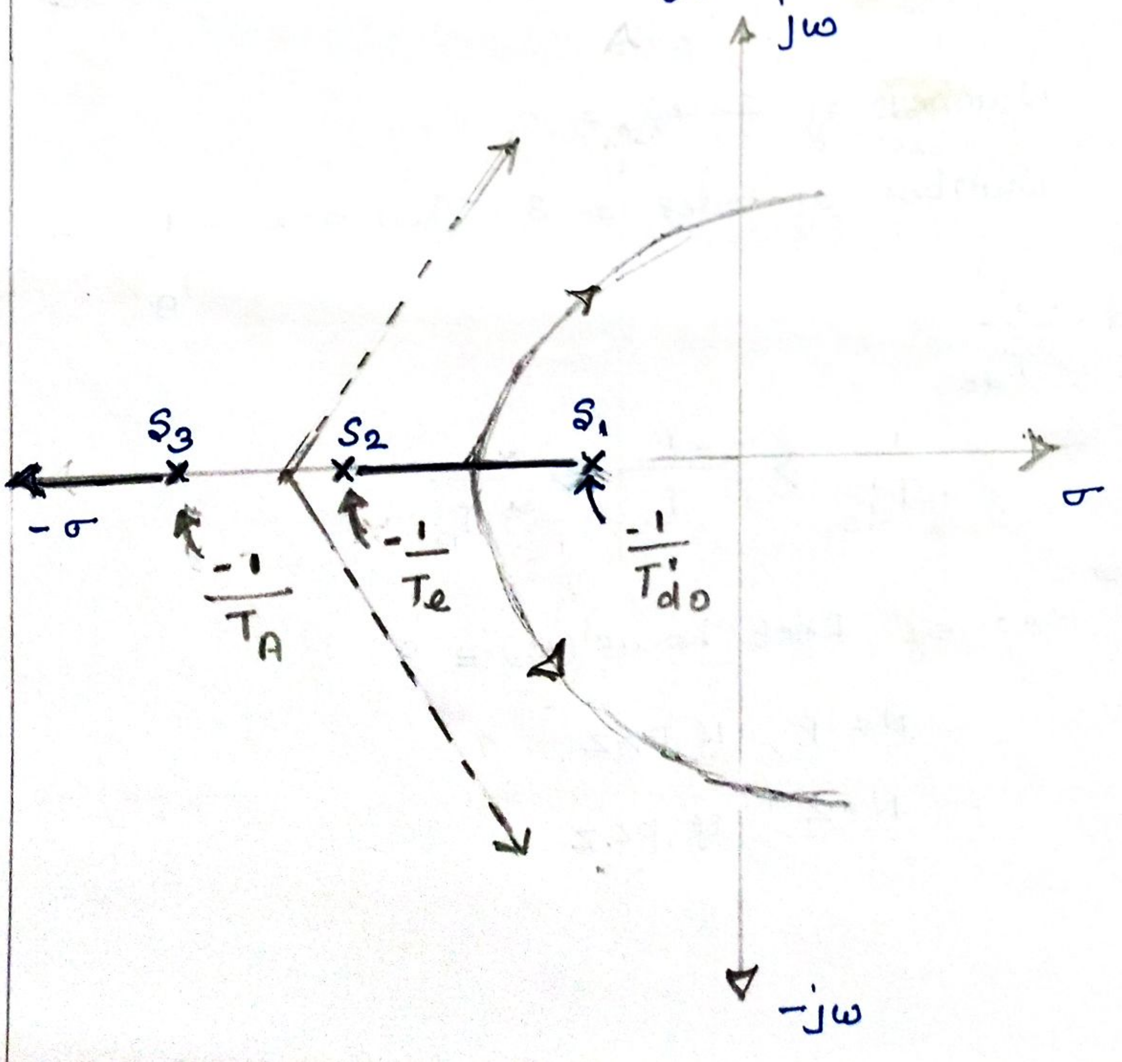
$q = 0, 1 \ldots (3-0-1)$

$q = 0, 1, 2$

when $q = 0$, $\alpha^\circ = \frac{\pi}{3}$

$q = 1$, $\alpha^\circ = \frac{3\pi}{3} = \pi$

$q = 2$; $\alpha^\circ = \frac{5\pi}{3}$.



By increasing the loop gain, the open loop pole S_3 moves towards the left hand of the S plane. But the poles S_2 and S_1 moves in opposite direction and at a point Collide each other and travels towards the Right hand Side of the S plane. This makes the System become unstable.

Therefore to improves the dynamic response characteristics without affecting the static loop gain, we go for stability Compensation methods.

a) Series Compensation

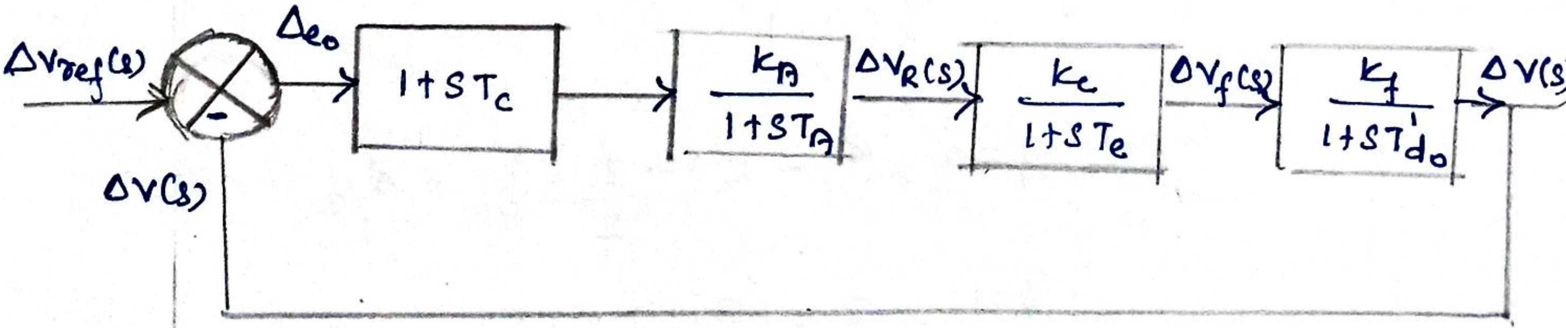
b) Feedback Stablity Compensation.

a) Series Compensation

In this method, the stablity is improved by adding a series phase lead compensator.

Transfer function of Series Compensator is

$$G_S = 1 + ST_c$$



The open loop transfer function for above series stability compensation AVR loop is given by

$$G(s) = \frac{K_A K_e K_f (1+sT_c)}{(1+sT_A)(1+sT_e)(1+sT'_{do})}$$

If we tune $T_c = T_e$, then

$$G(s) = \frac{K_A K_e K_f}{(1+sT_A)(1+sT'_{do})}$$

Number of zeros = 0

Number of poles = 2, They are $-\frac{1}{T_A}$, $-\frac{1}{T'_{do}}$

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

Number of root locus (N) = 2.

Angle of Asymptode $\theta = \frac{(2q+1)\pi}{P-Z}$,

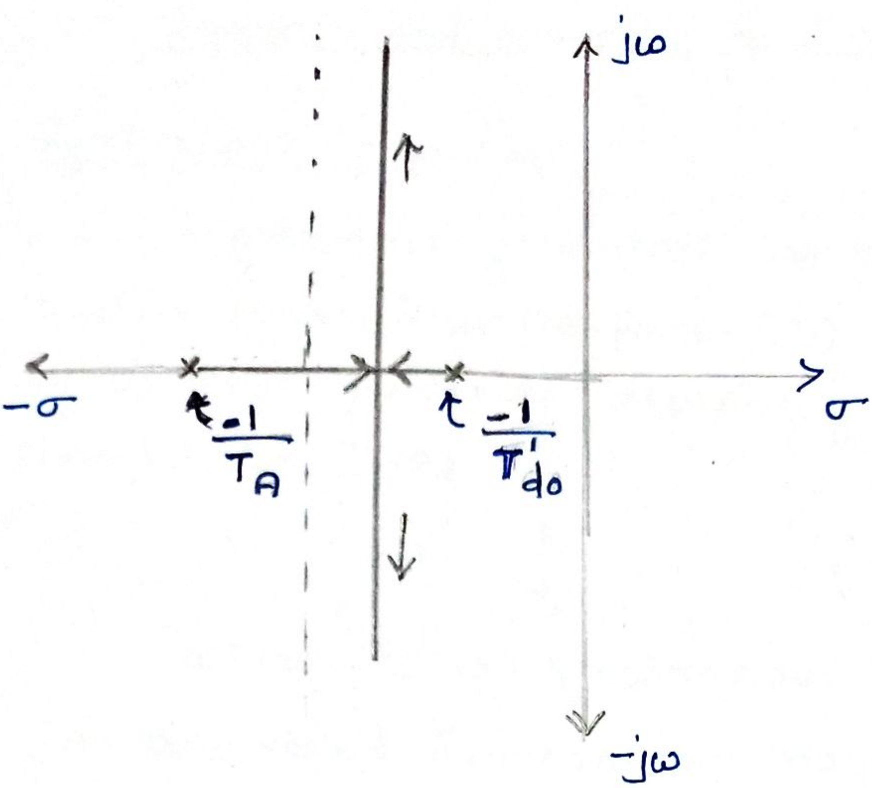
where $q = 0, 1, 2 \ldots (P-Z-1)$.

$q = 0, \ldots (2-0-1)$

$q = 0, 1$

When $q=0$, $\theta = \frac{(2\times 0+1)\pi}{2} = \pi/2$

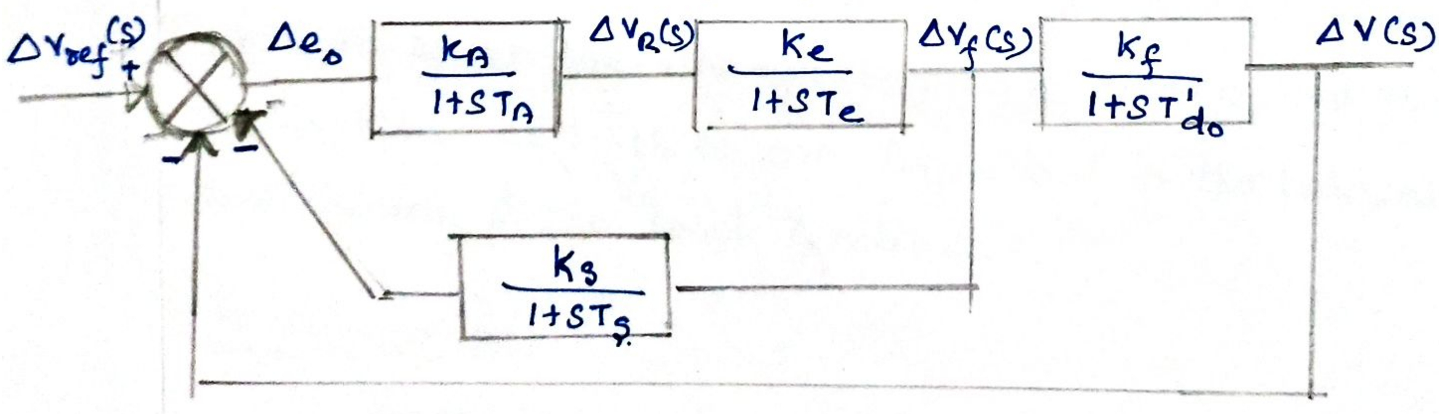
$q=1$, $\theta = \frac{(2\times 1+1)\pi}{2} = \frac{3\pi}{2}$.



From this AVR root loci, we seen that increase in loop gain, does'nt allow the poles to travel right hand side of the s plane. Hence the system is stable.

b) Feedback stablity Compensation.

This Compensator introduce a zero to the AVR open loop transfer function.



By proper adjustment of k_s and T_s, a satisfactory Response can be obtained.

Relation between Voltage, Power and Reactive Power at a Node

The phase voltage 'v' at a node is a function of real and Reactive power at a node is given by

$$V = f(P, Q)$$

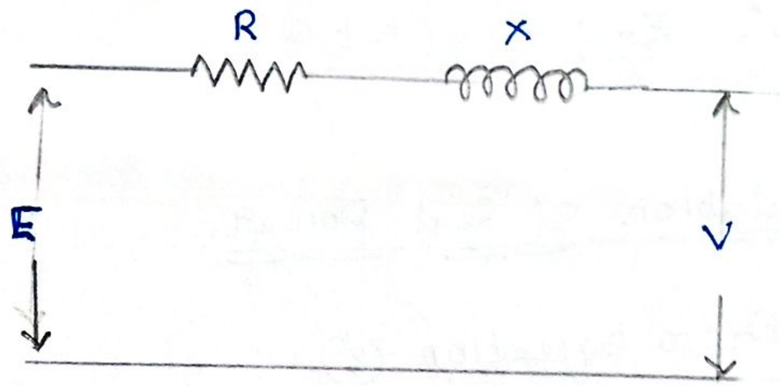
Differentiating

$$dv = \frac{\partial v}{\partial p} dp + \frac{\partial v}{\partial Q} dQ$$

$$dv = \frac{dP}{\partial P / \partial v} + \frac{dQ}{\partial Q / \partial v} \rightarrow (1)$$

The change in Voltage at a node is defined by $\frac{\partial P}{\partial V}$ and $\partial Q / \partial v$

Consider a short transmission line with series impedance $R + jX$



$$E = V + IZ$$

$$E = V + I(R + jX)$$

$$\vec{I} = \frac{S^*}{V^*} = \frac{P - jQ}{V}$$

$$E = V + \left(\frac{P - jQ}{V}\right) R + jX$$

The change in voltage is ΔV

$$\Delta V = E - V$$

$$E - V = V + \frac{(P - jQ)}{V} R + jX - V$$

$$E - V = \frac{(P + jQ)(R + jX)}{V}$$

$$E - V = \frac{PR + jPX - jQR + QX}{V}$$

$$E - V = \frac{PR + QX + j(PX - QR)}{V}$$

$\left(\frac{PX - QX}{V}\right)$ is very small, so it may be neglected)

$$\therefore E - V = \frac{PR + QX}{V} \rightarrow (2)$$

Calculation of Real Power

From Equation (2)

$$PR + QX = (E - V)V$$

$$PR = (E - V)V - QX$$

$$P = \frac{(E - V)V - QX}{R}$$

If x is small, $\frac{\partial Q}{\partial V}$ is large and has the value of 10-15 MVAR/kV.

The quantity $\frac{\partial Q}{\partial V}$ can be determined by using a network analyzer by the injection of a known quantity of VAR (Reactive power) at the node and measuring the difference in voltage produced at that node.

If the three phases at the receiving end are short circuited, $E = V$

From Equation ④

$$\frac{\partial Q}{\partial V} = \frac{E-2E}{X} = \frac{-E}{X} = \text{Short circuit current}$$

and sign decides the nature of the reactive power (absorbed or generated).

Substitute the equations ③ and ④ in Equation ①

$$dV = \frac{dP}{(E-2V)/R} + \frac{dQ}{(E-2V)/Q}$$

$$dV = \frac{R\,dP}{E-2V} + \frac{Q\,dQ}{E-2V}$$

For constant voltage

$$R\,dP + Q\,dQ = 0$$

$$\boxed{dQ = \frac{-R\,dP}{X}}$$

$$P = \frac{EV - V^2 - QX}{R} = \frac{EV}{R} - \frac{V^2}{R} - \frac{QX}{R}$$

Partially differentiating P with respect to V

$$\frac{\partial P}{\partial U} = \frac{E}{R} - \frac{2V}{R} - 0$$

$$\boxed{\frac{\partial P}{\partial V} = \frac{E - 2V}{R}} \rightarrow (3)$$

Calculation of Reactive power

From Equation (2)

$$(E - V)V = PR + QX$$

$$QX = (E - V)V - PR.$$

$$Q = \frac{(E - V)V - PR}{X}$$

$$Q = \frac{EV}{X} - \frac{V^2}{X} - \frac{PR}{X}$$

partially differentiating Q with respect to V

$$\frac{\partial Q}{\partial V} = \frac{E}{X} - \frac{2V}{X} \cdot 0$$

$$\boxed{\frac{\partial Q}{\partial V} = \frac{E - 2V}{X}} \rightarrow (4)$$

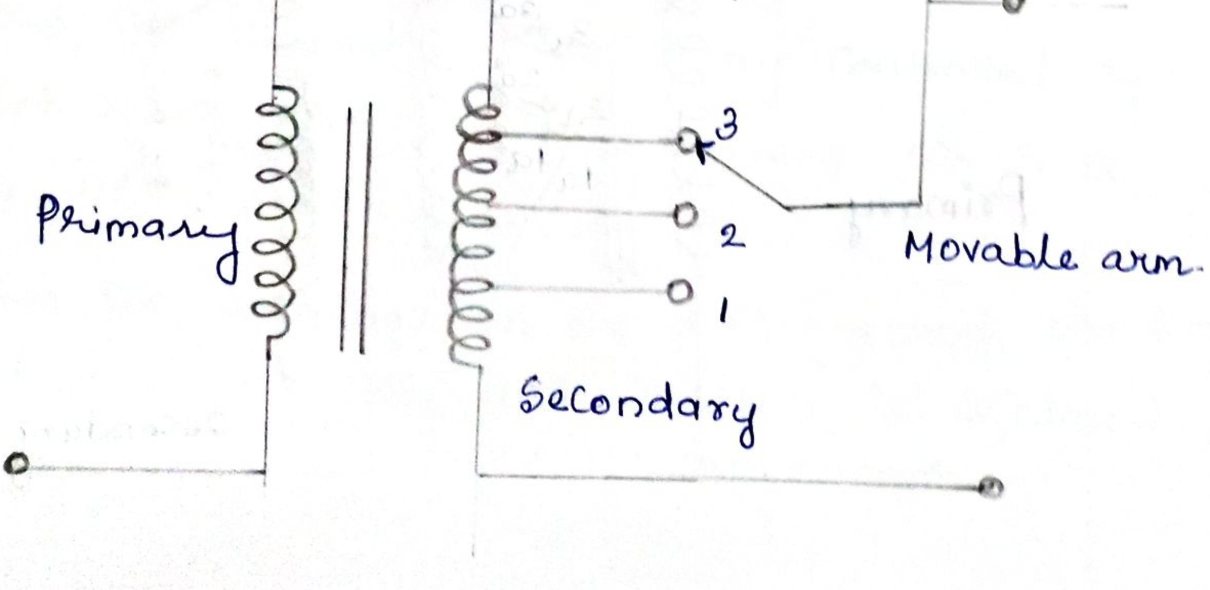
Tap Changing Transformer.

The voltage drop in the transmission line is supplied by changing the secondary emf of the Tap changing Transformer. In this transformer, a number of tappings are provided on the secondary side. Based on the position of the tap, the effective number of secondary turns are varied and hence the output voltage of the secondary can be changed.

There are two types of tap changing transformer
a) Off load tap changing transformer
b) ON load tap changing transformer (OLTC)

a) Off load tap changing transformer

This transformer requires the ~~dis~~ disconnection of transformer when the tap setting is to be changed.

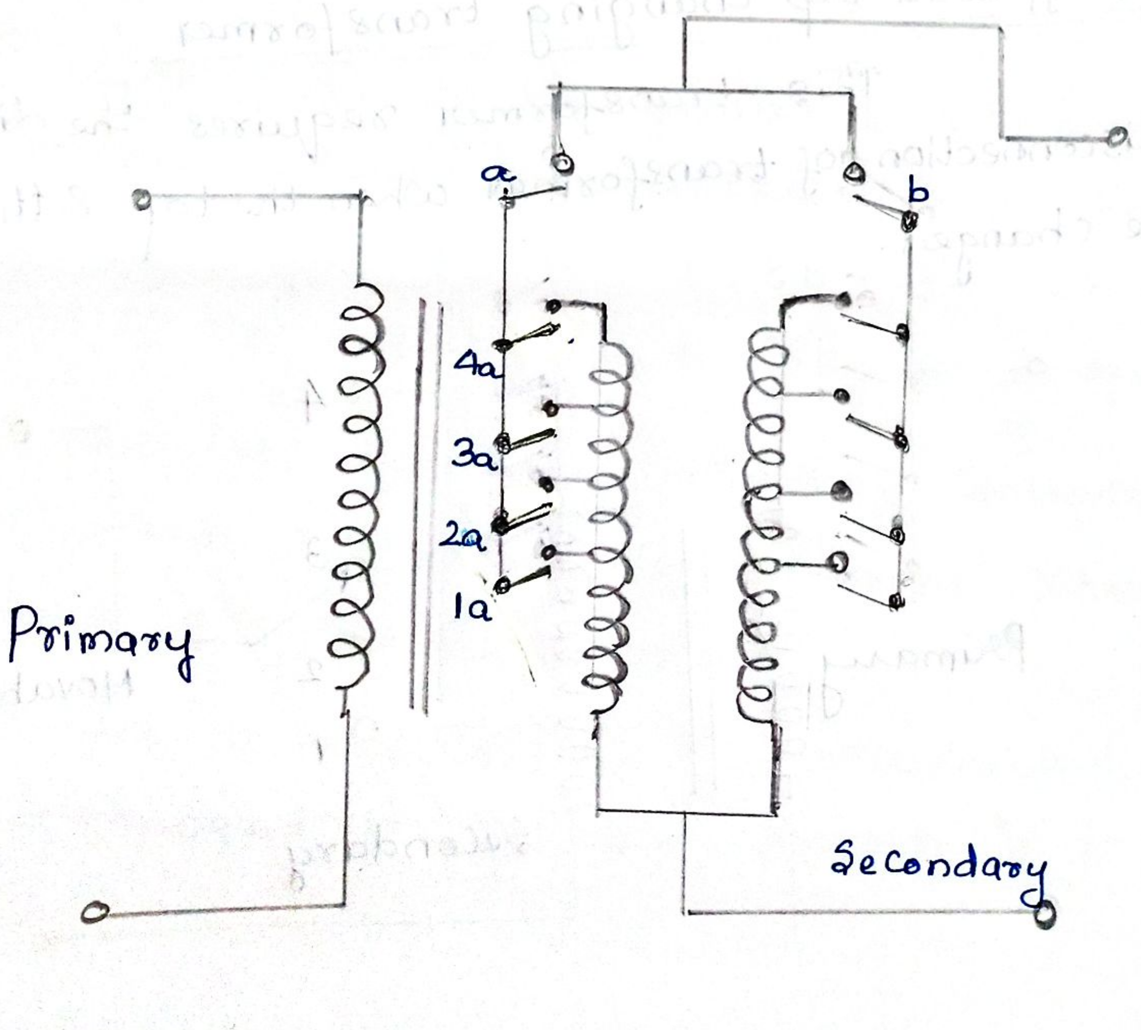


when the movable arm makes contact with stud 1, the Secondary voltage is minimum and when with stud 5, the secondary voltage is maximum.

During the period of light load, the voltage across the primary is not much below the alternator voltage and the movable arm is placed on stud 1

When the load increases, the voltage across the primary drops, but the secondary voltage can be kept at previous value by placing the movable arm to a higher stud.

b) On load tap changing transformer (OLTC)



This transformer doesn't requires the disconnection of transformer, when tap setting is to changed.

In this method, the secondary consists of two equal parallel ~~voltage~~ windings which have similiar tappings 1a .... 5a and 1b . . . 5b

In normal working conditions, switches a, b and tappings with the same number remain closed and each secondary winding carries one half of the total current.

The secondary voltage will be maximum, when switches 5a and 5b are closed. However, the secondary voltage will be minimum when switches 1a and 1b are closed.

Suppose that the transformer is working with tapping position 4a, 4b and it is desired to alter its position to 5a, 5b. For this purpose one of the switches a, b (say a) is opened.

Now the secondary winding controlled by switch b carries the total current which is twice its rated capacity

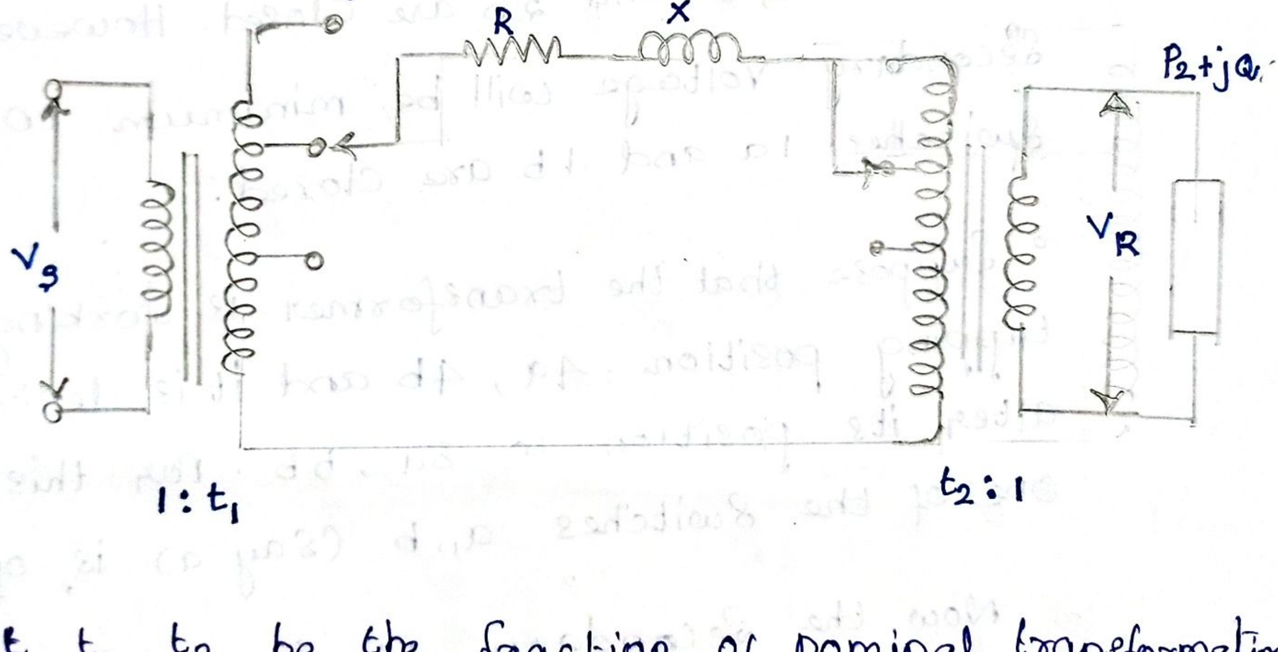
Then the tappings on the disconnected winding is changed to 5a and switch 'a' is closed.

After this, switch 'b' is opened to disconnect the winding, tapping position on this winding is changed to 5b and then switch 'b' is closed.

In this way, tapping position is changed without interrupting the supply.

System Level Control using Generator Voltage Magnitude Setting

Let us consider the tap changing transformer at both ends of a line



Let t_1, t_2 be the fraction of nominal transformation ratio

ie) $\frac{\text{tap ratio}}{\text{Nominal Value}}$

The actual voltages will be $t_1 V_1$ and $t_2 V_3$

Since the line has an impedance. It is necassary to compensate the voltage drop in the line at a desired level.

To maintain overall voltage level, the minimum range of taps on both transformer is used, $t_1 t_2$ is made unity ($t_1 t_2 = 1$)

From the figure, we know that

$$V_1 = V_2 + \Delta V$$

$$t_1 |V_1| = t_2 |V_2| + \frac{P_2 R + Q_2 X}{t_2 |V_2|}$$

$$t_2 = \frac{1}{t_1}$$

$$t_1 |V_1| = \frac{1}{t_1} |V_2| + \frac{P_2 R + Q_2 X}{\frac{1}{t_1} |V_2|}$$

$$t_1 |V_1| = \frac{|V_2|}{t_1} + \frac{t_1 (P_2 R + Q_2 X)}{|V_2|}$$

$$t_1 |V_1| = \frac{|V_2|^2 + t_1^2 (P_2 R + Q_2 X)}{t_1 |V_2|}$$

$$t_1^2 |V_1| |V_2| = |V_2|^2 + t_1^2 (P_2 R + Q_2 X)$$

$$t_1^2 |V_1| |V_2| - t_1^2 (P_2 R + Q_2 X) = |V_2|^2$$

$$t_1^2\left[|V_1||V_2| - (P_2R + Q_2X)\right] = |V_2|^2$$

Dividing by $|V_1||V_2|$

$$\frac{t_1^2\left[|V_1||V_2| - (P_2R + Q_2X)\right]}{|V_1||V_2|} = \frac{|V_2|^2}{|V_1||V_2|}$$

$$t_1^2\left[1 - \frac{P_2R + Q_2X}{|V_1||V_2}\right] = \frac{|V_2|}{|V_1|}$$

$$t_1^2 = \frac{|V_2|/|V_1|}{1 - \frac{P_2R + Q_2X}{|V_1||V_2|}}$$

For comple line drop compensation

$|V_1| = |V_2|$

$$t_1^2 = \frac{1}{1 - \frac{P_2R + Q_2X}{|V_1|^2}}$$

$$t_1 = \sqrt{\frac{1}{1 - \frac{P_2R + Q_2X}{|V_1|^2}}}$$

Sending end voltage $V_2 = t_1 V_1$

Now $t_2 = \frac{1}{t_1}$

For a given load, given the nominal voltages, we can find t_1 and t_2 as to keep $|V_2|$ Constant at a Specific value.

For Small voltage variation or line drop, tap Changing transformer is used to improve Voltage magnitude of the System.

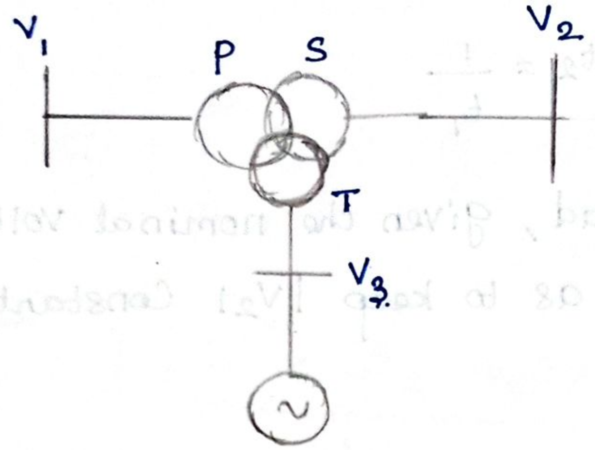
For high line drops, the tap changing transformer do not improve voltage profile because it does not have any reactive power generation capability.

<u>Combined use of Tap-Changing transformer and Reactive power Injection.</u>

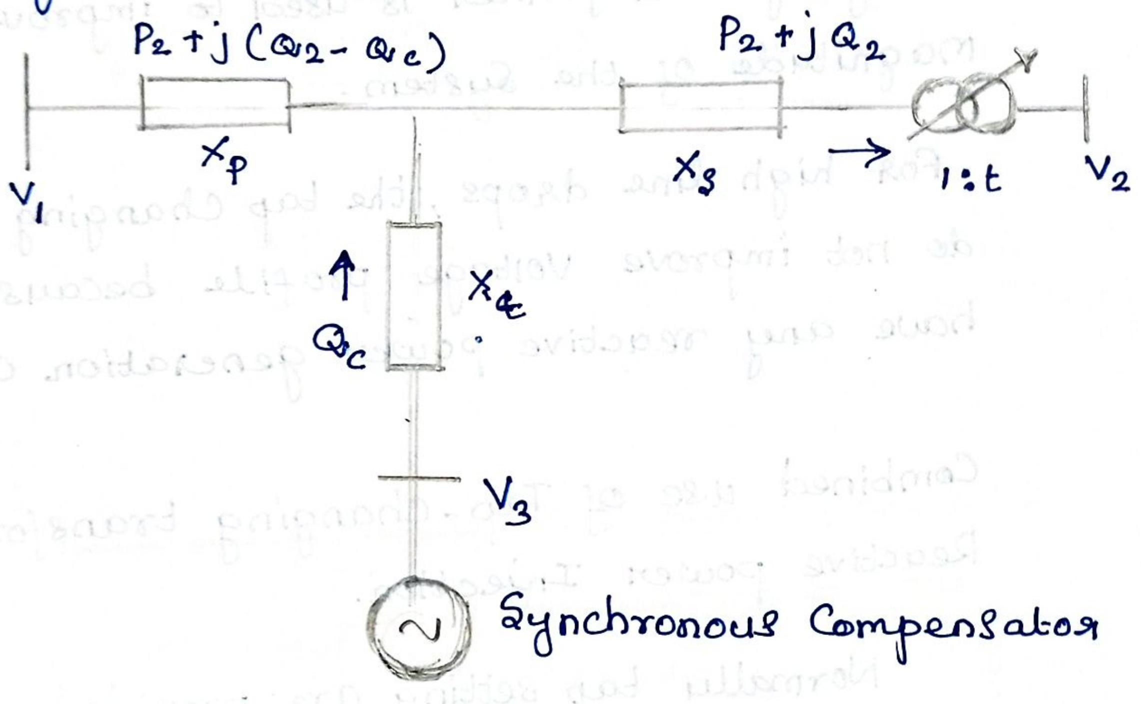
Normally tap setting are provided in steps for the range of ± 20%.

If the Setting exceeds the range, It is necessary to inject VARs at the load end and to maintain the voltage profile and to minimize transmission loss.

A Synchronous Compensator is connected to the tertiary winding of the 3 winding transformer



The equivalent circuit



Since the resistance of the line is neglected.

$$\Delta V = \frac{(Q_2 - Q_c) X_p}{|V_n|}$$

Quadrature voltage drop

$$\delta V = \frac{P_2 X_p}{|V_n|}$$

$$|V_1|^2 = (|V_n| + \Delta V)^2 + \delta V$$

$$|V_1|^2 = \left[|V_n| + \frac{(Q_2 - Q_c) X_p}{|V_n|}\right]^2 + \left[\frac{P_2 X_p}{|V_n|}\right]^2$$

$$|V_1|^2 = \left[\frac{|V_n|^2 + (Q_2 - Q_c) X_p}{|V_n|}\right]^2 + \left[\frac{P_2 X_p}{|V_n|}\right]^2$$

$$|V_1|^2 = \frac{(|V_n|^2 + (Q_2 - Q_c) X_p)^2 + (P_2 X_p)^2}{|V_n|^2}$$

$$|V_1|^2 |V_n|^2 = |V_n|^4 + ((Q_2 - Q_c) X_p)^2 + 2|V_n|^2 (Q_2 - Q_c) X_p + (P_2 X_p)^2$$

Solving the above equation, we get $|V_n|$

We can find out off nominal tap setting t,

$$t = \frac{|V_2|}{|V_n|}$$

STATCOM - Secondary Voltage Control

(Static compensator)

The STATCOM is a shunt connected reactive-power compensation device that is capable of generating and absorbing Reactive power and in which the output can be varied to control the specific parameters of an electric power system.

The STATCOM has the following components.

1) Voltage Source Converter (VSC)

Used to convert the DC input voltage to an AC output voltage. The following two types of VSC are

a) Square wave Inverters using Gate Turn off Thyristors (GTO)

In this type of VSC, output AC voltage is controlled by changing the DC capacitor input voltage.

b) PWM Inverters using Insulated Gate Bipolar Transistors (IGBT)

It uses pulse width modulation technique to create a AC voltage from a DC voltage source. In this method, variable AC output voltage is obtained by changing the modulation index of the PWM modulator.

2) DC capacitor

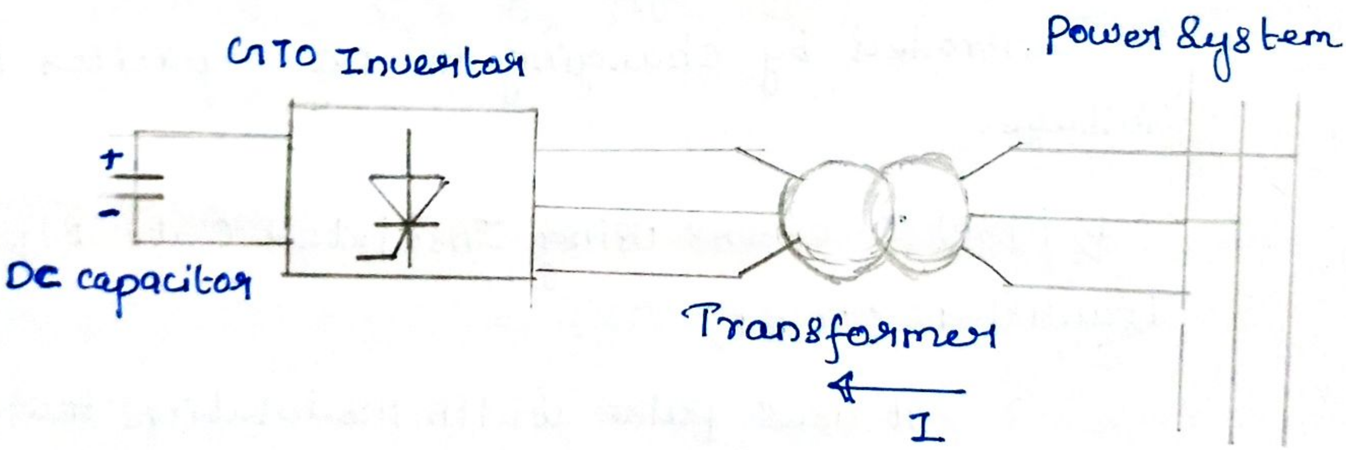
DC capacitor is used to supply constant DC Voltage to the Voltage Source Converter (VSC).

3) Inductive Reactance

A transformer is connected b/w the output of VSC and power system. Transformer basically act as a coupling medium. Transformer neutralise hormonics contained in the square waves produced by VSC

4) Harmonic filter

Harmonic filter attenuates the harmonics and other high frequency components due to the VSC



The operating is like a synchronous condensor. It is a 3Φ Inverter that is driven from the Voltage across the capacitor. VSC is coupled to circuit through a transformer which provides the safe operating voltage and small Reactance. An inverter generates three phase voltages in phase with the AC system voltage. Reactive power exchange between the converter and the AC system can be controlled by ~~Varing~~ Varying the amplitude of the three phase output voltage of the converter

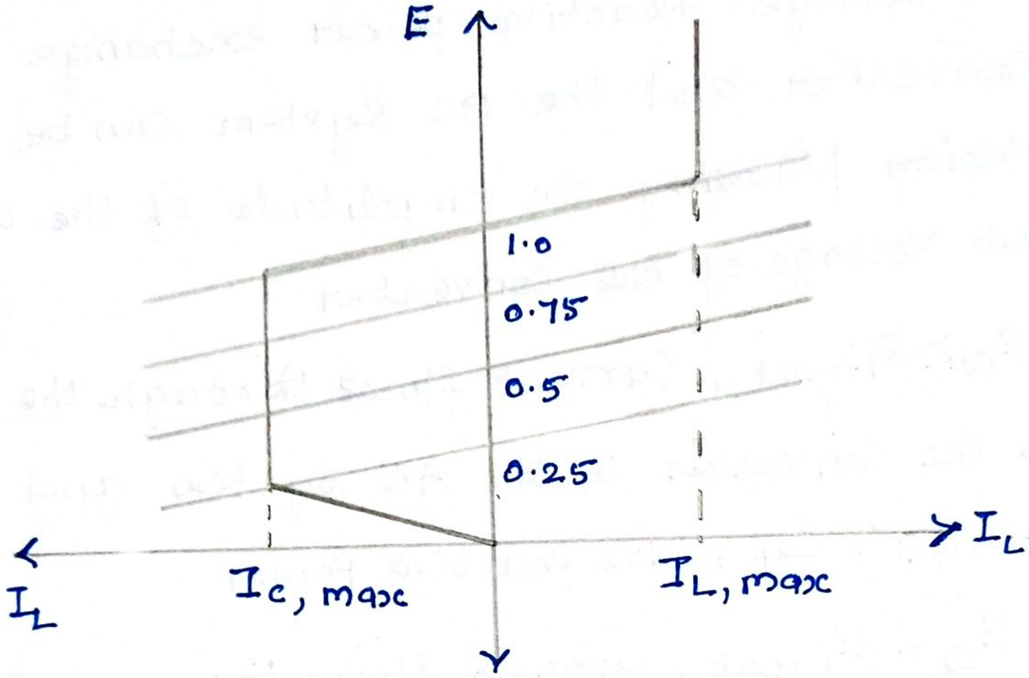
If $E_Q > E_{input}$, current flows through the reactance from the converter to the AC system and converter generates capacitive reactive power

If $E_Q < E_{input}$, current flows from the AC system to the converter and the converter absorbs inductive reactive power

If $E_Q = E_{input}$, the reactive power exchange become zero and the STATCOM is in floating state.

The current lags if the inverter voltage is less than the system voltage and leads if the system voltage is greater than the system voltage. Therefore the STATCOM provides continously controlled reactive power generation and absorption by means of electronic processing of voltage and current waveform in voltage source converter (VSC).

The typical V-I characteristics of a STATCOM is



From the curve

* The Statcom can supply both capacitive and inductive compensation.

* It controls the output current ($I_{c,max}$ and $I_{L,max}$)

* It gives full output of capacitive generation independently of system voltage.

Advantages of STATCOM

i) Compact design

ii) Low harmonic noise

iii) Low Magnetic Impacts.

EE8702 - POWER SYSTEM OPERATION AND CONTROL

UNIT IV

ECONOMIC OPERATION OF POWER SYSTEM

Statement of economic dispatch problem - input and output characteristics of thermal plant - incremental cost curve - optimal operation of thermal units without and with transmission losses (no derivation of transmission loss coefficients) - base point and participation factors method - statement of unit commitment (UC) problem - constraints on UC problem – solution of UC problem using priority list – special aspects of short term and long term hydrothermal problems.

Prepared by

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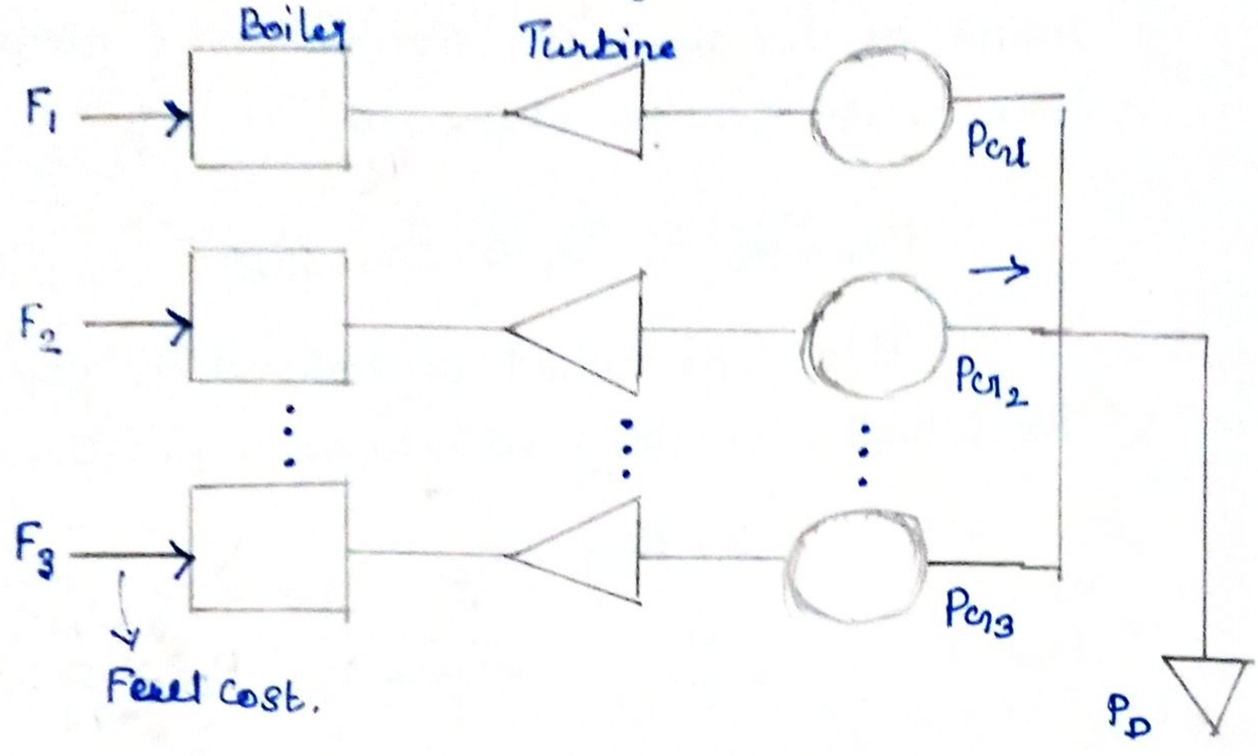
Economic load Dispatch.

The purpose of Economic dispatch is to reduce the fuel costs for the power System.



Consider a System consisting of 'N' Thermal generating units are Connected to a Single bus bar Supplying a load P_D

Input to each unit is expressed in terms of Cost rate $F_i(P_{Gi})$. Therefore total cost rate is the Sum of the Cost rate of individual units.

$$\therefore F_T = \sum_{i=1}^{N} F_i(P_{Gi})$$

Neglecting transmission losses, total generating power should meet the total load. Hence the equality Constraint is

$$\sum_{i=1}^{N} P_{Gi} = P_D$$

Based on the maximum and minimum power limits of the generator, the following inequality Constraints can be expressed as

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

This Constrained optimization problem can be solved by using Lagrange multiplier method.

$$H = F_T + \lambda \phi$$

$$\text{where } \phi = P_D - \sum_{i=1}^{N} P_{Gi}$$

$$H = \sum_{i=1}^{N} F_i(P_{Gi}) + \lambda \left[P_D - \sum_{i=1}^{N} P_{Gi} \right]$$

To find the necessary Condition for fuel cost (F_T) is to be minimum, take the derivative of Lagrangian Multiplier and Equate it to Zero

$$\frac{\partial H}{\partial P_{Gi}} = 0$$

$$\frac{\partial H}{\partial P_{Gi}} = \frac{\partial \left\{ F_i(P_{Gi}) + \lambda \left[P_D - \sum_{i=1}^{N} P_{Gi} \right] \right\}}{\partial P_{Gi}} = 0$$

$$\frac{\partial H}{\partial P_{Gi}} = \frac{\partial F_i}{\partial P_{Gi}} + 0 - \lambda = 0$$

$$\frac{\partial F_i}{\partial P_{Gi}} = \lambda \quad , \quad i = 1, 2, 3, \ldots N$$

$$\therefore \quad \frac{\partial F_1}{\partial P_{G1}} = \frac{\partial F_2}{\partial P_{G2}} = \ldots \frac{\partial F_n}{\partial P_{GN}} = \lambda$$

This equation is called as Coordination Equation without loss.

To minimise the fuel cost, the necessary. Condition is to have all the incremental fuel cost are same.

Analytical Solution of λ

The fuel cost characteristics of all generators are expressed as

$$F_i = a_i P_{Gi}^2 + b_i P_{Gi} + c_i$$

$$i = 1, 2, \ldots N$$

$$\frac{\partial F_i}{\partial P_{Gi}} = \lambda = 2a_i P_{Gi} + b_i$$

$$P_{Gi} = \frac{\lambda - b_i}{2a_i}$$

From power balance Equation

$$\sum_{i=1}^{N} P_{Gi} = P_D$$

$$\sum_{i=1}^{N} \frac{\lambda - b_i}{2a_i} = P_D$$

$$\sum_{i=1}^{N} \frac{\lambda}{2a_i} - \sum_{i=1}^{N} \frac{b_i}{2a_i} = P_D$$

$$\sum_{i=1}^{N} \frac{\lambda}{2a_i} = P_D + \sum_{i=1}^{N} \frac{b_i}{2a_i}$$

$$\lambda \sum_{i=1}^{N} \frac{1}{2a_i} = P_D + \sum_{i=1}^{N} \frac{b_i}{2a_i}$$

$$\boxed{\lambda = \frac{P_D + \sum_{i=1}^{N} \frac{b_i}{2a_i}}{\sum_{i=1}^{N} \frac{1}{2a_i}}}$$

The fuel cost of two units are given by

$$F_1 = 1.6 + 25 P_{G1} + 0.1 P_{G1}^2 \text{ Rs/hr.}$$

$$F_2 = 2.1 + 32 P_{G2} + 0.1 P_{G2}^2 \text{ Rs/hr}$$

If the total demand on the generators is 250 MW. Find the economic load scheduling of the two units.

Solution

The Condition for economic operating Schedule is

$$\frac{\partial F_i}{\partial P_{Gi}} = \lambda \text{ (without loss)}$$

Here there are two units, therefore above equation is modified as

$$\frac{\partial F_1}{\partial P_{G1}} = \frac{\partial F_2}{\partial P_{G2}} = \lambda \rightarrow (1)$$

$$\frac{\partial F_1}{\partial P_{G1}} = 0 + 25 + 2 \times 0.1 P_{G1} = 25 + 0.2 P_{G1}$$

$$\frac{\partial F_2}{\partial P_{G2}} = 0 + 32 + 2 \times 0.1 P_{G2} = 32 + 0.2 P_{G2}$$

From Equation (1)

$$25 + 0.2 P_{G1} = 32 + 0.2 P_{G2}$$

$$0.2 P_{G1} - 0.2 P_{G2} = 32 - 25$$

Given, those 2 units will going to share the load 250 MW. Therefore we can write the equation

$$P_{G_1} + P_{G_2} = 250 \rightarrow (3)$$

Solving Equations (2) and (3)

$$\boxed{P_{G_1} = 142.5 \text{ MW}}$$

$$\boxed{P_{G_2} = 107.5 \text{ MW}}$$

The fuel inputs per hour of plants 1 and 2 are given as

$$F_1 = 0.2 P_{G1}^2 + 40 P_{G1} + 120 \text{ Rs/hr}$$

$$F_2 = 0.25 P_{G2}^2 + 30 P_{G2} + 150 \text{ Rs/hr}$$

Calculate the economic operating schedule and the corresponding cost of generation. The maximum and the minimum loading on each unit are 100 MW and 25 MW. Assume the transmission losses are ignored and the total demand is 180 MW. Also determine the saving obtained if the load is equally shared by both the units ?

Solution

For economic operating schedule, the necessary condition exists is

$$\frac{\partial F_i}{\partial P_{Gi}} = \lambda$$

For 2 units, $\frac{\partial F_1}{\partial P_{G1}} = \frac{\partial F_2}{\partial P_{G2}} = \lambda \rightarrow (1)$

$$\frac{\partial F_1}{\partial P_{G1}} = 2 \times 0.2 P_{G1} + 40 = 0.4 P_{G1} + 40$$

$$\frac{\partial F_2}{\partial P_{G2}} = 2 \times 0.25 P_{G2} + 30 = 0.5 P_{G2} + 30$$

From Equation

$$0.4 P_{G1} + 40 = 0.5 P_{G2} + 30 = \lambda$$

$$0.4 P_{G1} + 40 = 0.5 P_{G2} + 30$$

$$0.4 P_{G1} - 0.5 P_{G2} = 30 - 40$$

$$0.4 P_{G1} - 0.5 P_{G2} = -10 \rightarrow (2)$$

Given, the units will share a load of 180 MW, Therefore we can write the equation

$$P_{G1} + P_{G2} = 180 \rightarrow (3)$$

Solving Equations (2) and (3), we get P_{G1} and P_{G2}

From Equation (3)

$$P_{G1} = 180 - P_{G2} \rightarrow (4)$$

From Equation (2)

$$0.4(180 - P_{G2}) - 0.5 P_{G2} = -10$$

$$72 - 0.4 P_{G2} - 0.5 P_{G2} = -10$$

$$-0.9 P_{G2} = -10 - 72$$

$$-0.9 P_{G2} = -82$$

$$P_{G2} = \frac{-82}{-0.9}$$

$$\boxed{P_{G2} = 91.111 \text{ MW}}$$

From Equation (4)

$$P_{G1} = 180 - 91.111$$

$$\boxed{P_{G1} = 88.889 \text{ MW}}$$

The total fuel cost of the 2 units are $F_T = F_1 + F_2$ → (5)

$F_{(P_{G1} = 88.889\,MW)} = 0.2 \times 88.889^2 + 40 \times 88.889 + 120$

$F_1 = 5255.811$ Rs/hr

$F_2 (P_{G2} = 91.11\,MW) = 0.25 \times 91.111^2 + 30 \times 91.111 + 150$

$F_2 = 4958.634$ Rs/hr

From Equation (5)

The total fuel cost when ($P_{G1} = 88.889$ MW and $P_{G2} = 91.11$ MW) is equal to 10,214.445 Rs/hr

ii) when load is shared equally by both units

$$P_{G1} = P_{G2} = \frac{180}{2} = 90\ MW$$

$F_1 (P_{G1} = 90\,MW) = 0.2 \times 90^2 + 40 \times 90 + 120$

$= 5340$ Rs/hr.

$F_2 (P_{G2} = 90\,MW) = 0.25 \times 90^2 + 30 \times 90 + 150$

$= 4875$ Rs/hr

From Equation (5)

The total fuel cost when ($P_{G1} = 90$ MW and $P_{G2} = 90$ MW) is equal to 10215 Rs/hr

Therefore net saving = 10215 − 10214.445

Net saving = 0.555 Rs/hr

Solution by λ iteration method without loss (Computer Approach)

Case i: Operating limits for power generation are not specified

Step 1 : Calculate λ by using

$$\lambda = \frac{P_D + \sum_{i=1}^{N} \frac{b}{2a_i}}{\sum_{i=1}^{N} \frac{1}{2a_i}}$$

Step 2 : Compute P_{Gi}

$$P_{Gi} = \frac{\lambda - b_i}{2a_i}$$

Step 3 : Check the Power balance Equation

$$\sum_{i=1}^{N} P_{Gi} = P_D$$

The power balance Equation is statisfied, then optimum Solution is obtained, otherwise go to next step.

Step 4 : If $\sum_{i=1}^{N} P_{Gi} < P_D$

Assign $\lambda = \lambda + \Delta\lambda$, and goto step 2

If $\sum_{i=1}^{N} P_{Gi} > P_D$

$\lambda = \lambda - \Delta\lambda$, and go to step 2

Case ii : Operating limits for power generation are given

Step 1 : Compute λ using the equation

$$\lambda = \frac{P_D + \sum_{i=1}^{N} \frac{b}{2a_i}}{\sum_{i=1}^{N} \frac{1}{2a_i}}$$

Step 2 : Compute P_{Gi}

$$P_{Gi} = \frac{\lambda - b_i}{2a_i}$$

Step 3 : Check if computed P_{Gi} satisfying the operating limits

$$P_{Gi,min} \leq P_{Gi} \leq P_{Gi,max} \quad i = 1, 2, \dots N$$

Step 4 : If P_{Gi} violates the operating limits, ~~then~~ fix the generation

$$P_{Gi} < P_{Gi,min} \quad , \quad \text{fix } P_{Gi} = P_{Gi,min}$$

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

Step 5 : Redistribute the remaining system load P_D

P_D (new) = P_D (old) − Sum of the fixed generation assigned.

Step 6 : Compute λ_{new} ~~and~~ and P_{Gi} for remaining units.

$$\lambda_{new} = \frac{P_{D(new)} + \sum \frac{b_i}{2a_i}}{\sum \frac{1}{2a_i}}$$

$$P_{Gi} = \frac{\lambda_{new} - b_i}{2a_i}$$

Step 7 : Check whether the optimality condition is statisfied

$$\frac{dF_i(P_{Gi})}{dP_{Gi}} = \lambda_{new} \quad \text{for } P_{Gi,min} \leq P_{Gi} \leq P_{Gi,max}$$

$$\frac{dF_i(P_{Gi})}{dP_{Gi}} \leq \lambda_{new} \quad \text{for } P_{Gi} = P_{Gi,max}$$

$$\frac{dF_i(P_{Gi})}{dP_{Gi}} \geq \lambda_{new} \quad \text{for } P_{Gi} = P_{Gi,min}$$

If the condition is statisfied, then stop. otherwise release the generation schedule of those units not statisfying optimality condition.

$$P_{D\,new1} = P_{D\,new} + \left\{ \begin{array}{l} \text{Sum of the fixed generators not statisfying} \\ \text{optimality condition.} \end{array} \right.$$

and go to step 6.

The fuel cost functions for three thermal plants in \$/h are given by

$$F_1 = 0.004\, P_{G1}^2 + 5.3\, P_{G1} + 500$$

$$F_2 = 0.006\, P_{G2}^2 + 5.5\, P_{G2} + 400$$

$$F_3 = 0.009\, P_{G3}^2 + 5.8\, P_{G3} + 200$$, where

P_{G1}, P_{G2} and P_{G3} are in MW.

Find the optimal dispatch and the total cost when the total load is 925 MW with the following generator limits.

$$100\ \text{MW} \le P_{G1} \le 450\ \text{MW}$$

$$100\ \text{MW} \le P_{G2} \le 350\ \text{MW}$$

$$100\ \text{MW} \le P_{G2} \le 222\ \text{MW}.$$

<u>Solution</u>

The necessary condition to find optimal dispatch is

$$\frac{\partial F_i}{\partial P_{Gi}} = \lambda$$

Here i varies from 1 to 3. Therefore the above equation is rewritten as

$$\frac{\partial F_1}{\partial P_{G1}} = \frac{\partial F_2}{\partial P_{G2}} = \frac{\partial F_3}{\partial P_{G3}} = \lambda \quad \longrightarrow (1)$$

$$\frac{\partial F_1}{\partial P_{G1}} = 2 \times 0.004\, P_{G1} + 5.3 = 0.008\, P_{G1} + 5.3.$$

$$\frac{\partial F_2}{\partial P_{G2}} = 2 \times 0.006\, P_{G2} + 5.5 = 0.012\, P_{G2} + 5.5$$

$$\frac{\partial F_3}{\partial P_{G3}} = 2 \times 0.009\, P_{G3} + 5.8 = 0.018\, P_{G3} + 5.8$$

$$\lambda = \frac{P_D + \sum_{i=1}^{3} \frac{b_i}{2a_i}}{\sum_{i=1}^{3} \frac{1}{2a_i}}$$

$$\therefore \lambda = \frac{P_D + \frac{b_1}{2a_1} + \frac{b_2}{2a_2} + \frac{b_3}{2a_3}}{\frac{1}{2a_1} + \frac{1}{2a_2} + \frac{1}{2a_3}}$$

$$\lambda = \frac{925 + \frac{5.3}{2 \times 0.004} + \frac{5.5}{2 \times 0.006} + \frac{5.8}{2 \times 0.009}}{\frac{1}{2 \times 0.004} + \frac{1}{2 \times 0.006} + \frac{1}{2 \times 0.009}}$$

$$\lambda = \frac{925 + 662.5 + 458.333 + 322.222}{125 + 83.333 + 55.556}$$

$$\lambda = \underline{\underline{8.974}} \text{ Rs/MWhr}$$

From Equation ①

$$\frac{\partial F_1}{\partial P_{G_1}} = \lambda$$

$$0.008\, P_{G_1} + 5.3 = 8.974$$

$$P_{G_1} = 8.974 - 5.3$$

$$P_{G_1} = \frac{8.974 - 5.3}{0.008}$$

$$\boxed{P_{G_1} = 459.210 \text{ MW}}$$

From Equation ②

$$\frac{\partial F_2}{\partial P_{G_2}} = \lambda$$

$$0.012\, P_{G_2} + 5.5 = 8.974$$

$$P_{G_2} = \frac{8.974 - 5.5}{0.012}$$

$$\boxed{P_{G_2} = 289.5 \text{ MW}}$$

From Equation ③

$$\frac{\partial F_3}{\partial P_{G_3}} = \lambda$$

$$0.018\, P_{G_3} + 5.8 = 8.974$$

$$P_{G_3} = \frac{8.974 - 5.8}{0.018}$$

$$\boxed{P_{G3} = 176.333 \text{ MW}}$$

<u>Check for limits</u>

Here P_{G1} lies outside the limit, but P_{G2} and P_{G3} lies with in the limit.

So we fix $\boxed{P_{G1} = 450 \text{ MW}}$ instead of 459.210 MW

Therefore the load shared by P_{G2}, P_{G3} increases.

$$P_{G2} + P_{G3} = P_D - P_{G1}$$

$$P_{G2} + P_{G3} = 925 - 450$$

$$P_{G2} + P_{G3} = 475 \quad \rightarrow (2)$$

From Equation (1)

$$\frac{\partial F_2}{\partial P_{G2}} = \frac{\partial F_3}{\partial P_{G3}}$$

$$0.012 P_{G2} + 5.5 = 0.018 P_{G3} + 5.8$$

$$0.012 P_{G2} - 0.018 P_{G3} = 5.8 - 5.5$$

$$0.012 P_{G2} - 0.018 P_{G3} = 0.3 \quad \rightarrow (3)$$

Solving Equations (2) and (3)

$$\boxed{P_{G2} = 295 \text{ MW}}, \quad \boxed{P_{G3} = 180 \text{ MW}}$$

Therefore the optimal dispatch from three units are

$$P_{G1} = 450 \text{ MW}$$
$$P_{G2} = 295 \text{ MW}$$
$$P_{G3} = 180 \text{ MW}$$

ii) Total Cost

Total Cost $F_T = F_1 + F_2 + F_3 \quad \rightarrow (4)$

F_1 (when $P_{G1} = 450$ MW) $= (0.004 \times 450^2) + (5.3 \times 450) + 500$

$F_1 = 3695$ Rs/hr

F_2 (when $P_{G2} = 295$ MW) $= (0.006 \times 295^2) + (5.5 \times 295) + 400$

$F_2 = 2544.65$ Rs/hr

F_3 (when $P_{G3} = 180$ MW) $= (0.009 \times 180^2) + (5.8 \times 180) + 200$

$F_3 = 1535.6$ Rs/hr

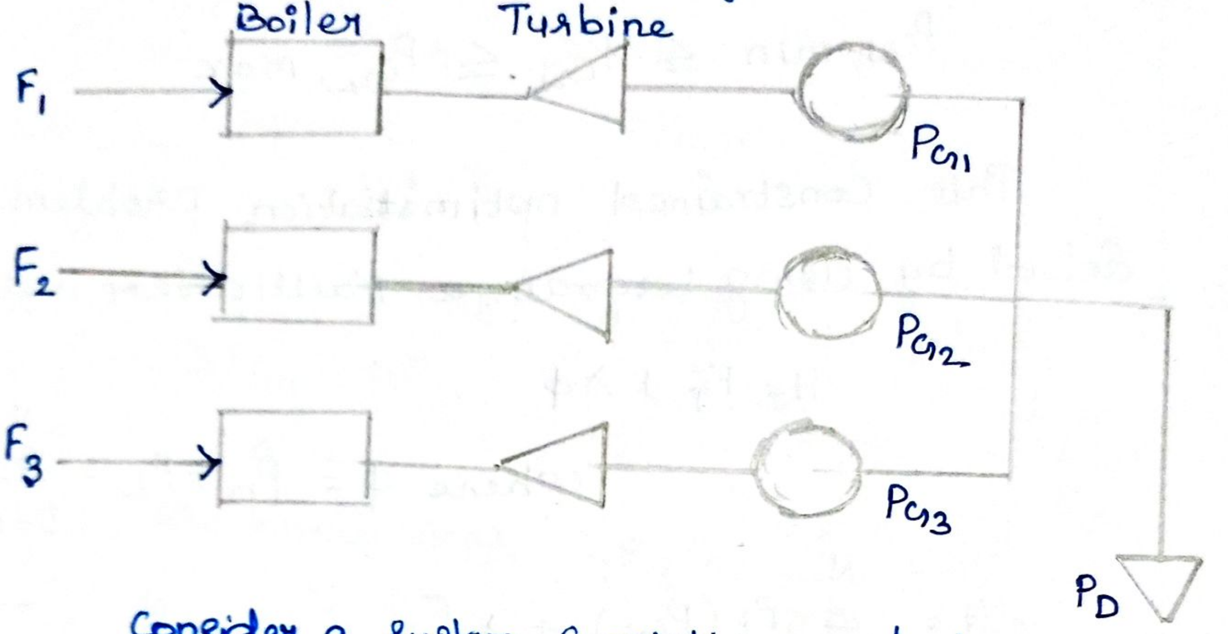
From Equation (4)

Total Cost $(F_T) = 3695 + 2544.65 + 1535.6$

$F_T = 7775.25$ Rs/hr

Economic Load Dispatch (with loss)

The purpose of Economic load dispatch is to reduce the fuel costs of the power system.



Consider a system consisting of 'N' Thermal generating units are connected to a single bus bar supplying a load P_D

Input to each unit is expressed interms of cost rate $F_i(P_{Gi})$. Therefore total cost rate is the sum of the cost rate of individual units

$$\therefore \; F_T = \sum_{i=1}^{N} F_i(P_{Gi})$$

By considering the transmission loss, the equality constraint is expressed as

$$\sum_{i=1}^{N} P_{Gi} = P_D + P_L$$

Based on the maximum and minimum power limits of the generator, the following inequality constraints can be expressed as

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

This constrained optimization problem can be solved by using Lagrange multiplier method.

$$H = F_T + \lambda \phi$$

$$\text{where } \phi = P_D + P_L - \sum_{i=1}^{N} P_{Gi}$$

$$H = \sum_{i=1}^{N} F_i(P_{Gi}) + \lambda \left[P_D + P_L - \sum_{i=1}^{N} P_{Gi} \right]$$

To find the necessary condition for fuel cost (F_T) is to be minimum, take the derivative of Lagrangian multiplier and equate it to zero

$$\frac{\partial H}{\partial P_{Gi}} = 0$$

$$\frac{\partial H}{\partial P_{Gi}} = \frac{\partial}{\partial P_{Gi}} \left[\sum_{i=1}^{N} F_i(P_{Gi}) + \lambda \left(P_D + P_L - \sum_{i=1}^{N} P_{Gi} \right) \right] = 0$$

$$\frac{\partial H}{\partial P_{Gi}} = \frac{\partial}{\partial P_{Gi}} \sum_{i=1}^{N} F_i(P_{Gi}) + \frac{\lambda \partial}{\partial P_{Gi}} \left[P_D + P_L - \sum_{i=1}^{N} P_{Gi} \right] = 0$$

$$\frac{\partial F_i}{\partial P_{Gi}} + \lambda \frac{\partial P_D}{\partial P_{Gi}} + \lambda \frac{\partial P_L}{\partial P_{Gi}} - \lambda \frac{\partial}{\partial P_{Gi}} \sum_{i=1}^{N} P_{Gi} = 0$$

$$\frac{\partial F_i}{\partial P_{Gri}} + 0 + \lambda \frac{\partial P_L}{\partial P_{Gri}} - \lambda = 0$$

$$\frac{\partial F_i}{\partial P_{Gri}} = \lambda - \lambda \frac{\partial P_L}{\partial P_{Gri}}$$

$$\frac{\partial F_i}{\partial P_{Gri}} = \lambda \left(1 - \frac{\partial P_L}{\partial P_{Gri}}\right)$$

We know that $IF_i = \frac{\partial F_i}{\partial P_{Gri}}$

$$IT_{Li} = \frac{\partial P_L}{\partial P_{Gri}}$$

$$IF_i = \lambda (1 - IT_{Li})$$

$$\boxed{\lambda = \frac{IF_i}{1 - IT_{Li}}}$$

This equation is Called Exact Coordination Equation.

$$\lambda = L_i \, IF_i$$

L_i is Called Penalty factor and is equal to

$$L_i = \frac{1}{1 - IT_{Li}}$$

Analytical Solution to find Transmission loss (P_L)

Transmission Loss is given by

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

For 2 bus system, $N = 2$

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

$$P_L = P_G \; B_{ij} \; P_G^T$$

$$= \begin{bmatrix} P_{G1} & P_{G2} \end{bmatrix} \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} \begin{bmatrix} P_{G1} \\ P_{G2} \end{bmatrix}$$

$$P_L = \begin{bmatrix} P_{G1} B_{11} + P_{G2} B_{21} & P_{G1} B_{12} + P_{G2} B_{22} \end{bmatrix} \begin{bmatrix} P_{G1} \\ P_{G2} \end{bmatrix}$$

$$P_L = (P_{G1} B_{11} + P_{G2} B_{21}) P_{G1} + (P_{G1} B_{12} + P_{G2} B_{22}) P_{G2}$$

$$P_L = P_{G1}^2 B_{11} + P_{G2} B_{21} P_{G1} + P_{G1} B_{12} P_{G2} + P_{G2}^2 B_{22}$$

$$B_{21} = B_{12}$$

$$\boxed{P_L = P_{G1}^2 B_{11} + 2 P_{G1} P_{G2} B_{12} + P_{G2}^2 B_{22}}$$

$$ITL_1 = \frac{\partial P_L}{\partial P_{G1}} = 2 P_{G1} B_{11} + 2 P_{G2} B_{12} = 2 \left[P_{G1} B_{11} + P_{G2} B_{12} \right]$$

$$ITL_2 = \frac{\partial P_L}{\partial P_{G2}} = 2 P_{G1} B_{12} + 2 P_{G2} B_{22} = 2 \left[P_{G2} B_{22} + P_{G1} B_{12} \right]$$

The incremental costs of two generating plants are

$$\frac{dF_1}{dP_{G1}} = 20 + 0.1 P_{G1} \text{ Rs/MWhr}$$

$$\frac{dF_2}{dP_{G2}} = 22.8 + 0.15 P_{G2} \text{ Rs/MWhr}$$

The System is operating on economic dispatch with $P_{G1} = P_{G2} = 100$ MW and $\frac{\partial P_L}{\partial P_{G2}} = 0.2$. Find the ~~penalty~~ penalty factor of plant 1.

__Solution__

The Coordination Equation with loss is

$$\frac{\partial F_i}{\partial P_{Gi}} = \lambda \left(1 - \frac{\partial P_L}{\partial P_{Gi}}\right)$$

$$\lambda = \frac{\frac{\partial F_i}{\partial P_{Gi}}}{1 - \frac{\partial P_L}{\partial P_{Gi}}}$$

$$\lambda = \frac{IF_i}{1 - ITL_i}$$

For 2 units

$$\lambda = \frac{IF_1}{1 - ITL_1} = \frac{IF_2}{1 - ITL_2} \rightarrow (1)$$

$$\lambda = L_1 IF_1 = L_2 IF_2 \rightarrow (2)$$

where $L_1 \rightarrow$ penalty factor of first unit, $L_1 = \dfrac{1}{1 - ITL_1}$

$L_2 \rightarrow$ Penalty factor of second unit, $L_2 = \dfrac{1}{1 - ITL_2}$

From Equation ①

$$\frac{20 + 0.1 P_{G1}}{1 - ITL_1} = \frac{22.8 + 0.15 P_{G2}}{1 - ITL_2}$$

Given $P_{G1} = P_{G2} = 100$ MW, $\dfrac{\partial P_L}{\partial P_{G2}} = ITL_2 = 0.2$

$$\frac{20 + (0.1 \times 100)}{1 - ITL_1} = \frac{22.8 + (0.15 \times 100)}{1 - 0.2}$$

From Equation ② $L_1 = \dfrac{1}{1 - ITL_1}$

$$L_1 (20 + (0.1 \times 100)) = \frac{22.8 + 15}{0.8}$$

$$L_1 = \frac{37.8}{0.8 (20 + 10)}$$

$$L_1 = \frac{37.8}{24} = 1.57$$

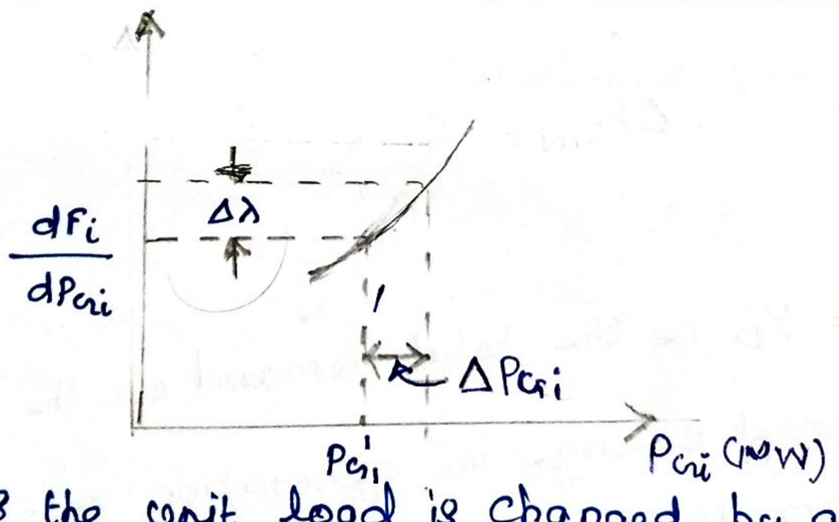
Penalty factor of unit 1 is $\underline{\underline{1.57}}$

Base point and participation factor

If the economic dispatch problem has to be solved repeatly by moving the generator from one economically optimum schedule to another as the load changes by a reasonably small amount

The initial optimal schedule inwhich the generator operates is called Base point

The factor indicating how much the generating units needs to participate in the load changes so as to serve the new load at the most economic operating point is called Participation factor



As the unit load is changed by an amount ΔP_D, the system cost moves from λ^0 to $\lambda^0 + \Delta\lambda$

For a small change in power output on the single unit

$$F_i = a_i P_{Gi}^2 + b_i P_{Gi} + c_i$$

$$F_i' = \frac{\partial F_i}{\partial P_{Gi}} = 2a_iP_{Gi} + b_i = \lambda$$

$$F_i'' = \frac{\Delta\lambda}{\Delta P_{Gi}} = 2a_i$$

$$\Delta\lambda = F_i'' \Delta P_{Gi}$$

$$\boxed{\Delta P_{Gi} = \frac{\Delta\lambda}{F_i''}} \rightarrow (1)$$

For n units on the System

$$\Delta P_{G1} = \frac{\Delta\lambda}{F_1''}$$

$$\Delta P_{G2} = \frac{\Delta\lambda}{F_2''}$$

$$\vdots$$

$$\Delta P_{GN} = \frac{\Delta\lambda}{F_N''}$$

Let P_D be the total demand on the Generation,

The total change in generation = change in total System demand

The change in demand ΔP_D is given by

$$\Delta P_D = \Delta P_{G1} + \Delta P_{G2} + \cdots + \Delta P_{GN}$$

$$\Delta P_D = \frac{\Delta\lambda}{F_1''} + \frac{\Delta\lambda}{F_1''} + \cdots + \frac{\Delta\lambda}{F_N''}$$

$$\Delta P_D = \Delta \lambda \sum_{i=1}^{N} \frac{1}{F_i''} \rightarrow (2)$$

Dividing the equation (2) by (1), we get the participati
participation factor

$$\frac{\Delta P_{Gi}}{\Delta P_D} = \frac{\frac{\Delta \lambda}{F_i''}}{\Delta \lambda \sum_{i=1}^{N} \frac{1}{F_i''}}$$

$$\frac{\Delta P_{Gi}}{\Delta P_D} = \frac{\frac{1}{F_i''}}{\sum_{i=1}^{N} \frac{1}{F_i''}}$$

Suppose P_D increases to $P_D + \Delta P_D$. The new value of generation is calculated using

$$P_{new,i} = P_{base,i} + \left(\frac{\Delta P_{Gi}}{\Delta P_D}\right) \Delta P_D, \quad i = 1, 2, \ldots N$$

where

ΔP_D = change in load demand

$P_{base,i}$ = Old value of Generation

$P_{new,i}$ = New Value of Generation.

Advantages of using participation factor

i) Computer implementation of economic dispatch is straight forward

ii) Reduces the execution time for the economic dispatch

iii) It will always give consistent answers when units reach limits

iv) It gives linear incremental cost functions (or) have non convex cost curves.

The input-Output Curve characteristics of three units are

$$F_1 = 940 + 5.46\, P_{G1} + 0.0016\, P_{G1}^2$$

$$F_2 = 820 + 5.35\, P_{G2} + 0.0019\, P_{G2}^2$$

$$F_3 = 99 + 5.65\, P_{G3} + 0.0032\, P_{G3}^2$$

Total load is 600 MW. Use the participation factor method to Calculate the dispatch for a load reduced to 550 MW ?

Solution

By using the participation factor, the new load shared by the units are expressed as

$$P_{Gi}\,(\text{New}) = P_{Gi}\,(\text{old}) + \left(\frac{\Delta P_{Gi}}{\Delta P_D}\right) \Delta P_D \rightarrow ①$$

$$\frac{\Delta P_{Gi}}{\Delta P_D} \rightarrow \text{participation factor} = \frac{\dfrac{1}{F_i''}}{\sum_{i=1}^{N} \dfrac{1}{F_i''}} \rightarrow ②$$

$\Delta P_D \rightarrow$ Change in load demand $= 550 - 600 = -50$ MW.

To find P_{Gi} (old), use the Co-ordination Equation

$$\frac{\partial F_1}{\partial P_{G1}} = \frac{\partial F_2}{\partial P_{G2}} = \frac{\partial F_3}{\partial P_{G3}} = \lambda \rightarrow ③$$

$$\frac{\partial F_1}{\partial P_{G1}} = F_1' = 5.46 + (2 \times 0.0016\, P_{G1}) = 5.46 + 0.0032\, P_{G1} \rightarrow ④$$

$$\frac{\partial F_2}{\partial P_{G2}} = F_2' = 5.35 + (2 \times 0.0019 P_{G2}) = 5.35 + 0.0038 P_{G2} \rightarrow (5)$$

$$\frac{\partial F_2}{\partial P_{G3}} = F_3' = 5.65 + (2 \times 0.0032 P_{G3}) = 5.65 + 0.0064 P_{G3} \rightarrow (6)$$

Equating (4) and (5),

$$5.46 + 0.0032 P_{G1} = 5.35 + 0.0038 P_{G2}$$

$$0.0032 P_{G1} - 0.0038 P_{G2} = -0.11 \rightarrow (7)$$

Equating (5) and (6)

$$5.35 + 0.0038 P_{G2} = 5.65 + 0.0064 P_{G3}$$

$$0.0038 P_{G2} - 0.0064 P_{G3} = 0.3 \rightarrow (8)$$

And also we know that this 3 units are going to share the load 600 MW. Therefore we form the third equation as

$$P_{G1} + P_{G2} + P_{G3} = 600 \rightarrow (9)$$

Solving Equations (7), (8) and (9), we get

P_{G1} (old) = 256.4958 MW

P_{G2} (old) = 244.9438 MW

P_{G3} (old) = 98.5604 MW

From Equation ②

$$\frac{\Delta P_{G_1}}{\Delta P_D} = \frac{\frac{1}{F_1''}}{\frac{1}{F_1''} + \frac{1}{F_2''} + \frac{1}{F_3''}}$$

From Equations ④, ⑤ and ⑥

$$F_1'' = \frac{\partial F_1'}{\partial P_{G_1}} = \frac{\partial (5.46 + 0.0032 P_{G_1})}{\partial P_{G_1}} = 0.0032$$

lly

$$F_2'' = 0.0038 \quad \text{and} \quad F_3'' = 0.0064$$

$$\frac{\Delta P_{G_1}}{\Delta P_D} = \frac{\frac{1}{0.0032}}{\frac{1}{0.0032} + \frac{1}{0.0038} + \frac{1}{0.0064}} = \underline{\underline{0.427}}$$

$$\frac{\Delta P_{G_2}}{\Delta P_D} = \frac{\frac{1}{F_2''}}{\frac{1}{F_1''} + \frac{1}{F_2''} + \frac{1}{F_3''}}$$

$$= \frac{\frac{1}{0.0038}}{\frac{1}{0.0032} + \frac{1}{0.0038} + \frac{1}{0.0064}} = \underline{\underline{0.3596}}$$

$$\frac{\Delta P_{G_3}}{\Delta P_D} = \frac{\frac{1}{F_3''}}{\frac{1}{F_1''} + \frac{1}{F_2''} + \frac{1}{F_3''}}$$

$$\frac{\Delta P_{G3}}{\Delta P_D} = \frac{\frac{1}{0.0064}}{\frac{1}{0.0032} + \frac{1}{0.0038} + \frac{1}{0.0064}} = 0.2135$$

From Equation ①

$$P_{G1}(new) = 256.4958 + (0.427 \times -50)$$
$$= 256.4958 - 21.35$$
$$= \underline{\underline{235.1458}} \text{ MW}$$

$$P_{G2}(new) = 244.9438 + (0.3596 \times -50)$$
$$= 244.9438 - 17.98$$
$$= \underline{\underline{226.9638}} \text{ MW}$$

$$P_{G3}(new) = 98.5604 + (0.2135 \times -50)$$
$$= 98.5604 - 10.675$$
$$= \underline{\underline{87.8854}} \text{ MW}$$

The input - Output curve characteristics of three units are

$$H_1 \text{ (MBtu/hr)} = 750 + 6.49 P_{G_1} + 0.0035 P_{G_1}^2$$

$$H_2 \text{ (MBtu/hr)} = 870 + 5.75 P_{G_2} + 0.015 P_{G_2}^2$$

$$H_3 \text{ (MBtu/hr)} = 620 + 8.56 P_{G_3} + 0.001 P_{G_3}^2$$

The fuel cost of unit 1 is 1.0 Rs/MBtu, 1.0 Rs/MBtu for unit 2 and 1.0 Rs/MBtu for unit 3. Total load is 800 MW. Use the participation factor method to calculate the dispatch for a load increased to 880 MW ?

Solution

Convert the Heat rate function to Cost function

$$F_i = k \times H_i$$

$$F_1 = 1 \times (750 + 6.49 P_{G_1} + 0.0035 P_{G_1}^2)$$

$$F_1 = 750 + 6.49 P_{G_1} + 0.0035 P_{G_1}^2$$

$$F_2 = 1 \times (870 + 5.75 P_{G_2} + 0.015 P_{G_2}^2)$$

$$F_2 = 870 + 5.75 P_{G_2} + 0.015 P_{G_2}^2$$

$$F_3 = 1 \times (620 + 8.56 P_{G_3} + 0.001 P_{G_3}^2)$$

$$F_3 = 620 + 8.56 P_{G_3} + 0.001 P_{G_3}^2$$

By using the participation factor, the new load shared by the units are expressed as

$$P_{Gi}(new) = P_{Gi}(old) + \left(\frac{\Delta P_{Gi}}{\Delta P_D}\right) \Delta P_D \rightarrow (1)$$

$$\frac{\Delta P_{Gi}}{\Delta P_D} \rightarrow \text{participation factor} = \frac{\frac{1}{F_i''}}{\sum_{i=1}^{N} \frac{1}{F_i''}}$$

ΔP_D ≑ Change in load demand = 880 - 800 = 80 MW

To find P_{Gi} (old), use the Coordination Equation

$$\frac{\partial F_1}{\partial P_{G1}} = \frac{\partial F_2}{\partial P_{G2}} = \frac{\partial F_3}{\partial P_{G3}} \rightarrow (3)$$

$$\frac{\partial F_1}{\partial P_{G1}} = F_1' = 6.49 + 0.007 P_{G1} \rightarrow (4)$$

$$\frac{\partial F_2}{\partial P_{G2}} = F_2' = 5.75 + 0.03 P_{G2} \rightarrow (5)$$

$$\frac{\partial F_3}{\partial P_{G3}} = F_3' = 8.56 + 0.002 P_{G3} \rightarrow (6)$$

Equating (4) and (5)

$$6.49 + 0.007 P_{G1} = 5.75 + 0.03 P_{G2}$$

$$0.007 P_{G1} - 0.03 P_{G2} = -0.74 \rightarrow (7)$$

Equating (5) and (6)

$$5.75 + 0.03 P_{G2} = 8.56 + 0.002 P_{G3}$$

$$0.03 P_{G2} - 0.002 P_{G3} = 2.81 \rightarrow (8)$$

we form the next equation as

$$P_{G_1} + P_{G_2} + P_{G_3} = 800 \rightarrow (9)$$

Solving the equations (7), (8) and (9)

$$P_{G_1},(\text{old}) = 382.465 \text{ MW}$$

$$P_{G_2},(\text{old}) = 113.908 \text{ MW}$$

$$P_{G_3},(\text{old}) = 303.627 \text{ MW}$$

Now the load is increased from 800 to 880 MW, then

$$\frac{\Delta P_{Gi}}{\Delta P_D} = \frac{\frac{1}{F_i''}}{\frac{1}{F_1''} + \frac{1}{F_2''} + \frac{1}{F_3''}}$$

$$F_1'' = \frac{\partial F_1'}{\partial P_{G_1}} = \frac{\partial (6.49 + 0.007 P_{G_1})}{\partial P_{G_1}} = 0.007$$

Ily

$$F_2'' = 0.03, \text{ and } F_3'' = 0.002$$

$$\frac{\Delta P_{G_1}}{\Delta P_D} = \frac{\frac{1}{F_1''}}{\frac{1}{F_1''} + \frac{1}{F_2''} + \frac{1}{F_3''}} = \frac{\frac{1}{0.007}}{\frac{1}{0.007} + \frac{1}{0.03} + \frac{1}{0.002}}$$

$$\frac{\Delta P_{G_1}}{\Delta P_D} = \frac{142.857}{142.857 + 33.333 + 500} = 0.211$$

$$\frac{\Delta P_{G2}}{\Delta P_D} = \frac{\frac{1}{F_2''}}{\frac{1}{F_1''} + \frac{1}{F_2''} + \frac{1}{F_3''}} = \frac{\frac{1}{0.03}}{\frac{1}{0.007} + \frac{1}{0.03} + \frac{1}{0.002}}$$

$$\frac{\Delta P_{G2}}{\Delta P_D} = \frac{33.333}{(142.857 + 33.333 + 500)} = 0.049$$

$$\frac{\Delta P_{G3}}{\Delta P_D} = \frac{\frac{1}{F_3''}}{\frac{1}{F_1'} + \frac{1}{F_2''} + \frac{1}{F_3''}} = \frac{\frac{1}{0.002}}{\frac{1}{0.007} + \frac{1}{0.03} + \frac{1}{0.002}}$$

$$\frac{\Delta P_{G3}}{\Delta P_D} = \frac{500}{(142.857 + 33.333 + 500)} = 0.739$$

From Equation ①

$$P_{G1}(new) = P_{G1}(old) + \left(\frac{\Delta P_{G1}}{\Delta P_D}\right) \times \Delta P_D$$

$$P_{G1}(new) = 382.465 + (0.211 \times 80)$$

$$P_{G1}(new) = 399.345 \text{ MW}$$

$$P_{G2}(new) = P_{G2}(old) + \left(\frac{\Delta P_{G2}}{\Delta P_D}\right) \times \Delta P_D$$

$$P_{G2}(new) = 113.908 + (0.049 \times 80)$$

$$P_{G2}(new) = 117.828 \text{ MW}$$

$$P_{G3}(new) = P_{G3}(old) + \left(\frac{\Delta P_{G3}}{\Delta P_D}\right) \times \Delta P_D$$

$$= 303.627 + (0.739) \times 80$$

$$P_{G3}(new) = 262.747 \text{ MW}$$

Statement of Unit Commitment problem.

To select the generating units that will supply the forecasted load of the system over a required period of time at minimum cost as well as provide a specified margin of the operating Reserve. This procedure is called **Unit Commitment**

Tommorrow's unit commitment problem may be stated as follows

Given : The expected system demand levels for the 24 hours of tomorrow and the operating cost, star up cost and shut down cost of the available N units.

To determine : If "N" generating units, $(2^n - 1)$ number of combinations will be obtained. From many feasible subsets, determine the subset of units that would statisfy the expected demand at minimum operating cost.

Need for unit commitment

* Enough units will be committed to supply the system load
* To reduce the loss (or) fuel cost
* By running the most economic unit, the load can be supplied by that unit operating closer to its best efficiency.

Constraints in Unit Commitment

Each 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

a) Spinning Reserve

b) Thermal Constraints
- minimum uptime
- minimum downtime
- crew constraint
- start-up-cost

c) Other Constraints
- Hydro Constraint
- Must-run Constraint
- Fuel Constraint

a) Spinning Reserve

Spinning Reserve is the total amount of generation available from all units synchronized on the system minus the present load and losses being supplied.

Spinning Reserve = [Total amount of generation] − [Present load + Losses]

If one unit is lost, the Spinning Reserve unit has to make up for the loss in a Specified time period.

Spinning Reserve is the reserve generating Capacity running at no load. Spinning Reserve includes quick start diesel or gas turbine unit, or hydro units and pumped Storage hydro units that Can be brought on line, Synchronized and brought up to full load Capacity

Typical Rules for Spinning Reserve Set by Regional Reliability Council

* Reserve must be given percentage of forecasted Peak demand

* Reserve must be capable of making up the loss of the most heavily loaded unit in a given period of time

* Calculate Reserve Requirements as a function of the probability of not having sufficient generation to meet the load.

b) Thermal Constraints.

A thermal unit Can withstand only gradual temperature changes and is required to take Some hours to bring the unit on-line.

The thermal Unit Constraints are minimum up time, minimum down time; Crew Constraints and start up

i) minimum up time

Once the unit is running, it should not be turned off immediately

ii) Minimum down time

Once the unit is decommitted, there is a minimum time before it can be recommitted.

iii) Crew constraints.

If a plant consists of two (or) more units, they cannot be turned ON at the same time.

iv) Start up cost

It depends on the time interval between shut down and restart.

Start up cost = 0, If unit is stopped and started immediately.

a) Start up cost when cooling

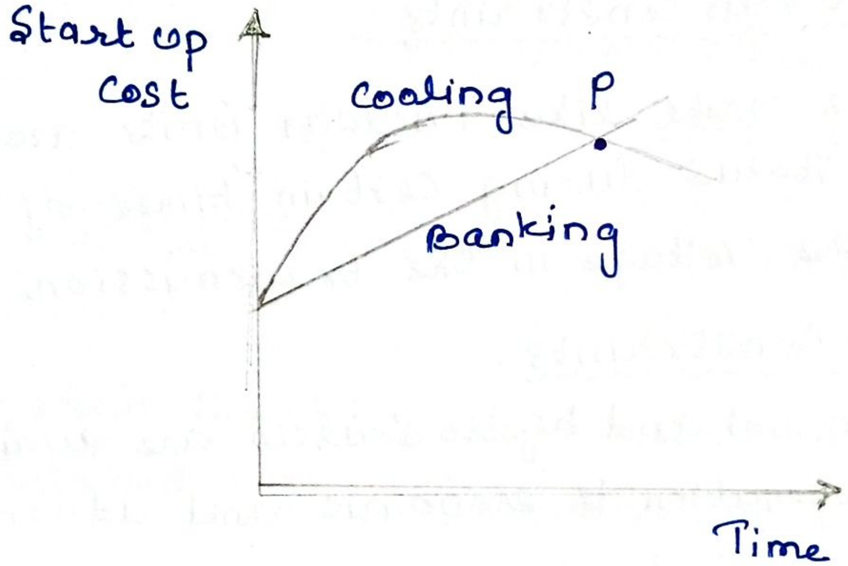
During shut down period, the unit's boiler to cool down and then heat back up to operating temperature in time for a scheduled turn ON.

Start up cost $\propto$ Cooling of the unit

b) Start-up cost when banking (Shut down cost)

During the shut-down period, the boiler may be allowed to cool down and thus no shut down cost will be incurred.

Banking Requires that sufficient energy be input to the boiler to just maintain operating temperature and pressure.



Upto point P, Cost of banking < Cost of Cooling

When the shut down cost is incurred, the unit may be said to be in hot Reserve.

Finally, the capacity limits of thermal units may change frequently, so we must consider the thermal constraints for solving unit commitment.

c) Other Constraints

i) Hydro Constraints.

In hydro - thermal scheduling, Hydro units are allocated to maximum during rainy season and thermal units are allocated for the remaining period.

In hydro units, the start up and shut down time, operating cost are negligible; hence we couldn't get the optimal solution. Therefore the hydro unit are not considered for unit commitment.

ii) Must Run Constraints

Some units like nuclear units are given a must run status during certain times of a year to maintain the voltage in the transmission system.

iii) Fuel constraints.

If thermal and hydro sources are avaible, a combined operation is economic and advantageous to reduce the fuel cost of thermal unit over a commitment period.

Unit commitment Solution methods.

The following three methods are widely used

1) Brute Force technique

2) Priority List method (Using full load average production cost FLAPC)

3) Dynamic programming method.

Brute Force Technique (Simple priority List Scheme)

In brute force technique, we are trying all combinations of the units at each hour ie) $2^n - 1$ combinations.

Constraint : Enough units will be committed to supply the load.

$$\sum_{i=1}^{N} P_{Gi} < P_D$$ → Infeasible Solution (or) decommit some generating units.

$$\sum_{i=1}^{N} P_{Gi} > P_D$$ → Feasible Solution (or) Commit some generating units.

For each feasible combination, the units will be dispatched using coordination Equation. But it is not possible to get an optimum Solution.

Priority list method

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 is given by

$$FLAPC = \frac{\text{Net heat rate}}{\text{at full load}} \times \text{fuel cost}$$

$$FLAPC = \frac{F_i(P_{Gi})}{P_{Gi}} = \frac{k_i \cdot H_i(P_{Gi})}{P_{Gi}}$$

Assumptions

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

Procedure

Step 1: Determine the FLAPC for each unit

$$FLAPC = \frac{F_i(P_{Gi})}{P_{Gi}} = \frac{k_i \times H_i(P_{Gi})}{P_{Gi}}$$

Step.2 : Form priority order based on FLAPC.

Step 3 : Commit number of units corresponding to the priority order.

Step 4 : Calculate $P_{G1}, P_{G2} \ldots P_{Gn}$ from economic dispatch problem for the feasible combination only.

Step 5 : At each hour when load is 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.

Step 6 : Determine the number of hours "H", before the unit will be needed again.

Step 7 : Check H < minimum shut down time.

If Yes, go the last step

If Not, go the Next Step.

Step 8 : Calculate 2 costs.

* Sum of hourly production costs for the next H hours with the unit start up.

* Recalculate the same for the unit shut down plus startup cost for either cooling or banking.

If there is sufficient savings from shutting down the unit, it should be shut down. Otherwise keep it ON.

Step 9 : Repeat this procedure, until the priority list is prepared

Merits

* No need to go for N. combinations.
* Take only one constraint.
* Ignore minimum up time and minimum down time.
* Complication reduced.

Demerits

* Start up cost are fixed
* No load costs are not considered.

obtain the priority list of unit commitment using Full load average production cost for the given data.

$$H_1 = 510 + 7.2\, P_{G_1} + 0.00142\, P_{G_1}^2$$

$$H_2 = 310 + 7.85\, P_{G_2} + 0.00194\, P_{G_2}^2$$

$$H_3 = 78 + 7.97\, P_{G_3} + 0.00482\, P_{G_3}^2$$

Unit	Minimum (MW)	Maximum (MW)	Fuel cost (R)
1	150	600	1.1
2	100	400	1.0
3	50	200	1.2

and the load Demand is 550 MW.

Solution

In priority list method, the priority of a unit is assigned based on the Full load Average production cost (FLAPC)

$$FLAPC = \frac{F_i(P_{Gi})}{P_{Gi}(max)} = \frac{K\, H_i(P_{Gi})}{P_{Gi}(max)}$$

As per the given data, Select $FLAPC = \frac{K\, H_i(P_{Gi})}{P_{Gi}(max)}$.

Step 1: Find FLAPC for each unit

$$\text{FLAPC for first unit} = \frac{1.1 \times (510 + (7.2 \times 600) + (0.00142 \times 600^2))}{600}$$

$$= \underline{9.79}\ Rs/MWhr$$

FLAPC for Second unit $= \dfrac{1.0 \times (310 + (7.85 \times 400) + (0.00194 \times 400^2))}{400}$

$= \underline{\underline{9.4}}$ Rs | Mwhr.

FLAPC for third unit $= \dfrac{1.2 \times (78 + (7.97 \times 200) + (0.00482 \times 200^2))}{200}$

$= \underline{\underline{11.188}}$ Rs | Mwhr

Step2 : priority order

Unit	FLAPC	Min (MW)	Max (MW)
2	9.4	100	400
1	9.79	150	600
3	11.188	50	200

Step 3 : Unit Commitment

Combination	Minimum MW from Combination	Maximum MW from Combination
2+1+3	300	1200
2+1	250	1000
2	100	400

All the three units would be held on until load reached to 1000 MW.

Units 2 and 1 would be held on until the load reached 400 MW, then unit 1 would be dropped.

For demand of 550 MW, unit 1 and 2 would be operated.

Dynamic Programming method

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
* If a strict priority order is imposed, the number of combinations for 4 unit case

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.

Assumptions

* Total number of units available, their individual cost characteristics and the load cycle on the station are assumed prior.
* 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 (ie, 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.

Types — Forward - Algorithm may run forward from initial hour to final hour
Types — Backward - Algorithm may run backward from final hour to initial hour

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
* Previous history of the unit can be computed at each stage.
* Initial conditions are easily specified.

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 untill 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

$$F_{cost}(k, I) = \min \left\{ P_{cost}(k, I) + S_{cost}(k-1, L; k, I) + F_{cos}(k-I, L) \right\}$$

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 is

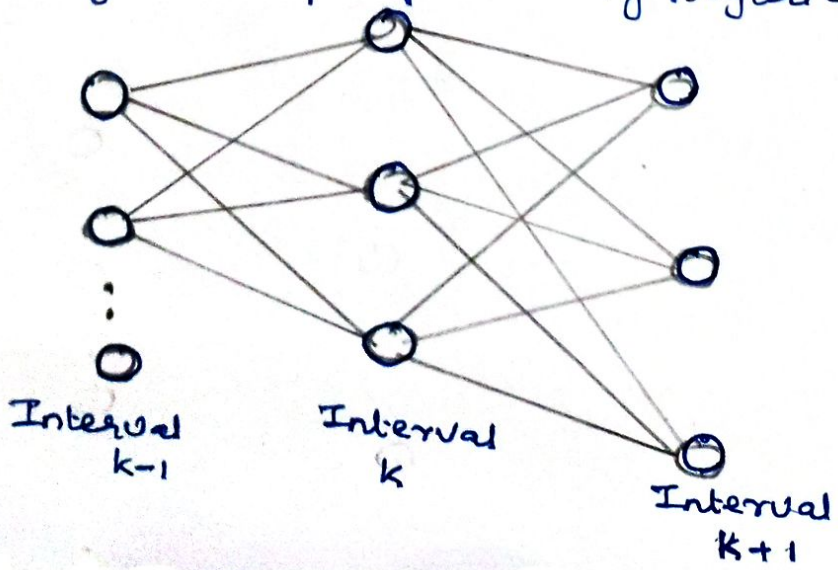
State (k, I) = I^{th} combination in hour k.

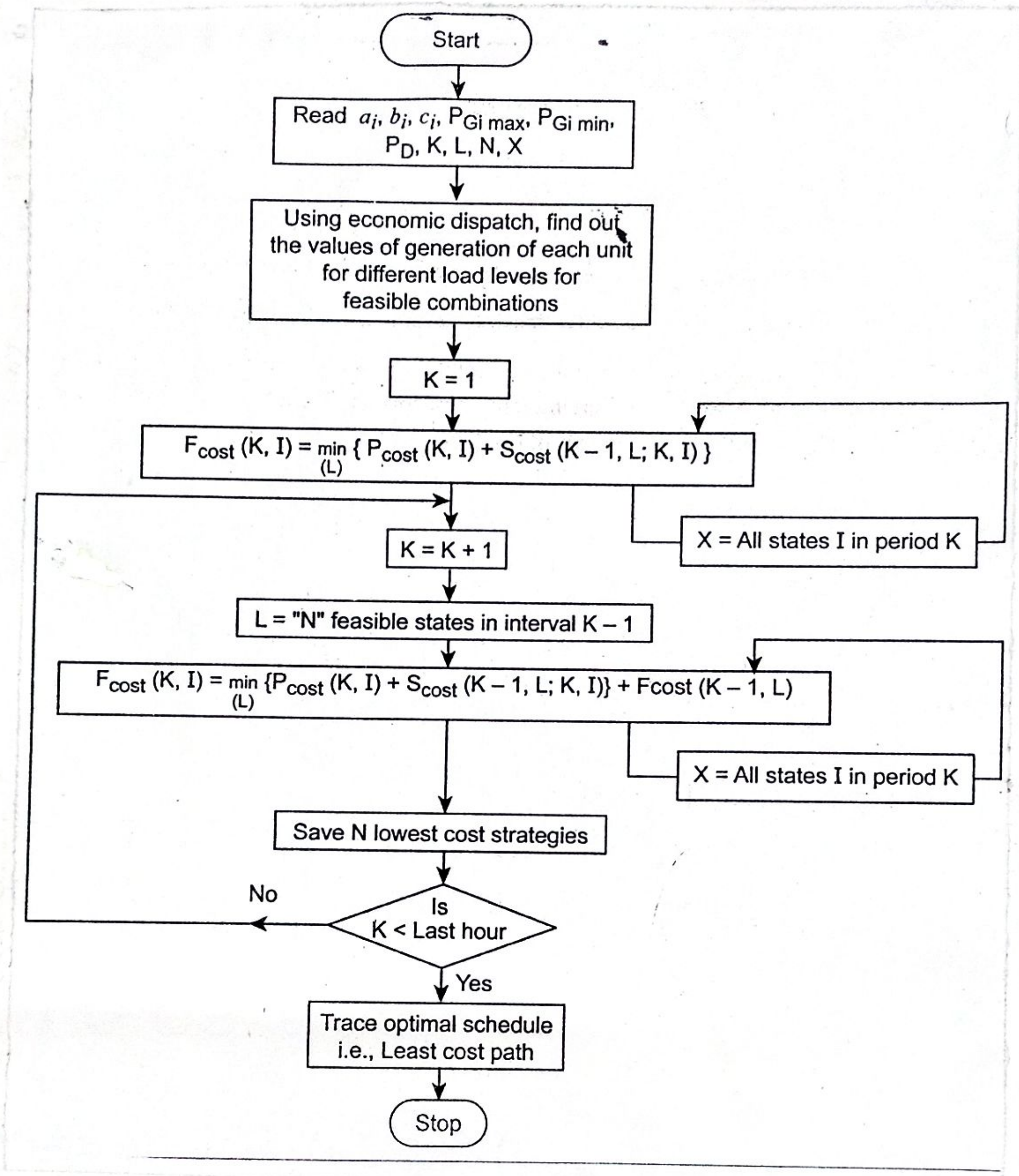
L = "N" feasible state in interval k-I

Let X be number of states to search each period.

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

Dynamic programming Algorithm with N=2 and X=3.





Flowchart of forward Dynamic programming method.

EE8702 - POWER SYSTEM OPERATION AND CONTROL

UNIT V

COMPUTER CONTROL OF POWER SYSTEMS

Need of computer control of power systems-concept of energy control centers and functions – PMU - system monitoring, data acquisition and controls - System hardware configurations - SCADA and EMS functions - state estimation problem – measurements and errors - weighted least square estimation - various operating states - state transition diagram.

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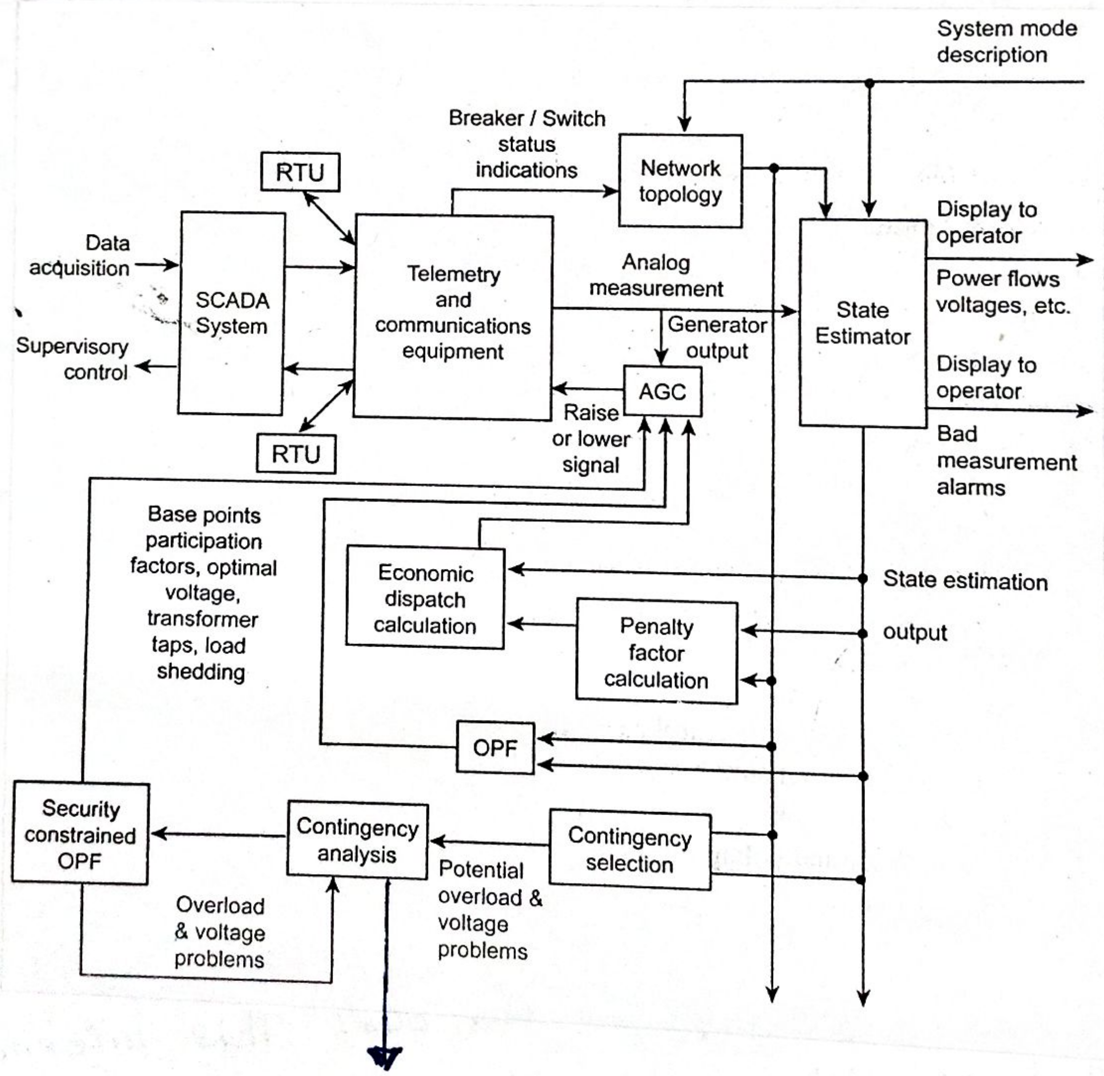
Energy Control Centre

When the 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.

The Energy Management performed at this control centre is called system control centre.



Display Alarms

Figure shows the information flow between various functions to be performed in an operations Control Centre. The centre gets information about the power system from remote terminal units (RTU). Based on the RTU, the Control Centre can transmit Control information such as raise / lower commands to the speed changer and in turn to the ~~gener~~ generators outputs. and open / close commands to circuit breakers (CBs)

The analog measurements of Generator outputs must be used directly by the Automatic Generation Control (AGC), whereas other data will be processed by State Estimator.

The objectives of AGC are

i) To hold frequency at (or) very close to a specified nominal value

ii) To maintain the correct value of interchange power between control values.

iii) To maintain each unit's generation at the most economic value.

In order to run the State estimator, we must know how the transmission lines are connected to the load and generator bus. This information is called as Network topology. The network topology programs must have a complete description of each

Substation and how the transmission lines are attached to the Substation equipment.

The electrical model of the transmission system is sent to the state estimation program together with the analog measurements. The output of the State estimator consists of all voltage magnitudes, and phase angles, transmission line MW and MVAR flows and busloads and generations calculated from the line flows.

These quanties together with the electrical model provide the basis for the economic dispatch program, contingency analysis program and generator corrective action program.

Real time operation are in two aspects.

a) Three level Control

i) Turbine-governor to adjust generation to balance changing load. Instantaneous Control

ii) Automatic Generation Control.

iii) Economic load dispatch.

b) Primary Voltage Control

i) Excitation Control regulate generator bus voltage

ii) Transmission Voltage Control devices include Static VAR Controllers, Shunt Capacitors, transformer taps, etc.

Energy control centre can perform the following functions.

i) Load forecasting - Estimating the future load in Advance

ii) power system planning → for generation
→ for Transmission and Distribution.

iii) Unit Commitment - Constraints are Spinning Reserve, minimum up time, minimum down time, hydro constraints and fuel constraints.

iv) Maintenance Scheduling - The planned maintenance outages of the generation equipment over a given future period.

v) Security Monitoring - Analyze the effects of outages contingencies on the steady state performance of the system.

vi) State Estimation - It produces best estimates of the power system state.

vii) Economic Dispatch - distribute the load among the generating units.

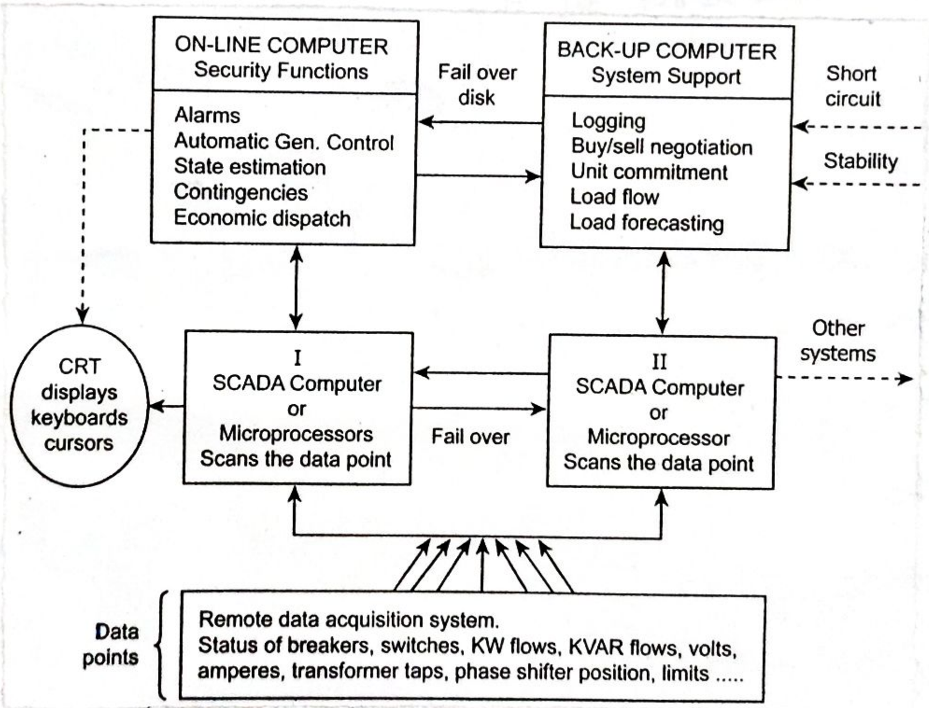
Supervisory Control and Data Acquisition (SCADA)

SCADA consists of a Master Station and RTUs linked by communication channel. The hardware components can be classified as

i) Process Computer and associated hardware at the Energy Control Centre.

ii) RTUs and the associated hardware at the remote Stations

iii) Communication equipment that links the RTUs and process computers at the master station.



Fig, Digital Computer Control and monitoring for power system.

All of the peripheral equipment is interfaced with the Computer through Input-Output microprocessors that have been programmed to communicate, as well as preprocess the analog information such as, Check for limits, convert to another System of units and So on.

The online computer is used to 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 b/w two computers.

Upon a fail over (or) Switch in Status Command, the Stored information of the Common disk is inserted in the memory of the on line Computer.

Software also allows for multilevel hardware failures and intialization of application programs. If failure occurs, critical operations and functions are maintained during either preventive or Corrective Maintenance.

The following Critical functions are Scanned every 2 Seconds.

i) All Status points Such as Switchgear position, Substation loads and Voltages, transformer tap positions and Capacitor loads.

ii) Tie-line flows and interchanges Selection.

iii) Generator loads, Voltage, operating limits and boiler capacity.

iv) Telemetry verification to detect failures and stores in the remote bilateral communication links between the digital computer and the remote equipment.

Components of SCADA

The components of SCADA are sensors, Relays Remote Terminal Units (RTU), master unit and communication links.

i) Sensors

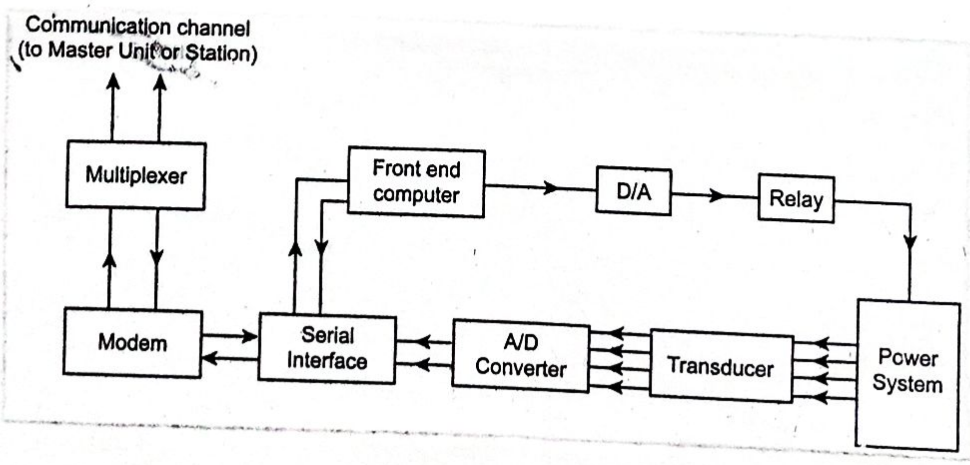
Analog and digital sensors are used to interface the systems.

ii) Relays

Relays are used to sense the abnormal conditions and protect the system.

iii) Remote Terminal Units (RTU).

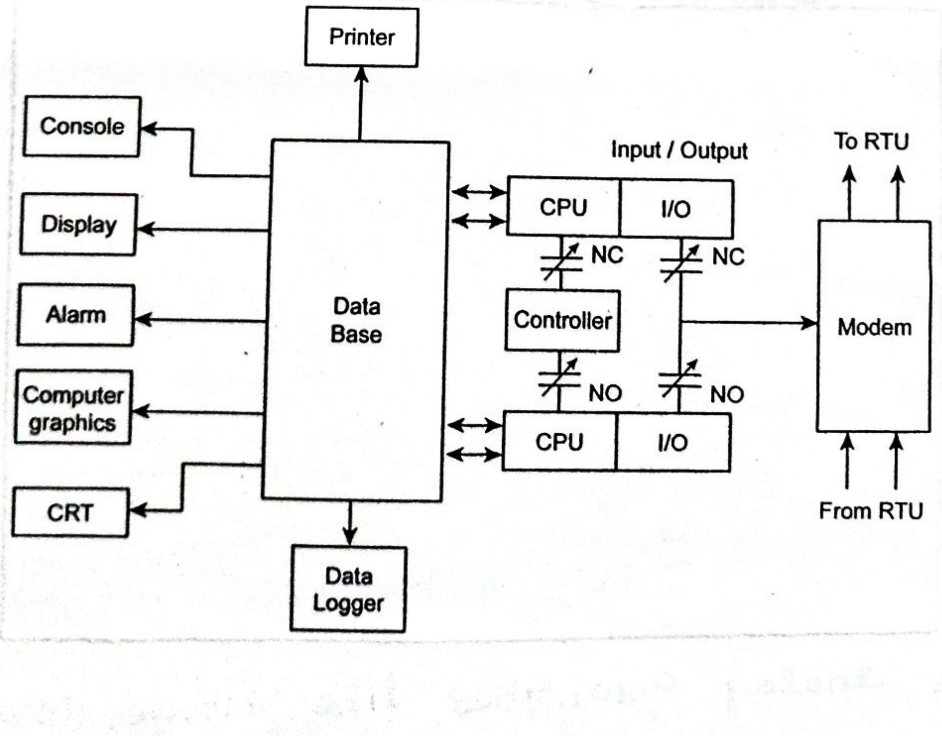
RTU's are microprocessors controlled electronic devices used to collect various datas and trasmit to SCADA system.



The anolog quantities like voltage, MW, MVAR and frequency measured at stations are converted into DC voltage (or) current signals, through transducer and fed to the A/D converters which convert the analog signals into digital form for transmission. The digital signal is fed to the front end computers and modems through the serial interface. MODEM sends the information to the master unit through multiplexer. MODEM will also receive commands from master units to control the station equipments through the control Relays.

iv) Master unit

Master unit is provided with a digital computer with associated interfacing devices and hardware to receive information from RTU (Remote terminal unit), process data and display salient information to the operator.



The master station scans the RTU sequentially and gather information such as voltage, current, line flows, generation and equipment status. This real time information is presented to the operator through CRT, computer graphic terminals, alarm panels, printer etc, so that the operator can supervise minute by minute and take control action to prevent system disturbances.

Functions of SCADA

i) Protection of equipment in a substation

ii) Fault Reporting

iii) Transformer Load balancing

iv) Voltage and Reactive Power Control

v) Equipment Condition monitoring

vi) Data Acquisition

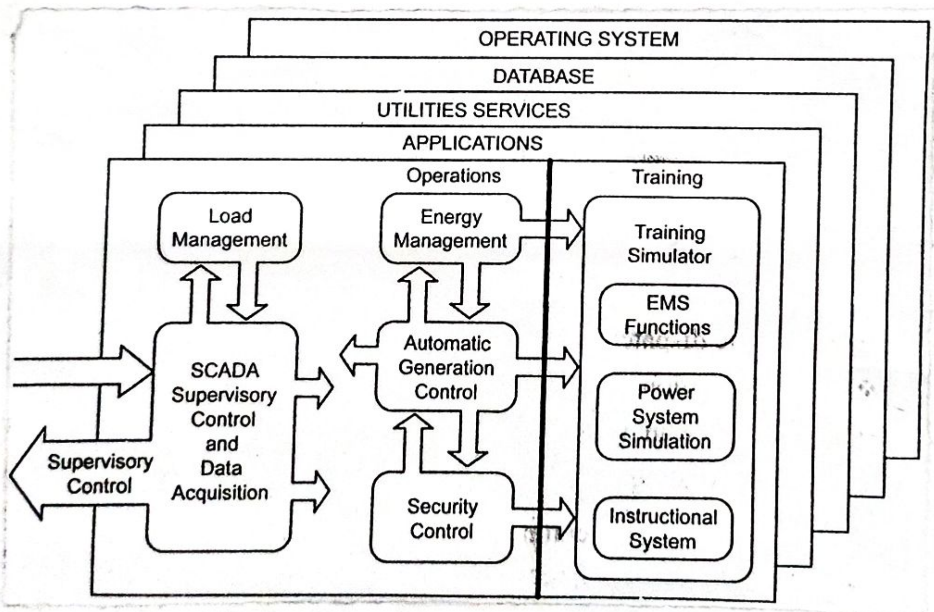
vii) Status Monitoring

viii) Data logging.

Energy Management System

Energy Management System is the process of ~~monito~~ monitoring, Coordinating and Controlling the generation, transmission and distribution of Electrical Energy. It is performed at centres called System Control Centres by a Computer System Called Energy Management System (EMS).

Data acquisition and remote Control is performed by the Computer System Called SCADA which forms the front end of EMS. The EMS Communicates with generating, transmission and distribution Systems through SCADA Systems.



Energy Management System Consists of Energy Management, AGC, Security Control, SCADA and Load Management.

Functions of Energy Management Systems

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 neighbouring System.
6) Transmission loss minimization.
7) Security Constrained dispatch.
8) Maintenance Scheduling
9) Production Cost Calculation.

Functions of Load Management

1) Data Acquisition
2) Monitoring, Sectionalizing switches and Creat circuit Configuration
3) Feeder Switch Control and preparing distribution map
4) Preparation of Switching orders
5) Customer meter reading
6) Fault location and Circuit topology Configuration
7) Service restoration
8) power factor and Voltage Control

9) Circuit Continuity Analysis

10) To Control Customer load through appliance Switching (Heater) and indirectly through Voltage Control.

Functions of AGC

1) hold frequency at (or) Very Close to a Specified nominal Value

2) To maintain the Correct value of interchange power between Control areas.

3) To maintain each unit's generation at the most economic Value.

Functions of Security Control

1) Network Topology Processor - To determine the model of the network.

2) State Estimator - To determine best estimate of the State of the System using real time Status and measurements

3) Power flow - To Calculate V, δ power flows for the Steady State Condition.

4) Contingency Analysis - To determine the events which are harmful to the System by determing the States.

5) Optimal Power flow - To optimize a Specified objective function by using Controller action.

6) preventive action - Before the occurrence of Contingency event, preventive action has to be taken.

7) Bus load forecasting - To forecast the load by using real time measurements.

Functions of SCADA

1) Data Acquisition - It provides telemetered measurements and status information to operator.

2) Supervisiory Control - on/off circuit breakers, raise/lower command to Generators etc.

3) Load Shedding - provides both automatic and operator-initiated tripping of load in response to System Emergencies.

4) Control of position of devices

5) Control and Monitoring functions.

State Transition Diagram and Control Strategies

A power system may be operated in several operating states. They are

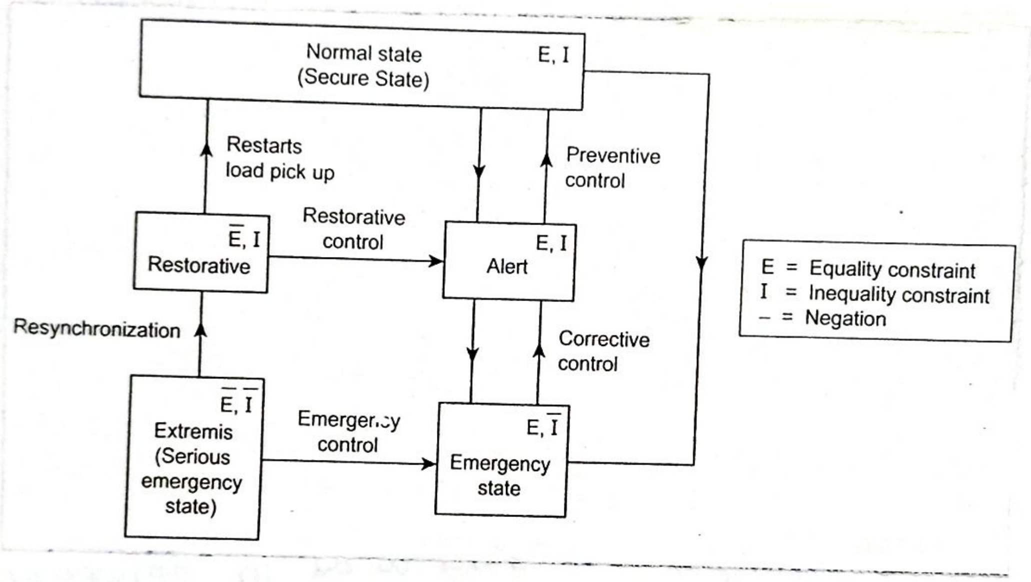
i) Normal State

ii) Alert State

iii) Emergency State

iv) Extremis State

v) Restorative State.



Fig, System States and transition.

i) Normal State

A System is said to be in normal, 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

If all the postulated Contingency States (frequency, bus voltage, Current flows in all transmission lines) are ~~sat~~ satisfied, then normal state is said to be in secure state.

If one of the postulated contingency states limits are violated, then normal state is moved to alert state.

ii) Alert State

When the security level falls below a certain level, the system may in Alert state.

The occurence of disturbance increases, the system may not satisfy all the Inequality constraints, then the system will push into Emergency state.

If a proper preventive action is taken, the system is bring back to secure state instead of Emergency state.

iii) 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.

In this state, the equality constraints are unchanged. By means of corrective control actions, the system will return to the normal state (or) alert state. Otherwise it will move into the extremis state.

iv) Extremis State

If there is no proper corrective action is taken in time, then the system is in Emergency State goes to Extremis State.

In this State, both operating and load Constraints are not satisfied. By means of any emergency control action the System is bring back to the Emergency State. otherwise the System is pushed to Restorative State.

V) Restorative State

From this State, the System may be brought back either to alert State or Secure State. The Secure State is a slow process. Hence in Certain Cases, first the System is brought back to alert State and then to the Secure State. This is done using restorative Control action.

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
Tieline System Interchange	Interchange Schedule.