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LECTURE NOTE

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UNIT-I

EconomicOperationofPowerSystems-1

Overview

- EconomicDistributionofLoads betweentheUnits ofaPlant
- GeneratingLimits
- EconomicSharingofLoadsbetweenDifferentPlants

AutomaticGenerationControl

- LoadFrequencyControl

CoordinationbetweenLFCandEconomicDispatch

A good business practice is the one in which the production cost is minimized without sacrificingthe quality. This is not any different in the power sector as well. The main aim here is to reduce theproduction cost while maintaining the voltage magnitudes at each bus. In this chapter we shall discuss theeconomic operation strategy along with the turbine-governor control that are required to maintain thepowerdispatcheconomically.

A power plant has to cater to load conditions all throughout the day, come summer or winter. It istherefore illogical to assume that the same level of power must be generated at all time. The powergeneration must vary according to the load pattern, which may in turn vary with season. Therefore theeconomic operation must take into account the load condition at all times. Moreover once the economicgeneration condition has been calculated, the turbine-governor must be controlled in such a way that thisgenerationconditionismaintained.Inthischapterweshalldiscussthesetwoaspects.

EconomicoperationofpowersystemsIn troduction:

One of the earliest applications of on-line centralized control was to provide a central facility, tooperate economically, several generating plants supplying the loads of the system. Modern integratedsystems have different types of generating plants, such as coal fired thermal plants, hydel plants, nuclearplants, oil and natural gas units etc. The capital investment, operation and maintenance costs are differentfordifferenttypesof plants.

Theoperationeconomicscanagainbesubdividedintotwoparts.

i) Problemof *economicdispatch*,whichdeals withdeterminingthepoweroutputofeachplant to meetthespecifiedload,suchthatthe overallfuelcostisminimized.

ii) Problemof*optimalpowerflow*,whichdealswithminimum–lossdelivery,whereinthepowerflow,isoptimizedtominimizelossesinthesystem.

Inthischapterweconsidertheproblemofeconomicdispatch.Duringoperationoftheplant,ageneratormaybeinone of thefollowingstates:

i) Basesupply without regulation:theoutputisaconstant.

ii) Basesupplywithregulation:outputpoweris regulatedbasedonsystemload.

iii) Automatic non-economic regulation: output level changes around a base setting as area control errorchanges.

iv) Automatic economic regulation: output level is adjusted, with the area load and area control error,while tracking an economic setting. Regardless of the units operating state, it has a contribution to theeconomicoperation,eventhoughitsoutputischangedfordifferentreasons.

Thefactorsinfluencingthecostofgenerationarethegeneratorefficiency,fuelcostandtransmission losses. The most efficient generator may not give minimum cost, since it may be located in aplace where fuel cost is high. Further, if the plant is located far from the load centers, transmission lossesmay be high and running the plant may become uneconomical. The economic dispatch problem basicallydeterminesthegenerationofdifferentplantstominimizetotaloperatingcost.

Modern generating plants like nuclear plants, geo-thermal plants etc, may require capital investment ofmillions of rupees. The economic dispatch is however determined in terms of fuel cost per unit powergenerated and doesnotinclude capital investment, maintenance,depreciation,start-up and shutdowncostsetc.

PerformanceCurvesInput-OutputCurve

Thisis thefundamentalcurveforathermalplant and isaplot oftheinput inBritish

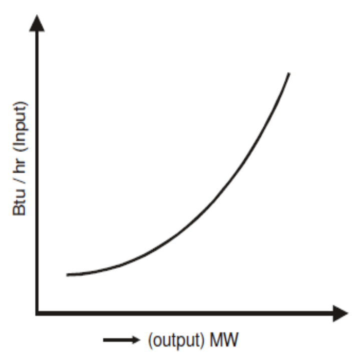


Fig 1: Input – output curve

Thermalunits(Btu)perhourversusthepoweroutput oftheplant inMWasshowninFig1

IncrementalFuelRateCurve

Theincrementalfuelrateisequaltoasmallchangeininputdividedbythecorrespondingchangeinoutput.

$$\text{Incremental fuel rate} = \frac{\Delta Input}{\Delta Output}$$

TheunitisagainBtu /KWh.AplotofincrementalfuelrateversustheoutputisshowninFig3

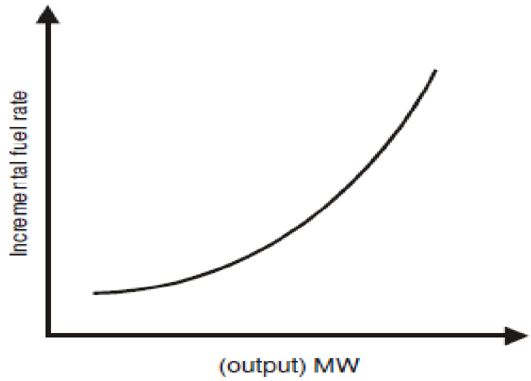


Fig 3: Incremental fuel rate curve

Incrementalcostcurve

Theincrementalcostistheproductofincrementalfuelrateandfuelcost(Rs/Btu)thecurveisshowninFig.4.T heunitof theincrementalfuelcostisRs/MWhr.

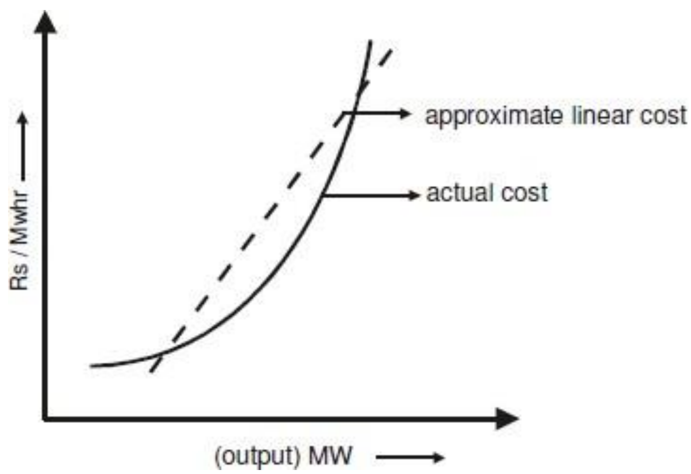


Fig4:Incrementalcostcurve

Ingeneral,thefuelcostFiforaplant,isapproximatedasaquadraticfunctionofthegeneratedoutputPGi.

Theincrementalfuelcostisgivenby

$$F_i = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \text{ Rs / h}$$

$$\frac{dF_i}{dP_{Gi}} = b_i + 2c_i P_{Gi} \quad \text{Rs / MWh}$$

The incremental fuel cost is a measure of how costly it will be produce an increment of power.The incremental production cost, is made up of incremental fuel cost plus the incremental cost of labor,water, maintenance etc. which can be taken to be some percentage of the incremental fuel cost, instead ofresorting to a rigorous mathematical model. The cost curve can be approximated by a linear curve. Whilethere is negligible operating cost for a hydel plant, there is a limitation on the power output possible. Inany plant, all units normally operate between PGmin, the minimum loading limit, below which it istechnicallyinfeasible tooperate aunitandPGmax,whichisthemaximumoutputlimit.

SectionI:EconomicOperationofPower System

- **EconomicDistributionofLoads betweentheUnits ofaPlant**
- **GeneratingLimits**
- **EconomicSharingofLoadsbetweenDifferentPlants**

In an early attempt at economic operation it was decided to supply power from the mostefficientplant at light load conditions. As the load increased, the power was supplied by thismost efficient planttill the pointofmaximum efficiency of this plantwas reached.With furtherincrease in load,the nextmost efficient plant would supply power till its maximum efficiency is reached. In this way the powerwouldbesuppliedbythemostefficienttotheleastefficientplanttoreachthepeakdemand.Unfortunately however, this method failed to minimize the total cost of electricity generation. We musttherefore search foralternative method which takes into account the total cost generation of all the unitsofaplantthatissupplyingaload.

EconomicDistributionofLoads betweentheUnits ofaPlant

To determine the economic distribution of a load amongst the different units of a plant, thevariable operating costs of each unit must be expressed in terms of its power output. The fuel cost is themain cost in a thermal or nuclear unit. Then the fuel cost must be expressed in terms of the power output.Other costs, such as the operation and maintenance costs, can also be expressed in terms of the poweroutput.Fixedcosts,suchas thecapitalcost,depreciationetc.,arenotincludedinthefuelcost.

The fuel requirement of each generator is given in terms of the Rupees/hour. Let us define theinput cost of an unit- *i*, $f_i$in Rs/h and the power output of the unit as P_i. Then the input cost can beexpressedintermsof thepoweroutputas

$$f_i = \frac{a_i}{2} P_i^2 + b_i P_i + c_i \quad \text{Rs/h} \qquad (1.1)$$

The operating cost given by the above quadratic equation is obtained by approximating the powerinMWversusthecostinRupees curve.Theincrementaloperatingcostofeachunitis thencomputedas

$$\lambda_i = \frac{df_i}{dP_i} = a_i P_i + b_i \quad \text{Rs/MWhr} \tag{1.2}$$

Letus now assume thatonly two units having differentincremental costs supply aload.Therewill be a reduction in cost if some amount of load is transferred from the unit with higher incremental costtotheunitwithlowerincrementalcost.Inthisfashion,theloadistransferredfromthelessefficientunitto the more efficient unit thereby reducing the total operation cost. The load transfer will continue till theincremental costs of both the units are same. This will be optimum point of operation for both the units.The above principle can be extended to plants with a total of N number of units. The total fuel cost willthenbethesummationof theindividual
fuelcostf_i,i= 1,..., Nofeachunit,i.e.,

$$f_T = f_1 + f_2 + \cdots + f_N = \sum_{k=1}^{N} f_k \tag{1.3}$$

Letus denotethatthetotalpowerthattheplantis requiredtosupplybyP_T,suchthat

$$P_T = P_1 + P_2 + \cdots + P_N = \sum_{k=1}^{N} P_k \tag{1.4}$$

WhereP_1,...,$P_N$arethepowersuppliedbythe$N$differentunits.
The objective is minimizing $f_T$for a given P_T. This can be achieved when the total difference df_Tbecomeszero,i.e.

$$df_T = \frac{\partial f_T}{\partial P_1} dP_1 + \frac{\partial f_T}{\partial P_2} dP_2 + \cdots + \frac{\partial f_T}{\partial P_N} dP_N = 0 \tag{1.5}$$

Nowsincethepowersuppliedisassumedtobeconstantwehave

$$dP_T = dP_1 + dP_2 + \cdots + dP_N = 0 \tag{1.6}$$

Multiplying(1.6) byλandsubtractingfrom(1.5) we get

$$\left(\frac{\partial f_T}{\partial P_1} - \lambda\right) dP_1 + \left(\frac{\partial f_T}{\partial P_2} - \lambda\right) dP_2 + \cdots + \left(\frac{\partial f_T}{\partial P_N} - \lambda\right) dP_N = 0 \tag{1.7}$$

Theequalityin(5.7)issatisfiedwheneachindividualtermgiveninbrackets iszero.Thisgives us

$$\frac{\partial f_T}{\partial P_i} - \lambda = 0, \quad i = 1, \ldots, N \qquad (1.8)$$

Alsothepartialderivativebecomesafullderivativesinceonlytheterm$f_i$of$f_T$varieswithP_i,i=1...N.

Wethenhave

$$\lambda = \frac{df_1}{dP_i} = \frac{df_2}{dP_2} = \cdots = \frac{df_N}{dP_N} \qquad (1.9)$$

GeneratingLimits

It is not always necessary that all the units of a plant are available to share a load. Some of theunits may be taken off due to scheduled maintenance. Also it is not necessary that the less efficient unitsare switched off during off peak hours. There is a certain amount of shut down and start up costsassociated with shutting down a unit during the off peak hours and servicing it back on-line during thepeak hours. To complicate the problem further, it may take about eight hours or more to restore the boilerof a unit and synchronizing the unit with the bus. To meet the sudden change in the power demand, it maytherefore be necessary to keep more units than it necessary to meet the load demand during that time. Thissafetymarginingenerationiscalledspinningreserve.

The optimal load dispatch problem must then incorporate this startup and shut down cost for withoutendangeringthesystemsecurity.

Thepowergenerationlimitofeachunitis thengivenbytheinequalityconstraints

$$P_{\min,i} \le P_i \le P_{\max,i}, \quad i = 1, \ldots, N \qquad (1.10)$$

The maximum limit $P_{Gmax}$is the upper limit of power generation capacity of each unit. On the other hand,the lower limit P_{Gmin}pertains to the thermal consideration of operating a boiler in a thermal or nucleargenerating station. An operational unit must produce a minimum amount of power such that the boilerthermalcomponentsarestabilizedatthe minimumdesignoperatingtemperature.

Example1

Considertwounitsofaplant thathavefuelcosts of

$$f_1 = \frac{0.8}{2}P_1^2 + 10P_1 + 25 \text{ Rs/h} \quad \text{and} \quad f_2 = \frac{0.7}{2}P_2^2 + 6P_2 + 20 \text{ Rs/h}$$

Thentheincremental costs willbe

$$\lambda_1 = \frac{df_1}{dP_1} = 0.8P_1 + 10 \text{ Rs/MWhrand} \quad \lambda_2 = \frac{df_2}{dP_2} = 0.7P_2 + 6 \text{ Rs/MWhr}$$

Ifthesetwounitstogethersupplyatotalof220MW,thenP_1=100MWandP_2=120MWwillresultinanincrementalcostof

$\lambda_1 = 80 + 10 = 90$ Rs/MWhr and $\lambda_2 = 84 + 6 = 90$ Rs/MWhr

Thisimpliesthattheincrementalcostsofboththeunitswillbesame,i.e.,thecostofoneextraMWofgenerationwillbe Rs.90/MWhr.Thenwe have

$f_1 = \frac{0.8}{2}100^2 + 10 \times 100 + 25 = 5025$ Rs/hand $f_2 = \frac{0.7}{2}120^2 + 6 \times 120 + 20 = 5780$ Rs/h

Andtotalcostofgenerationisp

$f_T = f_1 + f_2 = 10{,}805$ Rs/h

Nowassumethatweoperateinsteadwith$P1$=90MWand$P2$=130MW.Thentheindividualcostofeachunitwillbe

$f_1 = \frac{0.8}{2}90^2 + 10 \times 90 + 25 = 4{,}165$ Rs/hand $f_2 = \frac{0.7}{2}130^2 + 6 \times 130 + 20 = 6{,}175$ Rs/h

Andtotalcostofgenerationis

$f_T = f_1 + f_2 = 10{,}880$ Rs./h

This implies that an additional cost of Rs. 75 is incurred for each hour of operation with this non-optimalsetting. Similarly it can be shown that the load is shared equally by the two units, i.e. P_1= P_2= 110 MW,thenthetotalcostisagain10,880Rs/h.

Example2

Let us consider a generating station that contains a total number of three generating units. The fuel costsof theseunitsaregivenby

$f_1 = \frac{0.8}{2}P_1^2 + 10P_1 + 25$ Rs/h

$f_2 = \frac{0.7}{2}P_2^2 + 5P_2 + 20$ Rs/h

$f_3 = \frac{0.95}{2}P_3^2 + 15P_3 + 35$ Rs/h

Thegenerationlimitsof theunitsare

$30\text{ MW} \le P_1 \le 500\text{ MW}$

$30\text{ MW} \le P_2 \le 500\text{ MW}$

$30\text{ MW} \le P_3 \le 250\text{ MW}$

The total load that these units supply varies between 90 MW and 1250 MW. Assuming that all the threeunits are operational all the time,we have to compute the economicoperating settings as the loadchanges.

Theincrementalcostsof theseunitsare

$$\frac{df_1}{dP_1} = 0.8P_1 + 10$$ Rs/MWhr

$$\frac{df_2}{dP_2} = 0.7P_2 + 5$$ Rs/MWhr

$$\frac{df_3}{dP_3} = 0.95P_3 + 15$$ Rs/MWhr

Attheminimumloadtheincrementalcostoftheunits are

$$\frac{df_1}{dP_1} = \frac{0.8}{2}30^2 + 10 = 34$$ Rs/MWhr

$$\frac{df_2}{dP_2} = \frac{0.7}{2}30^2 + 5 = 26$$ Rs/MWhr

$$\frac{df_3}{dP_3} = \frac{0.95}{2}30^2 + 15 = 43.5$$ Rs/MWhr

Since units 1 and 3 have higher incremental cost, they must therefore operate at 30 MW each. Theincremental cost during this time will be due to unit-2 and will be equal to 26 Rs/MWhr. With thegeneration ofunits1 and 3 remaining constant, the generation ofunit-2isincreased till itsincrementalcost is equal to that of unit-1, i.e., 34 Rs/MWhr. This is achieved when P_2 is equal to 41.4286 MW, at atotalpowerof 101.4286MW.

An increase in the total load beyond 101.4286 MW is shared between units 1 and 2, till their incrementalcostsareequaltothatofunit-3,i.e.,43.5 Rs/MWhr.ThispointisreachedwhenP_1=41.875MWandP_2 = 55 MW. The total load that can be supplied at that point is equal to 126.875. From this point onwardsthe load isshared between the three unitsin such a way thatthe incremental costsof all the unitsaresame.Forexamplefora totalloadof200MW,from(5.4)and(5.9)we have

$$P_1 + P_2 + P_3 = 200$$

$$0.8P_1 + 10 = 0.7P_2 + 5$$

$$0.7P_2 + 5 = 0.95P_3 + 15$$

Solving the above three equations we get P_1= 66.37 MW, P_2= 80 MW and P_3= 50.63 MW and anincrementalcost(λ)of63.1Rs./MWhr.Inasimilarwaytheeconomicdispatchforvariousotherload settings are computed. The load distribution and the incremental costs are listed in Table 5.1 for varioustotalpowerconditions.

At a total load of 906.6964, unit-3 reaches its maximum load of 250 MW. From this point onwards then,the generation of this unit is kept fixed and the economic dispatch problem involves the other two units.Forexampleforatotalload of1000MW,wegetthefollowingtwoequationsfrom(1.4)and(1.9)

$$P_1 + P_2 = 1000 - 250$$

$$0.8P_1 + 10 = 0.7P_2 + 5$$

Solving which we getP_1= 346.67 MW and P_2= 403.33 MW and an incremental costof287.33Rs/MWhr. Furthermore, unit-2 reaches its peak output at a total load of 1181.25. Therefore any furtherincrease in the total load must be supplied by unit-1 and the incremental cost will only be borne by thisunit.Thepowerdistributioncurve isshowninFig.5.

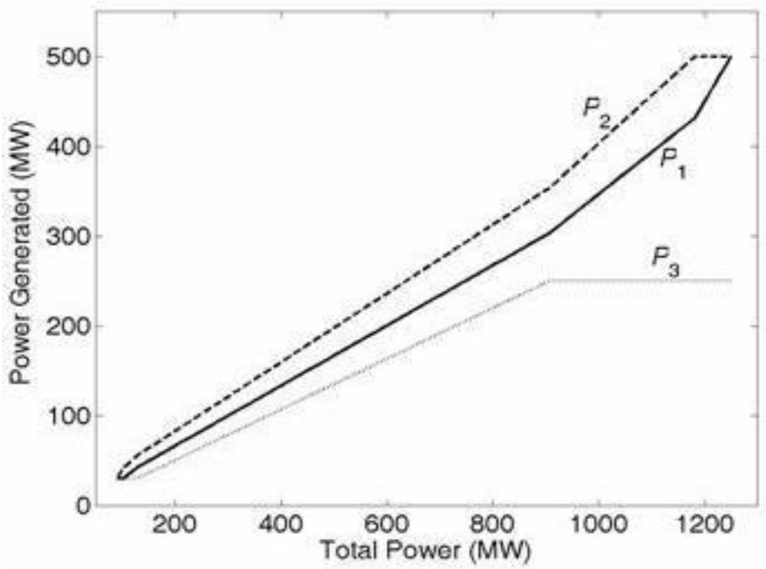


Fig5.Powerdistributionbetweentheunits ofExample2

Example3

Considertwogeneratingplantwithsamefuelcostandgeneration limits.Thesearegivenby

$$f_i = \frac{0.8}{2}P_i^2 + 10P_i + 25 \text{ Rs./h} \quad i = 1,2$$

$$100 \text{ MW} \le P_i \le 500 \text{ MW}, \quad i = 1,2$$

For a particular time of a year, the total load in a day varies as shown in Fig. 5.2. Also an additional costof Rs. 5,000 is incurred by switching of a unit during the off peak hours and switching it back on duringthe during the peak hours. We have to determine whether it is economical to have both units operationalallthetime.

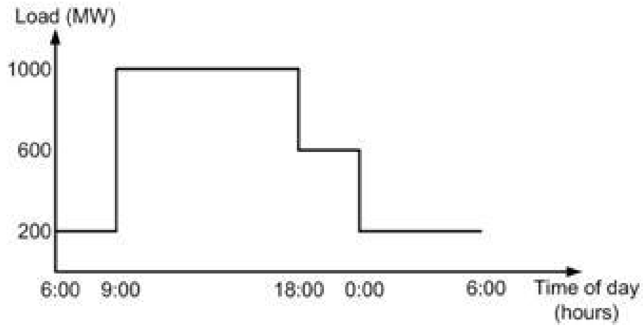


Fig.6.Hourly distributionofaloadfortheunits ofExample2

Since both the units have identical fuel costs, we can switch of any one of the two units during the offpeak hour. Therefore the cost of running one unit from midnight to 9 in the morning while delivering 200MWis

$$\left(\frac{0.8}{2}200^2+10\times 200+25\right)\times 9=162{,}225$$ Rs.

Adding thecostofRs.5,000fordecommissioning andcommissioningtheotherunitafterninehours,thetotalcostbecomesRs. 167,225.0

On theotherhand,ifbothheunitsoperateallthroughtheoffpeakhourssharing powerequally,then wegetatotalcostof

$$\left(\frac{0.8}{2}100^2+10\times 100+25\right)\times 9\times 2=90{,}450$$ Rs.

Whichis significantlylessthat thecost ofrunning oneunitalone?

Table1.1Loaddistributionandincrementalcostfortheunitsof<u>Example1</u>

P_T(MW)	P_1(MW)	P_2(MW)	P_3(MW)	λ(Rs./MWh)
90	30	30	30	26
101.4286	30	41.4286	30	34
120	38.67	51.33	30	40.93
126.875	41.875	55	30	43.5
150	49.62	63.85	36.53	49.7
200	66.37	83	50.63	63.1
300	99.87	121.28	78.85	89.9
400	133.38	159.57	107.05	116.7
500	166.88	197.86	135.26	143.5

600	200.38	236.15	163.47	170.3
700	233.88	274.43	191.69	197.1
800	267.38	312.72	219.9	223.9
906.6964	303.125	353.5714	250	252.5
1000	346.67	403.33	250	287.33
1100	393.33	456.67	250	324.67
1181.25	431.25	500	250	355
1200	450	500	250	370
1250	500	500	250	410

DERIVATIONOFTRANSMISSIONLOSSFORMULA:

AnaccuratemethodofobtaininggenerallosscoefficientshasbeenpresentedbyKroc.Themethodiselaborateandasimplerapproachispossiblebymakingthefollowingassumptions:

(i) Allloadcurrentshavesamephaseangle withrespecttoacommonreference

(ii) TheratioX/Risthesameforallthenetworkbranches

Considerthe simple case oftwo generating plantsconnected to an arbitrary numberofloadsthrough atransmissionnetwork asshowninFiga

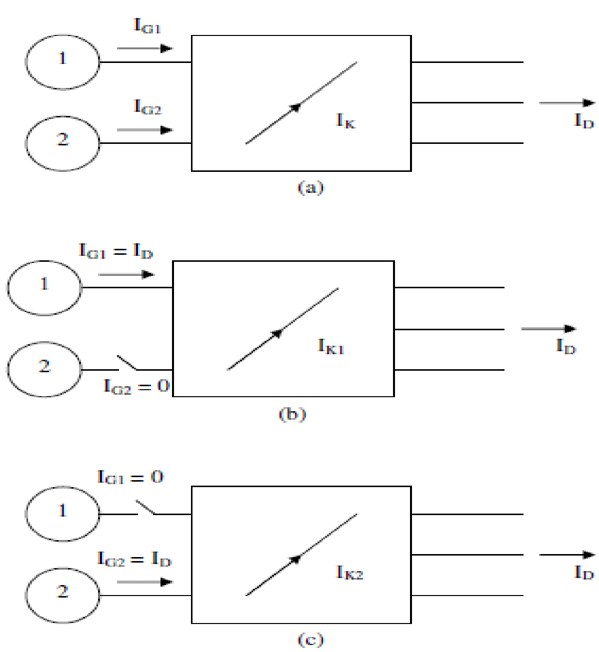


Fig.2.1Twoplantsconnectedtoanumberofloadsthroughatransmissionnetwork

Let"sassumethatthetotalloadissuppliedbyonlygenerator1asshowninFig8.9b.LetthecurrentthroughabranchKin the networkbeIK1.We define

$$N_{K1} = \frac{I_{K1}}{I_D}$$

It is tobenotedthat IG1 = IDinthis case.Similarlywithonlyplant2 supplyingtheloadCurrentID,asshowninFig8.9c,wedefine

$$N_{K2} = \frac{I_{K2}}{I_D}$$

NK1 and NK2 are called current distribution factors and their values depend on the impedances of thelines and the network connection. They are independent of ID. When both generators are supplying theload,thenbyprincipleof superpositionIK =NK1IG1+NK2IG2

Where IG1, IG2 are the currents supplied by plants 1 and 2 respectively, to meet the demand ID. Becauseof the assumptions made, IK1 and ID have same phase angle, as do IK2 and ID. Therefore, the currentdistributionfactorsarerealratherthancomplex.Let

$$I_{G1} = |I_{G1}|\angle\sigma_1 \text{ and } I_{G2} = |I_{G2}|\angle\sigma_2 .$$

Where$\sigma_1$and$\sigma_2$arephaseanglesofIG1andIG2withrespecttoacommonreference.Wecanwrite

$$|I_K|^2 = \left(N_{K1}|I_{G1}|\cos\sigma_1 + N_{K2}|I_{G2}|\cos\sigma_2\right)^2 + \left(N_{K1}|I_{G1}|\sin\sigma_1 + N_{K2}|I_{G2}|\sin\sigma_2\right)^2$$

$$= \begin{matrix} N_{K1}{}^2|I_{G1}|^2\left[\cos^2\sigma_1 + \sin^2\sigma_1\right] + N_{K2}{}^2|I_{G2}|^2\left[\cos^2\sigma_2 + \sin^2\sigma_2\right] \\ + 2\left[N_{K1}|I_{G1}|\cos\sigma_1 N_{K2}|I_{G2}|\cos\sigma_2 + N_{K1}|I_{G1}|\sin\sigma_1 N_{K2}|I_{G2}|\sin\sigma_2\right] \end{matrix}$$

$$= N_{K1}{}^2|I_{G1}|^2 + N_{K2}{}^2|I_{G2}|^2 + 2N_{K1}N_{K2}|I_{G1}||I_{G2}|\cos(\sigma_1 - \sigma_2)$$

$$\text{Now } |I_{G1}| = \frac{P_{G1}}{\sqrt{3}|V_1|\cos\phi_1} \text{ and} |I_{G2}| = \frac{P_{G2}}{\sqrt{3}|V_2|\cos\phi_2}$$

Where PG1, PG2 are three phase real power outputs of plant1 and plant 2; V1, V2 are the line to line busvoltagesof theplantsand Φ_1 and$\Phi_2$arethepowerfactorangles.

Thetotaltransmissionlossinthesystemisgivenby

$$P_L = \sum_K 3|I_K|^2 R_K$$

Wherethesummationis takenoverallbranchesofthenetworkandRK isthebranchresistance.Substitutingweget

$$P_L = \frac{P_{G1}^{\,2}}{|V_1|^2(\cos\phi_1)^2}\sum_K N_{K1}^{\,2}R_K + \frac{2P_{G1}P_{G2}\cos(\sigma_1-\sigma_2)}{|V_1||V_2|\cos\phi_1\cos\phi_2}\sum_K N_{K1}N_{K2}R_K + \frac{P_{G2}^{\,2}}{|V_2|^2(\cos\phi_2)^2}\sum_K N_{K2}^{\,2}R_K$$

$$P_L = P_{G1}^{\,2}B_{11} + 2P_{G1}P_{G2}B_{12} + P_{G2}^{\,2}B_{22}$$

where $$B_{11} = \frac{1}{|V_1|^2(\cos\phi_1)^2}\sum_K N_{K1}^{\,2}R_K$$

$$B_{12} = \frac{\cos(\sigma_1-\sigma_2)}{|V_1||V_2|\cos\phi_1\cos\phi_2}\sum_K N_{K1}N_{K2}R_K$$

$$B_{22} = \frac{1}{|V_2|^2(\cos\phi_2)^2}\sum_K N_{K2}^{\,2}R_K$$

Theloss–coefficientsarecalledtheB– coefficientsandhaveunitMW^{-1}

Forageneralsystemwithnplants thetransmission lossis expressedas

$$P_L = \frac{P_{G1}^{\,2}}{|V_1|^2(\cos\phi_1)^2}\sum_K N_{K1}^{\,2} + \ldots\ldots + \frac{P_{Gn}^{\,2}}{|V_n|^2(\cos\phi_n)^2}\sum_K N_{Kn}^{\,2}R_K + 2\sum_{\substack{p,q=1\\ p\neq q}}^{n}\frac{P_{GP}P_{Gq}\cos(\sigma_p-\sigma_q)}{|V_p||V_q|\cos\phi_p\cos\phi_q}\sum_k N_{KP}N_{Kq}R_K$$

Inacompactform

$$P_L = \sum_{p=1}^{n}\sum_{q=1}^{n} P_{Gp}B_{Pq}P_{Gq}$$

$$B_{Pq} = \frac{\cos(\sigma_p-\sigma_q)}{|V_p||V_q|\cos\phi_P\cos\phi_q}\sum_K N_{KP}N_{Kq}R_K$$

B – Coefficients can be treated as constants over the load cycle by computing them at average operatingconditions,withoutsignificantlossof accuracy.

EconomicSharingofLoadsbetweenDifferentPlants

So far we have considered the economic operation of a single plant in which we have discussedhowaparticularamountofloadissharedbetweenthedifferentunitsofaplant.Inthisproblemwedidnot have to consider the transmission line losses and assumed that the losses were a part of the loadsupplied.Howeverifnowconsiderhowaloadisdistributedbetweenthedifferentplantsthatarejoined bytransmissionlines,thenthelinelosseshavetobeexplicitlyincludedintheeconomicdispatchproblem.Inthissectio nweshalldiscussthisproblem.

Whenthetransmissionlossesareincludedintheeconomicdispatchproblem

$$P_T = P_1 + P_2 + \cdots + P_N - P_{LOSS} \quad (2.1)$$

$$0 = dP_1 + dP_2 + \cdots + dP_N - dP_{LOSS} \quad (2.2)$$

Where$P_{LOSS}$is thetotallineloss.Since$P_T$is assumedtobeconstant,wehave

$$dP_{LOSS} = \frac{\partial P_{LOSS}}{\partial P_1} dP_1 + \frac{\partial P_{LOSS}}{\partial P_2} dP_2 + \cdots + \frac{\partial P_{LOSS}}{\partial P_N} dP_N \quad \text{................(2.3}$$

IntheaboveequationdP_{LOSS}includesthepowerloss dueto everygenerator,i.e.,

Also minimumgenerationcostimpliesdf_T= 0asgivenin(1.5).Multiplying both(2.2)and (2.3)byλ andcombiningweget

$$0 = \left(\lambda \frac{\partial P_{LOSS}}{\partial P_1} - \lambda\right) dP_1 + \left(\lambda \frac{\partial P_{LOSS}}{\partial P_2} - \lambda\right) dP_2 + \cdots + \left(\lambda \frac{\partial P_{LOSS}}{\partial P_N} - \lambda\right) dP_N \quad (2.4)$$

$$0 = \sum_{i=1}^{N} \left(\frac{\partial f_T}{\partial P_i} + \lambda \frac{\partial P_{LOSS}}{\partial P_i} - \lambda \right) dP_i \quad (2.5)$$

Adding(2.4)with(1.5)weobtain

$$\frac{\partial f_T}{\partial P_i} + \lambda \frac{\partial P_{LOSS}}{\partial P_i} - \lambda = 0, \quad i = 1, \ldots, N \quad (2.6)$$

Theaboveequationsatisfieswhen

$$\frac{\partial f_T}{\partial P_i} = \frac{df_T}{dP_i}, \quad i = 1, \ldots, N$$

Againsince

$$\lambda = \frac{df_1}{dP_i} L_1 = \frac{df_2}{dP_2} L_2 = \cdots = \frac{df_N}{dP_N} L_N \quad (2.7)$$

From(2.6)weget

$$L_i = \frac{1}{1 - \partial P_{LOSS} / \partial P_i}, \quad i = 1, \ldots, N \quad (2.8)$$

Where$L_i$iscalledthe**penaltyfactor** ofload- *i*andis givenby

$$P = \begin{bmatrix} P_1 & P_2 & \cdots & P_N \end{bmatrix}^T$$

Consideranareawith*N*numberofunits.Thepowergeneratedaredefinedbythevector

$$P_{LOSS} = P^T BP \quad (2.9)$$

Thenthetransmissionlossesareexpressedingeneralas Whe

re*B*isasymmetricmatrixgivenby

$$B = \begin{bmatrix} B_{11} & B_{12} & \cdots & B_{1N} \\ B_{12} & B_{22} & \cdots & B_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ B_{1N} & B_{2N} & \cdots & B_{NN} \end{bmatrix}$$

The elements $B_{ij}$of the matrix B are called the **loss coefficients.** These coefficients are not constant butvary with plant loading. However for the simplified calculation of the penalty factor $L_i$these coefficientsareoftenassumedtobeconstant.

When the incremental cost equations are linear, we can use analytical equations to find out the economicsettings. However in practice, the incremental costs are given by nonlinear equations that may evencontainnonlinearities.Inthatcaseiterativesolutions arerequiredtofindtheoptimalgeneratorsettings.

UNIT-

IIHYDROTHERMALSCHEDULINGLON

G

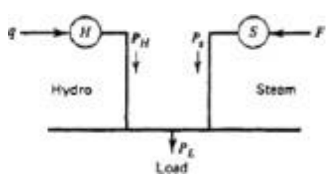
Long-RangeHydro-Scheduling:

The long-range hydro-scheduling problem involves the long-range forecasting of water availabilityand the scheduling of reservoir water releases (i.e., “drawdown”) for an interval of time that depends onthe reservoir capacities. Typical long range scheduling goes anywhere from 1 wk to 1 yr or several years.For hydro schemes with a capacity of impounding water over several seasons, the long-range probleminvolvesmeteorologicalandstatisticalanalyses.

Short-RangeHydro-Scheduling

Short-range hydro-scheduling (1 day to I wk) involves the hour-by-hour scheduling of all generationon a system to achieve minimum production cost for the given time period. In such a scheduling problem,the load, hydraulic inflows, and unit availabilities are assumed known. A set of starting conditions (e.g.,reservoir levels) is given, and the optimal hourly schedule that minimizes a desired objective, whilemeetinghydraulic steam,andelectric systemconstraints,issought.

Hydrothermalsystemswherethehydroelectricsystemisbyfarthelargestcomponentmaybescheduled by economically scheduling the system to produce the minimum cost for the thermal system.The schedules are usually developed to minimize thermal generation production costs, recognizing all thediversehydraulic constraintsthatmayexist



2.8 OPTIMAL POWER FLOW PROBLEM: Basic approach to the solution of this problem is toincorporate the power flow equations as essential constraints in the formal establishment of theoptimizationproblem.Thisgeneralapproachisknownastheoptimalpowerflow.Anotherapproachisbyusing loss-formula method. Different techniques are: 1) the lambda-iteration method 2) Gradient methodsof economic dispatch 3) Newton's method 4) Economic dispatch with piecewise linear cost functions 5)Economicdispatchusingdynamic programming

UNIT–III

MODELINGOFTURBINE,GENERATORANDAUTOMATICC ONTROLLERSMODELINGOF TURBINE

Introduction

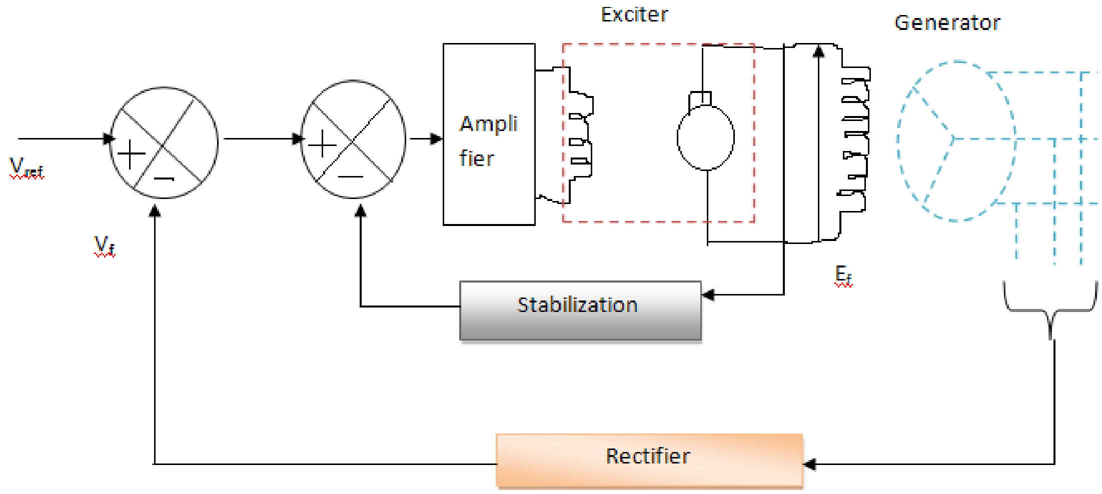
The main objective of power system operation and control is to maintain continuoussupply of powerwith an acceptable quality, to all the consumers in the system. The system will be in equilibrium, whenthere is a balance between the power demand and the power generated. As the power in AC form has realandreactivecomponents:therealpowerbalance;aswellasthereactivepowerbalanceistobeachieved.

There are two basic control mechanisms used to achieve reactive power balance (acceptable voltageprofile) and real power balance (acceptable frequency values). The former is called the automatic voltageregulator (AVR) and the latter is called the automatic load frequency control (ALFC) or automaticgenerationcontrol(AGC).

GeneratorVoltageControlSystem

The voltage of the generatoris proportional to the speed and excitation (flux) ofthe generator.Thespeedbeingconstant,theexcitationisusedtocontrolthevoltage.Therefore,thevoltagecontrolsystemisalsocalledasexcitationcontrolsystemorautomaticvoltageregulator(AVR).

For the alternators, the excitation is provided by a device (another machine or a static device) calledexciter. For a large alternator the exciter may be required to supply a field current of as large as 6500A at500V and hence the exciter is a fairly large machine. Depending on the way the dc supply is given to thefield winding of the alternator (which is on the rotor), the exciters are classified as: i) DC Exciters; ii) ACExciters;andiii) Static Exciters.Accordingly,several standard block diagramsare developed by theIEEE working group to represent the excitation system. A schematic of an excitation control system isshowninFig2.1.



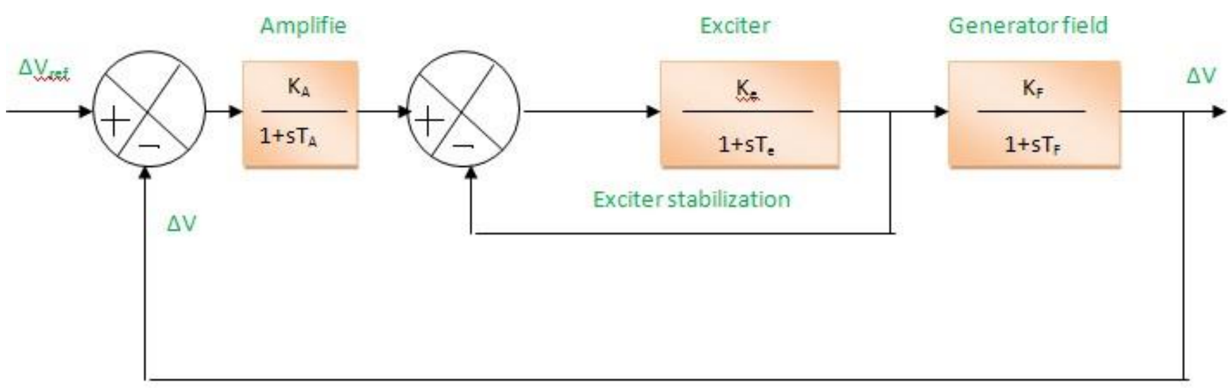
A schematic of excitation (voltage) control system

Fig2.1:AschematicofExcitation(Voltage)ControlSystem.

A simplified block diagram of the generator voltage control system is shown in Fig2.2.The generatorterminal voltage Vt is compared with a voltage reference Vref to obtain a voltage error signal _V. Thissignal is applied to the voltage regulatorshown as a blockwith transferfunction KA/ (1+TAs). Theoutput of the regulator is then applied to exciter shown with a block of transfer function Ke/ (1+Tes). Theoutputof the excitere.m.fisthen applied to the field winding which adjuststhe generatorterminalvoltage. The generator field can be represented by a block with a transfer function KF/ (1+sTF). The totaltransferfunctionis

$$\frac{\Delta V}{\Delta V_{ref}} = \frac{G(s)}{1+G(s)} \quad \text{where,} \quad G(s) = \frac{K_A K_e K_F}{(1+sT_A)(1+sT_e)(1+sT_F)}$$

The stabilizing compensator shown in the diagram is used to improve the dynamic response of the exciter.The input to this block is the exciter voltage and the output is a stabilizing feedback signal to reduce theexcessiveovershoot.



A simplified block diagram of voltage (excitation) control system

***Fig2.2*:AsimplifiedblockdiagramofVoltage(Excitation)ControlSystem.**

PerformanceofAVR Loop

The purpose of the AVR loop is to maintain the generator terminal voltage with inacceptable values. Astatic accuracy limit in percentage is specified for the AVR, so that the terminal voltage is maintainedwithin that value. For example, if the accuracy limit is 4%, then the terminal voltage must be maintainedwithin4% of thebasevoltage.

The performance of the AVR loop is measured by its ability to regulate the terminal voltage of thegenerator within prescribed static accuracy limit with an acceptable speed of response. Suppose the staticaccuracy limit is denoted by Ac in percentage with reference to the nominal value. The error voltage is tobelessthan(Ac/100) |Vref.Fromtheblockdiagram,for asteadystateerrorvoltage

$$\Delta e = \Delta|V|_{ref} - \Delta|V|_t < \frac{Ac}{100}\Delta|V|_{ref}$$

$$\Delta e = \Delta|V|_{ref} - \Delta|V|_t = \Delta|V|_{ref} - \frac{G(s)}{1+G(s)}\Delta|V|_{ref}$$

$$= \{1 - \frac{G(s)}{1+G(s)}\}\Delta|V|_{ref}$$

$$\Delta e = \{1 - \frac{G(s)}{1+G(s)}\}\Delta|V|_{ref} = \{1 - \frac{G(0)}{1+G(0)}\}\Delta|V|_{ref}$$

$$= \frac{1}{1+G(0)}\Delta|V|_{ref} = \frac{1}{1+K}\Delta|V|_{ref}$$

Forconstantinputcondition,($s \to 0$)

Where, K=G(0)istheopenloopgainoftheAVR.Hence,

$$\frac{1}{1+K}\Delta|V|_{ref} < \frac{Ac}{100}\Delta|V|_{ref} \quad \text{or} \quad K > \{\frac{100}{Ac} - 1\}$$

AutomaticLoadFrequencyControl

The ALFC is to control the frequency deviation by maintaining the real power balance in the system. ThemainfunctionsoftheALFCaretoi)tomaintainthesteadyfrequency;ii)controlthetie-lineflows;and

iii) distribute the load among the participating generating units. The control (input) signals are the tie-linedeviation ΔPtie (measured from the tie line flows), and the frequency deviation Δf (obtained by measuringtheangledeviationΔδ).TheseerrorsignalsΔfandΔPtieareamplified,mixedandtransformedtoareal power signal, which then controls the valve position. Depending on the valve position, the turbine (primemover) changes its output power to establish the real power balance. The complete control schematic isshowninFig2.3

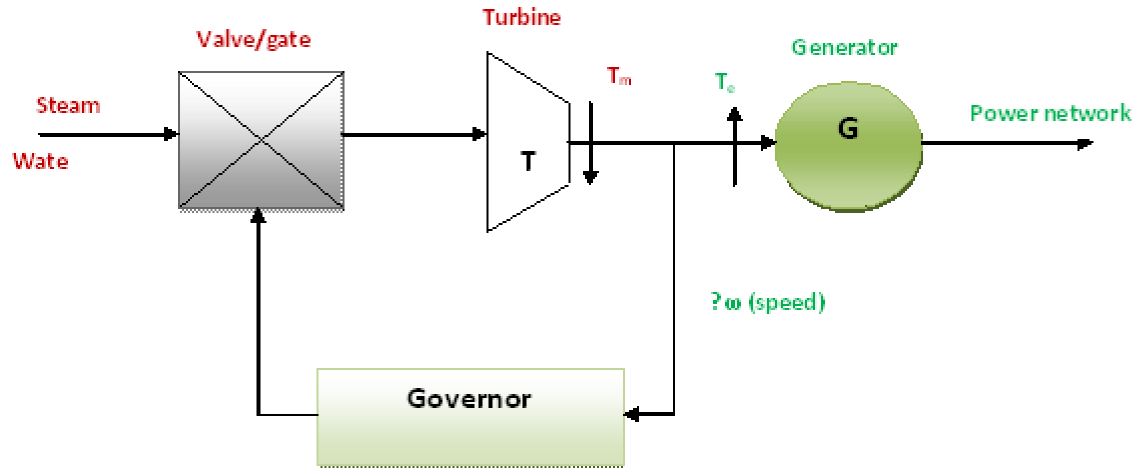


Fig2.3.TheSchematicrepresentationofALFC system

For the analysis, the models for each of the blocks in Fig2 are required. The generator and the electricalload constitute the power system. The valve and the hydraulic amplifier represent the speed governingsystem.Usingtheswingequation,the generatorcanbemodeledby

$$\frac{2Hd^2\Delta\delta}{\omega_s dt^2} = \Delta P_m - \Delta P_e$$

Expressingthespeeddeviationinpu,

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}(\Delta P_m - \Delta P_e)$$

ThisrelationcanberepresentedasshowninFig2.4.

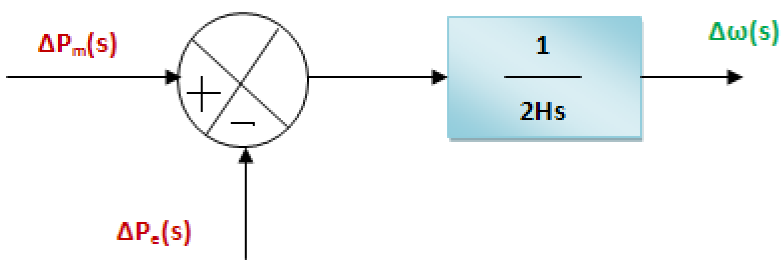


Fig2.4.TheblockdiagramrepresentationoftheGenerator

The load on the system is composite consisting of a frequency independent component and a frequency dependent component. The load can be written as $\Delta P_e = \Delta P_0 + \Delta P_f$ where, ΔP_e is the change in the load; ΔP_0 is the frequency independent load component; ΔP_f is the frequency dependent load component. $\Delta P_f = D\Delta\omega$ where, D is called frequency characteristic of the load (also called as damping constant) expressed in percent change in load for 1% change in frequency. If D=1.5%, then a 1% change in frequency causes 1.5% change in load. The combined generator and the load (constituting the power system) can then be represented as shown in Fig2.5

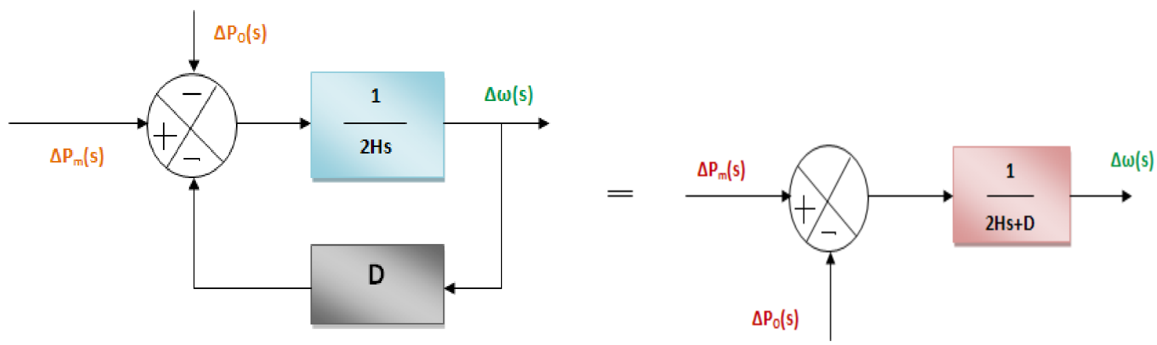
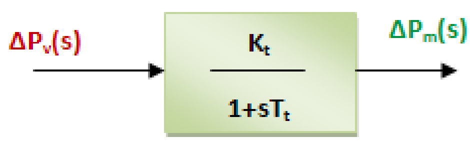


Fig2.5.The blockdiagramrepresentationofthe Generatorandload

TheturbinecanbemodeledasafirstorderlagasshownintheFig2.6



$$G_t(s) = \frac{\Delta P_m(s)}{\Delta P_V(s)} = \frac{K_t}{1+sT_t}$$

Fig2.6.Theturbinemodel

Gt(s)istheTFoftheturbine;ΔPV(s)isthechangeinvalveoutput(duetoaction).

ΔPm(s)isthe change in the turbine outputthe governorcan similarlymodeled as shown in Fig2.7.

Theoutputof the governorisby

$\Delta P_g = \Delta P_{ref} - \frac{\Delta\omega}{R}$ where ΔP_{ref} is the reference set power, and $\Delta\omega/R$ is the power given by governor speed characteristic. The hydraulic amplifier transforms this signal ΔP_g into valve/gate position corresponding to a power ΔP_V. Thus $\Delta P_V(s) = (K_g/(1+sT_g))\Delta P_g(s)$.

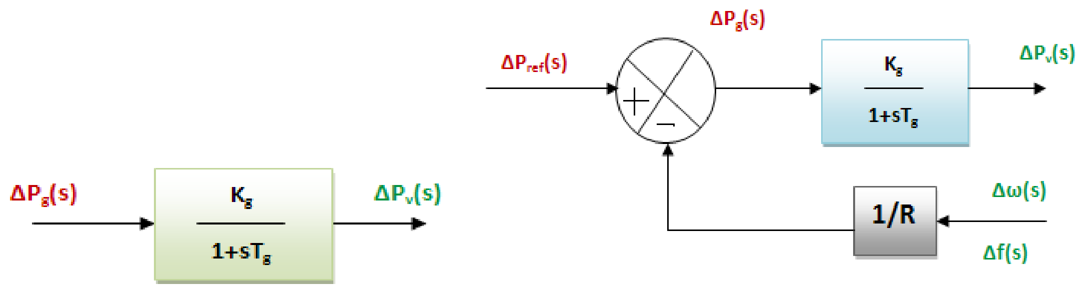


Fig2.7:The blockdiagramrepresentationofthe Governor

AlltheindividualblockscannowbeconnectedtorepresentthecompleteALFCloopasShowninFig5.1

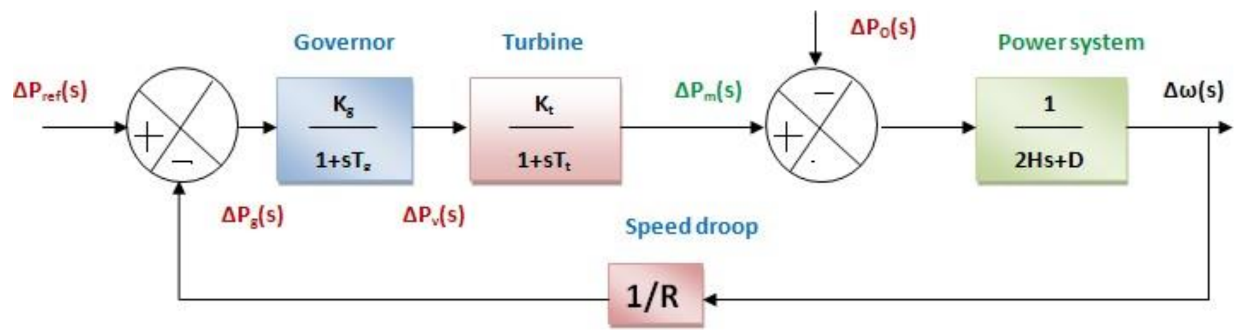


Fig2.8:Theblockdiagramrepresentationofthe ALFC.

2.2SteadystatePerformanceoftheALFCLoop:

Inthesteadystate,theALFCisin„open"state,andtheoutputisobtainedbysubstitutingS→0intheTF.

WithS→0,

2.4 Steady State Performance of the ALFC Loop

In the steady state, the ALFC is in 'open' state, and the output is obtained by substituting $s \to 0$ in the TF.

With $s \to 0$, Gg(s) and Gt(s) become unity, then, (note that $\Delta P_m = \Delta P_T = \Delta P_G = \Delta P_e = \Delta P_D$; That is turbine output = generator/electrical output = load demand)

$$\Delta P_m = \Delta P_{ref} - (1/R)\Delta\omega \quad \text{or} \quad \Delta P_m = \Delta P_{ref} - (1/R)\Delta f$$

When the generator is connected to infinite bus ($\Delta f = 0$, and $\Delta V = 0$), then $\Delta P_m = \Delta P_{ref}$.

If the network is finite, for a fixed speed changer setting ($\Delta Pref = 0$), then

$$\Delta P_m = -(1/R)\Delta f \text{ or } \quad \Delta f = -R\, \Delta P_m.$$

If the frequency dependent load is present, then

$$\Delta P_m = \Delta P_{ref} - (1/R + D)\Delta f \quad \text{or} \quad \Delta f = \frac{-\Delta Pm}{D + 1/R}$$

If there are more than one generator present in the system, then

$$\Delta P_{m.\,eq} = \Delta P_{ref.eq} - (D + 1/R_{eq})\Delta f$$

where,

$$\Delta P_{m.\,eq} = \Delta P_{m1} + \Delta P_{m2} + \Delta P_{m.3} + \ldots.$$

$$\Delta P_{ref.\,eq} = \Delta P_{ref1} + \Delta P_{ref2} + \Delta P_{ref3} + \ldots..$$

$$1/R_{eq} = (1/R_1 + 1/R_2 + 1/R_2 + \ldots.)$$

The quantity $\beta = (D + 1/R_{eq})$ is called the area frequency (bias) characteristic (response) or simply the stiffness of the system.

2.5 Concept of AGC (Supplementary ALFC Loop)

The ALFC loop shown in Fig2.8, is called the primary ALFC loop. It achieves the primary goal of real power balance by adjusting the turbine output ΔP_m to match the change in load demand ΔP_D. All the participating generating units contribute to the change in generation. But a change in load results in a steady state frequency deviation Δf. The restoration of the frequency to the nominal value requires an additional control loop called the supplementary loop. This objective is met by using integral controller which makes the frequency deviation zero. The ALFC with the supplementary loop is generally called the AGC. The block diagram of an AGC is shown in Fig2.9. The main objectives of AGC are i) to regulate the frequency (using both primary and supplementarycontrols);ii)andtomaintaintthescheduledtie-lineflows.Asecondaryobjectiveofthe

AGCistodistributetherequiredchangeingenerationamongtheconnectedgeneratingunitseconomically(toobtainleastoperatingcosts).

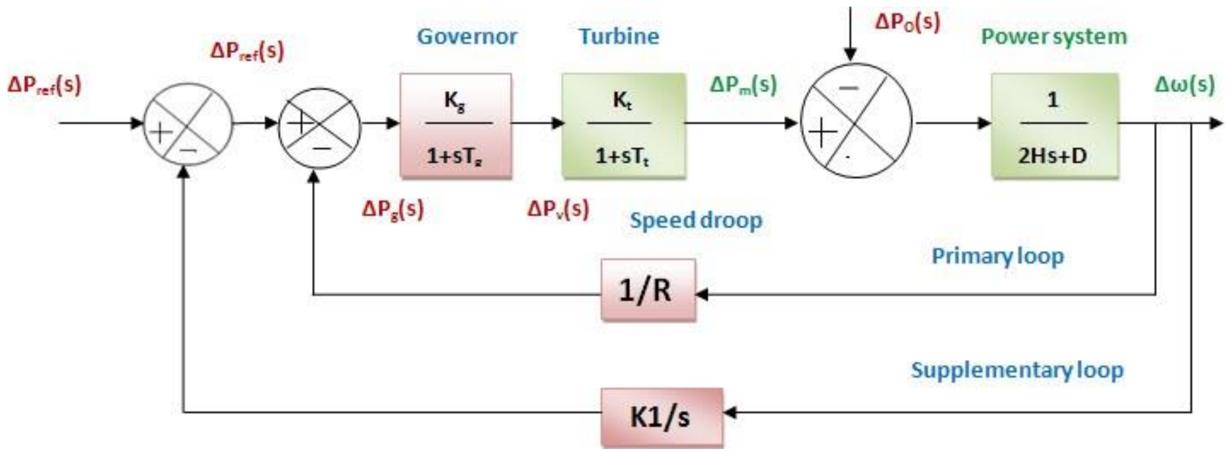


Fig2.9:The blockdiagramrepresentationoftheAGC

2.6 AGC in a Single Area System

In a single area system, there is no tie-line schedule to be maintained. Thus the function of the AGC is only to bring the frequency to the nominal value. This will be achieved using the supplementary loop (as shown in Fig.2.9) which uses the integral controller to change the reference power setting so as to change the speed set point. The integral controller gain K_I needs to be adjusted for satisfactory response (in terms of overshoot, settling time) of the system. Although each generator will be having a separate speed governor, all the generators in the control area are replaced by a single equivalent generator, and the ALFC for the area corresponds to this equivalent generator.

2.7 AGC in a Multi Area System

In an interconnected (multi area) system, there will be one ALFC loop for each control area (located at the ECC of that area). They are combined as shown in Fig2.10 for the interconnected system operation. For a total change in load of ΔP_D, the steady state deviation in frequency in the two areas is given by $\Delta f = \Delta\omega_1 = \Delta\omega_2 = \dfrac{-\Delta P_D}{\beta_1 + \beta_2}$ where,

$\beta_1 = (D_1 + 1/R_1)$; and $\beta_2 = (D_2 + 1/R_2)$.

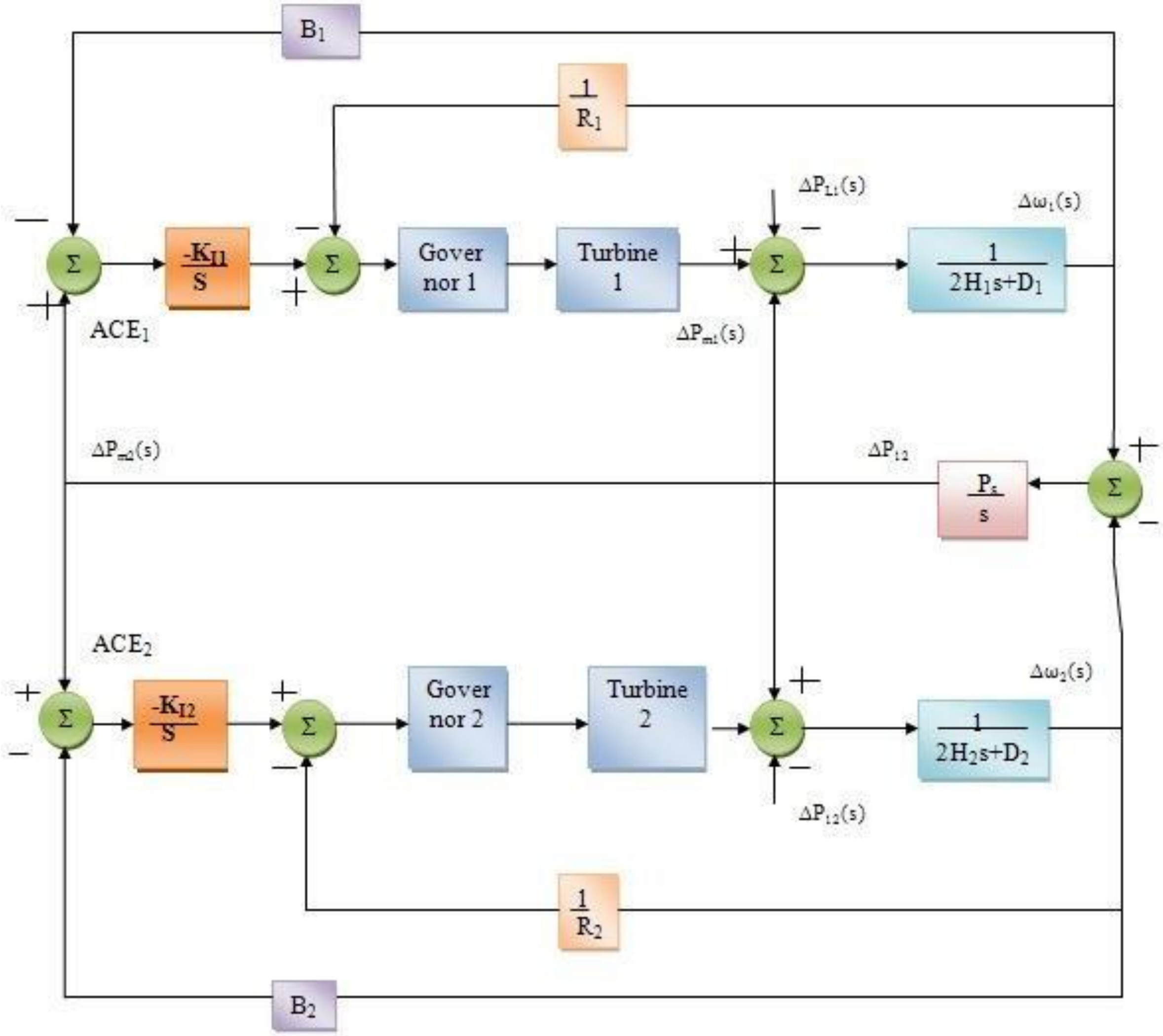


Fig.2.10.AGCfora multi-areaoperation

2.8 Expression for tie-line flow in a two-area interconnected system

Consider a change in load ΔP_{D1} in area1. The steady state frequency deviation Δf is the same for both the areas. That is $\Delta f = \Delta f_1 = \Delta f_2$. Thus, for area1, we have

$$\Delta P_{m1} - \Delta P_{D1} - \Delta P_{12} = D_1 \Delta f$$

where, ΔP_{12} is the tie line power flow from Area1to Area 2; and for Area 2

$$\Delta P_{m2} + \Delta P_{12} = D_2 \Delta f$$

The mechanical power depends on regulation. Hence

$$\Delta P_{m1} = -\frac{\Delta f}{R_1} \qquad \text{and} \qquad \Delta P_{m2} = -\frac{\Delta f}{R_2}$$

Substituting these equations, yields

$$(\frac{1}{R_1} + D_1)\Delta f = -\Delta P_{12} - \Delta P_{D1} \qquad \text{and} \qquad (\frac{1}{R_2} + D_2)\Delta f = \Delta P_{12}$$

Solving for Δf, we get

$$\Delta f = \frac{-\Delta P_{D1}}{(1/R_1 + D_1) + (1/R_2 + D_2)} = \frac{-\Delta P_{D1}}{\beta_1 + \beta_2}$$

and $$\Delta P_{12} = \frac{-\Delta P_{D1}\beta_2}{\beta_1 + \beta_2}$$

where, β_1 and β_2 are the composite frequency response characteristic of Area1 and Area 2 respectively. An increase of load in area1 by ΔP_{D1} results in a frequency reduction in both areas and a tie-line flow of ΔP_{12}. A positive ΔP_{12} is indicative of flow from Area1 to Area 2 while a negative ΔP_{12} means flow from Area 2 to Area1. Similarly, for a change in Area 2 load by ΔP_{D2}, we have

$$\Delta f = \frac{-\Delta P_{D2}}{\beta_1 + \beta_2}$$

and $$\Delta P_{12} = -\Delta P_{21} = \frac{-\Delta P_{D2}\beta_1}{\beta_1 + \beta_2}$$

Frequency bias tie line control

The tie line deviation reflects the contribution of regulation characteristic of one area to another. The basic objective of supplementary control is to restore balance between each area load generation. This objective is met when the control action maintains

- Frequency at the scheduled value
- Net interchangepower(tielineflow)withneighboringareasatthe scheduledValues

Thesupplementarycontrolshouldideallycorrectonlyforchangesinthatarea.Inotherwords,ifthereisa change in Area1 load, there should be supplementary control only in Area1 and not in Area 2. For thispurposetheareacontrolerror(ACE)isused(Fig2.9).The ACEofthetwoareasaregivenby

For area 1: $ACE_1 = \Delta P_{12} + \beta_1 \Delta f$

For area 2: $ACE_2 = \Delta P_{21} + \beta_2 \Delta f$

EconomicAllocationofGeneration

An important secondary function of the AGC is to allocate generation so that each generating unit isloaded economically. That is, each generating unit is to generate that amount to meet the present demandin such a way that the operating cost is the minimum. This function is called Economic Load Dispatch(ELD).

Systemswithmorethantwo areas

Themethoddescribedforthefrequencybiascontrolfortwoareasystemisapplicable tomultiage systemalso.

SectionII:AutomaticGenerationControl

- **LoadFrequencyControl**

AutomaticGenerationControl

Electric power isgenerated by converting mechanical energy into electrical energy. The rotormass,which contains turbine and generator units, stores kinetic energy due to its rotation. This stored kineticenergy accounts for sudden increase in the load. Let us denote the mechanical torque input by $T_m$and theoutput electrical torque by T_e. Neglecting the rotational losses, a generator unit is said to be operating inthe steady state at a constant speed when the difference between these two elements of torque is zero. Inthiscasewesaythattheacceleratingtorqueiszero.

$T_a = T_m - T_e$ 5.20)

When the electric power demand increases suddenly, the electric torque increases. However, without anyfeedback mechanism to alter the mechanical torque, $T_m$remains constant. Therefore the acceleratingtorquegivenby(5.20)becomesnegativecausingadecelerationoftherotormass.Astherotordecelerates, kinetic energy is released to supply the increase in the load. Also note that during this time,the system frequency, which is proportional to the rotor speed, also decreases. We can thus infer that anydeviation in the frequency for its nominal value of 50 or 60 Hz is indicative of the imbalance between $T_m$andT_e.Thefrequencydropswhen $T_m < T_e$andriseswhen$T_m > T_e$.

Thesteadystatepower-frequencyrelationisshowninFig.5.3.InthisfiguretheslopeoftheΔP_{ref}lineisnegativeandisgivenby

$$-R=\frac{\Delta f}{\Delta P_m} \quad (5.21)$$

Where*R*is calledthe**regulatingconstant.**Fromthis figurewecan writethesteadystatepowerfrequencyrelationas

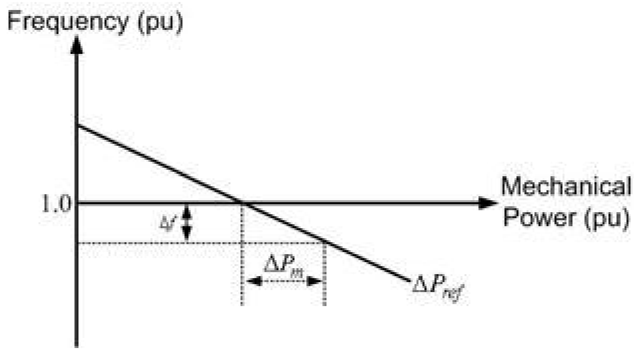


Fig.5.3Atypicalsteady-statepower-frequencycurve.

$$\Delta P_m=\Delta P_{ref}-\frac{1}{R}\Delta f \quad (5.22)$$

Supposeaninterconnectedpowersystemcontains*N*turbine-generatorunits.Thenthesteady-statepowerfrequencyrelationisgivenbythesummationof (5.22) foreachof theseunitsas

$$\begin{aligned}\Delta P_m &= \Delta P_{m1}+\Delta P_{m2}+\cdots+\Delta P_{mN}\\ &= \left(\Delta P_{ref1}+\Delta P_{ref2}+\cdots+\Delta P_{refN}\right)-\left(\frac{1}{R_1}+\frac{1}{R_2}+\cdots+\frac{1}{R_N}\right)\Delta f\\ &= \Delta P_{ref}-\left(\frac{1}{R_1}+\frac{1}{R_2}+\cdots+\frac{1}{R_N}\right)\Delta f \qquad (5.23)\end{aligned}$$

In the above equation, $\Delta P_m$is the total change in turbine-generator mechanical power and $\Delta P_{ref}$is the totalchange in the reference power settings in the power system. Also note that since all the generators aresupposed to work in synchronism, the change is frequency of each of the units is the same and is denotedbyΔf.Thenthe**frequencyresponse characteristics**isdefinedas

$$\beta=\frac{1}{R_1}+\frac{1}{R_2}+\cdots+\frac{1}{R_N} \quad (5.24)$$

Wecantherefore modify(5.23)as

$$\Delta P_m = \Delta P_{ref} - \beta \Delta f \quad (5.25)$$

Example5.5

Consider an interconnected 50-Hz power system that contains four turbine-generator units rated 750 MW,500 MW, 220 MW and 110 MW. The regulating constant of each unit is 0.05 per unit based on its ownrating. Each unit is operating on 75% of its own rating when the load is suddenly dropped by 250 MW.We shallchoose acommon base of500MWand calculate the risein frequency anddropin themechanicalpoweroutputofeachunit.

The first step in the process is to convert the regulating constant, which is given in per unit in the base ofeachgenerator,toa commonbase.Thisisgivenas

$$R_{new} = R_{old} \times \frac{S_{base}^{new}}{S_{base}^{old}} \quad (5.26)$$

Wecantherefore write

$$R_1 = 0.05 \times \frac{500}{750} = 0.033$$

$$R_2 = 0.05$$

$$R_3 = 0.05 \times \frac{500}{220} = 0.1136$$

$$R_4 = 0.05 \times \frac{500}{110} = 0.2273$$

Therefore

$$\beta = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \right) = 63.2 \quad \text{Perunit}$$

We can therefore calculate the total change in the frequency from (5.25) while assuming ΔP_{ref}= 0, i.e., forno change in the reference setting. Since the per unit change in load - 250/500 = - 0.5 with the negativesignaccountingforloadreduction,thechangeinfrequencyisgivenby

$$\Delta f = -\frac{\Delta P_m}{\beta} = -\frac{(-0.5)}{63.2} = 0.0079 \text{ per unit}$$

$$= 0.0079 \times 50 = 0.3956 \text{ Hz}$$

Thenthechangeinthemechanicalpowerofeachunitiscalculatedfrom(5.22)as

$$\Delta P_{m1} = -\frac{0.0079}{0.033} \times 500 = -118.67 \text{ MW}$$

$$\Delta P_{m2} = -\frac{0.0079}{0.05} \times 500 = -79.11 \text{ MW}$$

$$\Delta P_{m3} = -\frac{0.0079}{0.1136} \times 500 = -34.81 \text{ MW}$$

$$\Delta P_{m4} = -\frac{0.0079}{0.2273} \times 500 = -17.41 \text{ MW}$$

ItistobenotedthatonceΔP_{m2}iscalculatedtobe-79.11MW,wecanalsocalculatethechangesinthemechanicalpowerof theotherturbine-generatorsunitsas

$$\Delta P_{m1} = -79.11 \times \frac{750}{500} = -118.67 \text{ MW}$$

$$\Delta P_{m3} = -79.11 \times \frac{220}{500} = -34.81 \text{ MW}$$

$$\Delta P_{m3} = -79.11 \times \frac{110}{500} = -17.41 \text{ MW}$$

Thisimpliesthat eachturbine-generatorunit sharestheloadchangeinaccordancewithitsownrating.

Unit - IV

Single,TwoareaandLoad FrequencyControl

Modern day power systems are divided into various areas. For example in India, there are fiveregionalgrids,e.g.,EasternRegion,WesternRegionetc.Eachoftheseareasisgenerallyinterconnectedto its neighboring areas. The transmission lines that connect an area to its neighboring area are called **tie-lines.** Power sharing between two areas occurs through these tie-lines. Load frequency control, as thenamesignifies,regulates thepowerflowbetween differentareas whileholdingthefrequencyconstant.

As we have an Example 5.5 that the system frequency rises when the load decreases if$\Delta P_{ref}$is kept atzero. Similarly the frequency may drop if the load increases. However it is desirable to maintain thefrequencyconstantsuchthat$\Delta f=0$.Thepowerflowthroughdifferenttie-linesarescheduled-forexample, area- i may export a pre-specified amount of power to area- j while importing another pre-specified amount of power from area- k . However it is expected that to fulfill this obligation, area- $i$absorbsitsown loadchange,i.e.,increasegeneration to supplyextraloadin the areaordecreasegeneration when the load demand in the area has reduced. While doing this area- i must however maintainits obligation to areas j and k as far as importing and exporting power is concerned. A conceptual diagramofthe interconnectedareasisshowninFig.5.4.

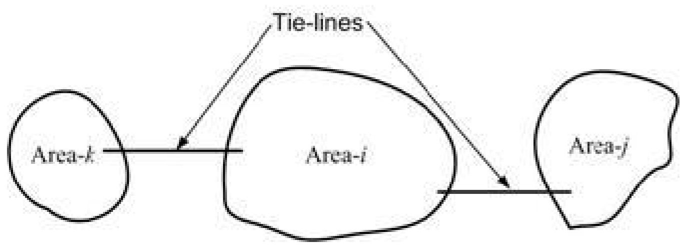


Fig.5.4Interconnectedareas inapowersystem

Wecanthereforestatethattheloadfrequencycontrol(LFC)hasthefollowingtwoobjectives:

- Holdthefrequencyconstant(Δf=0)againstanyloadchange.Eachareamustcontributetoabsorbanyloadc hangesuchthatfrequencydoesnotdeviate.
- Eachareamustmaintainthetie-linepowerflowtoits pre-specified value.
- $$\mathrm{ACE} = \left(P_{tie} - P_{sch}\right) + B_f \Delta f = \Delta P_{tie} + B_f \Delta f \quad (5.27)$$

ThefirststepintheLFCistoformthe **areacontrolerror(ACE)**thatisdefinedas

Where$P_{tie}$and $P_{sch}$are**tie-linepower**and **scheduledpower** throughtie-linerespectivelyandtheconstant $B_f$iscalledthe**frequencybias constant.**

Thechangeinthereferenceof thepowersetting$\Delta P_{ref,i}$,of thearea-$i$isthenobtainedby

$$\Delta P_{ref,i} = -K_i \int \mathrm{ACE}\, dt \quad (5.28)$$

The feedback of the ACE through an integral controllerof the form where $K_i$is the integral gain.TheACE is negative if the net power flow out of an area is low or if the frequency has dropped or both. In thiscase the generation must be increased. This can be achieved by increasing $\Delta P_{ref,i}$.This negative signaccounts for this inverse relation between $\Delta P_{ref,i}$and ACE. The tie-line power flow and frequency of eacharea are monitored in its control center. Once the ACE is computed and $\Delta P_{ref,i}$is obtained from (5.28),commands aregivento various turbine-generatorcontrols toadjusttheirreferencepowersettings.

Example5.6

Consider a two-area power system in which area-1 generates a total of 2500 MW, while area-2 generates2000 MW. Area-1 supplies 200 MW to area-2 through the inter-tie lines connected between the two areas.The bias constant of area-1 (β_1) is 875 MW/Hz and that of area-2 (β_2) is 700 MW/Hz. With the twoareas operating in the steady state, the load of area-2 suddenly increases by 100 MW. It is desirable thatarea-2absorbsitsownloadchangewhilenotallowingthefrequencytodrift.

Theareacontrolerrorsof thetwoareasaregivenby

$$\mathrm{ACE}_1 = \Delta P_{tie1} + B_1 \Delta f_1 \text{ And } \mathrm{ACE}_2 = \Delta P_{tie2} + B_2 \Delta f_2$$

Since the net change in the powerflow through tie-lines connecting these two areas must be zero, wehave

Alsoasthetransientsdieout,thedriftinthefrequencyofboththeseareasisassumedtobeconstant,i.e.

$$\Delta P_{tie1} + \Delta P_{tie2} = 0 \Rightarrow \Delta P_{tie1} = -\Delta P_{tie2}$$

$$\Delta f_1 = \Delta f_2 = \Delta f$$

If the load frequency controller(5.28) is able to set the powerreference of area-2 properly, the ACE ofthetwoareaswillbezero,i.e.,ACE_1 =ACE_2 =0.Thenwehave

$$\mathrm{ACE}_1 + \mathrm{ACE}_2 = (B_1 + B_2)\Delta f = 0$$

This will imply that Δfwill be equal to zero while maintaining ΔP_{tie1} =ΔP_{tie2} = 0. This signifies that area-2picksuptheadditionalloadinthesteadystate.

CoordinationbetweenLFCandEconomicDispatch

Both the load frequency control and the economic dispatch issue commands to change the powersettingof each turbine-governor unit. At a first glance it may seem that these two commands can be conflicting.This however is not true. A typical automatic generation control strategy is shown in Fig. 5.5 in whichboth theobjective are coordinated.Firstwe compute the areacontrolerror.A share ofthisACE,proportional to α_i, is allocated to each of the turbine-generator unit of an area. Also the share of unit- i ,γ_iXΣ(P_{DK}-P_k),forthedeviationoftotalgenerationfromactualgenerationiscomputed.Alsotheerror betweentheeconomicpowersettingandactualpowersettingofunit-$i$iscomputed.Allthesesignalsarethencombinedandpassedthroughaproportionalgain$K_i$toobtaintheturbine-governorcontrolsignal.

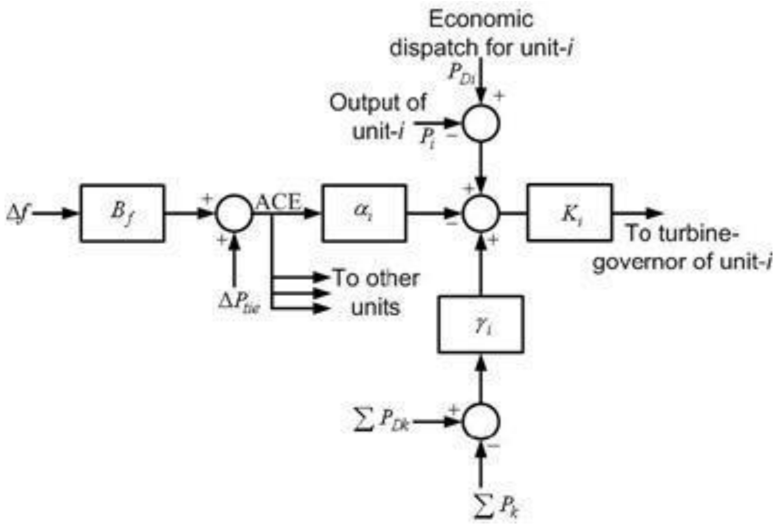


Fig.5.5Automaticgenerationcontrolofunit-i

SectionII: SwingEquation

Letusconsiderathree-phasesynchronousalternatorthatisdrivenbyaprimemover.Theequationofmotionof the machinerotorisgivenby

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

Where

J	isthetotalmoment ofinertiaoftherotormassinkgm^2
T_m	isthe mechanicaltorquesuppliedbytheprime moverinN-m
T_e	is theelectricaltorqueoutputofthealternatorinN-m
θ	istheangularpositionoftherotorinrad

Neglectingthelosses,thedifferencebetweenthemechanicalandelectricaltorquegivesthenetaccelerating torque T_a. In the steady state, the electrical torque is equal to the mechanical torque, andhence the accelerating power will be zero. During this period the rotor will move at **synchronous speed**$\omega_s$inrad/s.

The angular position θ is measured with a stationary reference frame. To represent it with respect to thesynchronouslyrotatingframe,wedefine

$$\theta = \omega_s t + \delta \quad (9.7)$$

Where$\delta$is theangularpositioninradianswithrespecttothesynchronouslyrotating

$$I_S = \frac{V_1\angle\delta - V_2}{jX} = \frac{V_1\cos\delta - V_2 + jV_1\sin\delta}{jX} \quad (9.8)$$

Referenceframe.TakingthetimederivativeoftheaboveequationwegetDefiningt heangular speedof therotoras

$$\omega_r = \frac{d\theta}{dt}$$

Wecanwrite(9.8)as

$$\omega_r - \omega_s = \frac{d\delta}{dt} \quad (9.9)$$

Wecanthereforeconcludethattherotorangularspeedisequaltothesynchronousspeedonlywhen$d\delta/dt$isequaltozer o.Wecanthereforeterm$d\delta\ /dt$asthe errorinspeed.

$$J\frac{d^2\delta}{dt^2} = T_m - T_e = T_a \quad (9.10)$$

Takingderivativeof(9.8),wecanthenrewrite(9.6)asMultiplyingbothside of(9.11)by$\omega_m$weget

$$J\omega_r\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \quad (9.11)$$

WhereP_m,$P_e$and$P_a$respectivelyarethemechanical,electricalandacceleratingpowerinMW.

$$H = \frac{\text{Stored kinetic energy at synchronou s speed in mega - joules}}{\text{Generator MVA rating}} = \frac{J\omega_s^2}{2S_{rated}} \quad (9.12)$$

WenowdefineanormalizedinertiaconstantasSubstituting(9.12)in(9.10)weget

$$2H\frac{S_{rated}}{\omega_s^2}\omega_r\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \quad (9.13)$$

In steady state, the machine angular speed is equal to the synchronous speed and hence we can replace $\omega_r$in the above equation by ω_s. Note that in (9.13) P_m,$P_e$and $P_a$are given in MW. Therefore dividing themby the generator MVA rating S_{rated}we can get these quantities in per unit. Hence dividing both sides of(9.13)byS_{rated}weget

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \quad \text{perunit} \quad (9.14)$$

Equation (9.14) describes the behavior of the rotor dynamics and hence is known as the swing equation.Theangleδistheangleoftheinternalemfofthegeneratoranditdictatestheamountofpowerthatcanbetransferred.Thisangleisthereforecalledthe**loadangle.**

Example9.2

A 50 Hz, 4-pole turbo generator is rated 500 MVA, 22 kV and has an inertia constant (*H*) of 7.5. Assumethat the generator is synchronized with a large power system and has a zero accelerating power whiledelivering a power of 450 MW. Suddenly its input power is changed to 475 MW. We have to find thespeed of the generator in rpm at the end of a period of 10 cycles. The rotational losses are assumed to bezero.

Wethenhave

$$\frac{d^2\delta}{dt^2} = \frac{\omega_s}{2H}\left(P_m - P_e\right) = \frac{100\pi}{15} \times 25 = 523.6 \text{ electrical deg/s}^2$$

$$= \frac{523.6\pi}{180} = 9.1385 \text{ electrical rad/s}^2$$

Notingthatthegeneratorhas fourpoles,wecanrewritetheaboveequationas

$$\frac{d^2\delta}{dt^2} = \frac{9.1385}{2} = 4.5693 \text{ mechanical rad/s}^2$$

$$= 60 \times \frac{4.5693}{2\pi} = 43.6332 \text{ rpm/s}$$

The machines accelerates for 10 cycles, i.e., 20 × 10 = 200 ms = 0.2 s, starting with a synchronous speedof 1500rpm.Thereforeatthe endof 10cycles

Speed=1500+43.6332´0.2=1508.7266rpm.

Unit-V

Reactivepowercompensation

CompensationofPowerTransmissionSystems **In troduction**

IdealSeriesCompensator

- ImpactofSeriesCompensatoronVoltageProfile
- ImprovingPower-AngleCharacteristics
- An AlternateMethodofVoltageInjection
- ImprovingStabilityMargin
- Comparisons oftheTwoModes

ofOperationPowerFlowControlandPowerSwingDam ping

Introduction

The two major problems that the modern power systems are facing are voltage and angle stabilities. Thereare various approaches to overcome the problem of stability arising due to small signal oscillations in aninterconnected power system. As mentioned in the previous chapter, installing power system stabilizerswithgeneratorexcitation control system providesdamping to theseoscillations.However,with theadvancementinthepowerelectronictechnology,variousreactivepowercontrolequipmentareincreasinglyus edinpowertransmissionsystems.

A power network is mostly reactive. A synchronous generator usually generates active power that isspecified by the mechanical power input. The reactive power supplied by the generator is dictated by thenetwork and load requirements. A generator usually does not have any control over it. However the lackof reactive power can cause voltage collapse in a system. It is therefore important to supply/absorb excessreactive power to/from the network. Shunt compensation is one possible approach of providing reactivepowersupport.

A device that is connected in parallel with a transmission line is called a **shunt compensator,** while adevice that is connected in series with the transmission line is called a *series compensator*. These arereferred to as compensators since they compensate for the reactive power in the ac system. We shallassumethat theshunt compensatorisalwaysconnected atthemidpointoftransmissionsystem,whilethe

- voltageprofile
- power-anglecharacteristics
- stabilitymargin
- dampingtopoweroscillations

- A **static var compensator (SVC)** is the first generation shunt compensator. It has been aroundsince 1960s.In the beginning it was used forload compensation such as to provide varsupportforlargeindustrialloads,forflickermitigationetc.Howeverwiththeadvancementofsemiconductortechnology,the SVCstarted appearing in the transmission systemsin 1970s.TodayalargenumberofSVCsareconnectedtomanytransmissionsystemsallovertheworld.An SVC is constructed using the thyristors technology and therefore does not have gate turn offcapability.
- With the advancement in the power electronic technology, the application of a gate turn offthyristors (GTO) to high power application became commercially feasible. With this the secondgeneration shunt compensator device was conceptualized and constructed. These devices usesynchronous voltage sources for generating or absorbing reactive power. A synchronous voltagesource (SVS) is constructed using a voltage source converter (VSC). Such a shunt compensatingdevice is called **static compensator or STATCOM.** A STATCOM usually contains an SVS thatis driven from a dc storage capacitor and the SVS is connected to the ac system bus through aninterface transformer. The transformer steps the ac system voltage down such that the voltagerating of the SVS switches are within specified limit. Furthermore, the leakage reactance of thetransformerplaysaverysignificantroleinthe operationof theSTATCOM.
- Like the SVC, **a thyristors controlled series compensator (TCSC)** is a thyristors based seriescompensator that connects a **thyristors controlled reactor (TCR)** in parallel with a fixedcapacitor. By varying the firing angle of the anti-parallel thyristors that are connected in serieswith a reactor in the TCR, the fundamental frequency inductive reactance of the TCR can bechanged. This effects a change in the reactance of the TCSC and it can be controlled to produceeitherinductive orcapacitivereactance.
- Alternativelya**staticsynchronousseriescompensatororSSSC**canbeusedforseriescompensation. An SSSC is an SVS based all GTO based device which contains a VSC. The VSCis driven by a dc capacitor. The output of the VSC is connected to a three-phase transformer. Theother end of the transformer is connected in series with the transmission line. Unlike the TCSC,which changes the impedance of the line, an SSSC injects a voltage in the line in quadrature withthe line current. By making the SSSC voltage to lead or lag the line current by 90° the SSSC canemulatethebehaviorofaninductance orcapacitance.

In this chapter, we shall discuss the ideal behavior of these compensating devices. For simplicity we shallconsidertheidealmodelsandbroadlydiscusstheadvantagesofseriesandshuntcompensation.

SectionI:IdealShuntCompensator

- **ImprovingVoltageProfile**
- **ImprovingPower-AngleCharacteristics**

- **ImprovingStabilityMargin**
- **ImprovingDampingtoPowerOscillations**

The ideal shunt compensator is an ideal current source. We call this an ideal shunt compensator becausewe assume that it only supplies reactive power and no real power to the system. It is needless to say thatthis assumption is not valid for practical systems. However, for an introduction, the assumption is morethan adequate. We shall investigate the behavior of the compensator when connected in the middle of atransmission line.This is shown in Fig.10.1,where the shunt compensator, represented by an idealcurrent source, is placed in the middle of a lossless transmission line. We shall demonstrate that such aconfigurationimprovesthefourpointsthatarementionedabove.

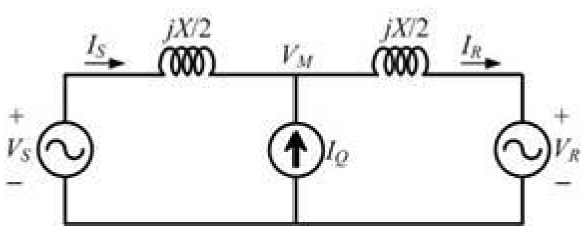


Fig10.1Schematicdiagramofanideal,midpointshuntcompensationImprovingVoltageProfile

Letthesendingandreceivingvoltagesbegivenby $V\angle\delta$ and $V\angle 0^\circ$ respectively.Theidealshuntcompensatoris expectedtoregulatethe midpointvoltageto

$V_M = V\angle(\delta/2)$ (10.1)

Against any variation in the compensator current.The voltage current characteristic of the compensator isshown in Fig. 10.2. This ideal behavior however is not feasible in practical systems where we get a slightdroopinthe voltagecharacteristic.Thiswillbediscussedlater.

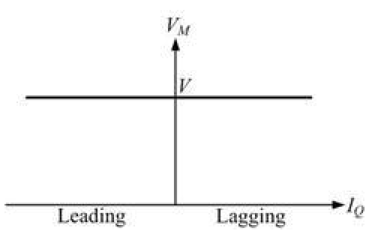


Fig. 10.2Voltage-currentcharacteristicofanidealshuntcompensator

Undertheassumptionthattheshuntcompensatorregulatesthemidpointvoltagetightlyasgivenby(10.1),wecanwritethefollowingexpressionsforthesendingandreceivingendcurrents

$$I_S = \frac{V\angle\delta - V\angle(\delta/2)}{jX/2} \quad (10.2)$$

$$I_S = \frac{V\angle\delta - V\angle(\delta/2)}{jX/2} \quad (10.3)$$

$$I_S + I_Q = I_R \quad (10.4)$$

AgainfromFig.10.1wewrite

$$I_Q = -j\frac{4V}{X}\{1-\cos(\delta/2)\}\angle(\delta/2) \quad (10.5)$$

Wethushavetogenerateacurrentthatisinphase withthe midpointvoltageandhasamagnitude of(4V/ X_L){1-cos(δ/2)}.Theapparentpowerinjectedbytheshuntcompensatortotheacbusisthen

$$P_Q + jQ_Q = V_M I_Q^* = -j\frac{4V^2}{X}\{1-\cos(\delta/2)\} \quad (10.6)$$

Since the real part of the injected power is zero, we conclude that the ideal shunt compensator injects onlyreactivepowertotheac systemandnorealpower.

ImprovingPower-AngleCharacteristics

Theapparentpowersuppliedbythesourceisgivenby

$$\begin{aligned} P_S + jQ_S &= V_S I_S^* = V\angle\delta\left[\frac{V\angle-\delta - V\angle-(\delta/2)}{-jX/2}\right] = \frac{V^2 - V\angle(\delta/2)}{-jX/2} \\ &= \frac{2V^2\sin(\delta/2)}{X} + j\frac{2V^2\{1-\cos(\delta/2)\}}{X} \end{aligned} \quad (10.7)$$

Similarlytheapparentpowerdeliveredat thereceivingendis

$$\begin{aligned} P_R + jQ_R &= V_R I_R^* = V\left[\frac{V\angle-(\delta/2) - V}{-jX/2}\right] \\ &= \frac{2V^2\sin(\delta/2)}{X} + j\frac{2V^2\{\cos(\delta/2)-1\}}{X} \end{aligned} \quad (10.8)$$

$$P_e = P_S = P_R = \frac{2V^2}{X}\sin(\delta/2) \quad (10.9)$$

Hencetherealpowertransmitted overthelineis givenby

$$Q_e = Q_S + Q_Q - Q_R = \frac{8V^2}{X}\{1-\cos(\delta/2)\} \quad (10.10)$$

Thepower-anglecharacteristicsoftheshuntcompensatedlineareshowninFig.10.3.InthisfigureP_{max} $=V^2/X$ ischosenasthepowerbase.

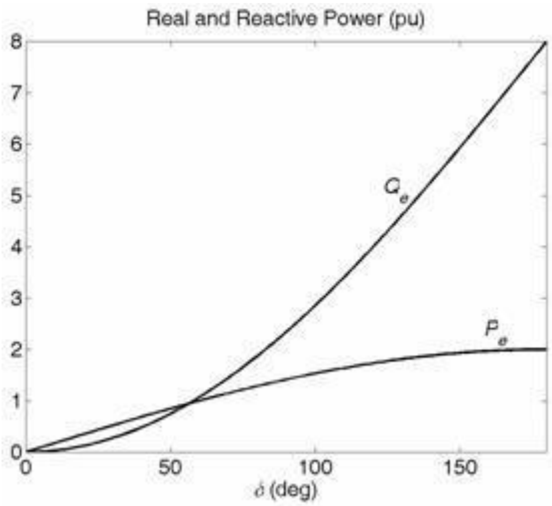


Fig. 10.3Power-anglecharacteristicsofidealshuntcompensatedline.

Fig.10.3 depictsP_e- δ and Q_Q- δ characteristics.It can be seen from fig 10.4 that for a real powertransfer of 1 per unit, a reactive power injection of roughly 0.5359 per unit will be required from the shuntcompensator if the midpoint voltage is regulated as per (10.1). Similarly for increasing the real powertransmitted to 2 per unit, the shunt compensator has to inject 4 per unit of reactive power. This willobviously increase the device rating and may not be practical. Therefore power transfer enhancementusingmidpointshuntcompensationmaynotbefeasiblefromthedeviceratingpointofview.

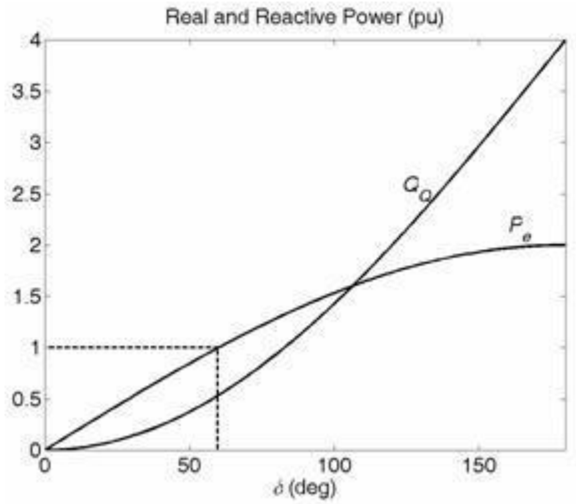


Fig.10.4Variationsintransmittedrealpowerandreactivepowerinjectionbytheshuntcompensatorwithloadangleforperfectmidpointvoltageregulation.

Let us now relax the condition that the midpoint voltage is regulated to 1.0 per unit. We then obtain somevery interesting plots as shown in Fig. 10.5. In this figure, the x-axis shows the reactive power availablefrom the shunt device, while the y-axis shows the maximum power that can be transferred over the linewithoutviolating thevoltage constraint.There are threedifferentP-Qrelationshipsgivenforthreemidpoint voltage constraints. For a reactive power injection of 0.5 per unit, the power transfer can beincreased from about 0.97 per unit to 1.17 per unit by lowering the midpoint voltage to 0.9 per unit. For areactivepowerinjectiongreaterthan2.0perunit,thebestpowertransfercapabilityisobtainedfor V_M= 1.0 per unit. Thus there will be no benefit in reducing the voltage constraint when the shunt device iscapable of injecting a large amount of reactive power. In practice, the level to which the midpoint voltagecanberegulateddependsontheratingof theinstalledshuntdeviceaswellthepowerbeing transferred.

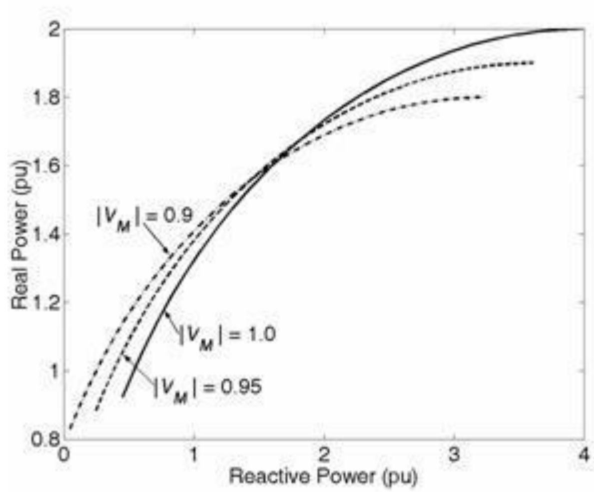
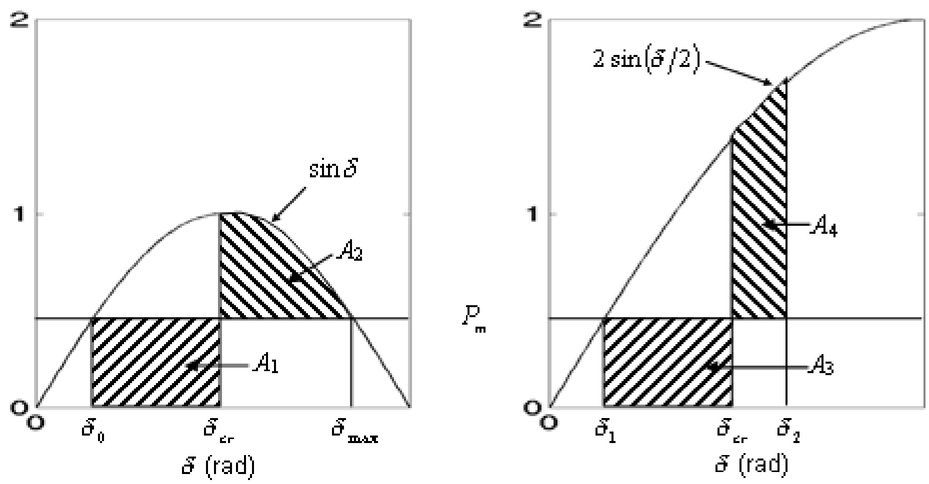


Fig.10.5Powertransferversusshuntreactiveinjectionundermidpointvoltageconstraint.ImprovingStabilityMargin

This is a consequence of the improvement in the power angle characteristics and is one of the majorbenefits of using midpoint shunt compensation. As mentioned before, the stability margin of the systempertainsto the regionsof acceleration and deceleration in the power-angle curve.We shall use thisconcepttodelineatetheadvantageofmidpointshuntcompensation.

Considerthepoweranglecurves shownin Fig.10.6.



The curve of Fig. 10.6 (a) is for an uncompensated system, while that of Fig. 10.6 (b) for the compensatedsystem. Both these curves are drawn assuming that the base power is V^2/X . Let us assume that theuncompensated system is operating on steady state delivering an electrical power equal to $P_m$with a loadangle of δ_0 when a three-phase fault occurs that forces the real power to zero. To obtain the criticalclearingangleforthe uncompensatedsystemis δ_{cr},weequatetheacceleratingareaA_1withthedeceleratingareaA_2 ,where

$$A_1 = \int_{\delta_0}^{\delta_{cr}} P_m dt = P_m\left(\delta_{cr} - \delta_0\right)$$

$$A_2 = \int_{\delta_{cr}}^{\delta_{max}} (\sin\ \delta - P_m) dt = (\cos \delta_{cr} - \cos \delta_{max}) - P_m\left(\delta_{max} - \delta_{cr}\right)$$

$$\delta_{cr} = \cos^{-1}\left[P_m\left(\delta_{max} - \delta_0\right) + \cos \delta_{max}\right] \quad (10.11)$$

With $\delta_{max}=\pi-\delta_0$. Equatingtheareasweobtainthevalueof δ_{cr} as

Let us now consider that the midpoint shunt compensated system is working with the same mechanicalpower input P_{m}. The operating angle in this case is δ_1 and the maximum power that can be transferred inthis case is 2 per unit. Let the fault be cleared at the same clearing angle δ_{cr} as before. Then equating areas A_3 and A_4 inFig.10.6(b)weget δ_2,where

$$A_3 = \int_{\delta_1}^{\delta_{cr}} P_m \, dt = P_m(\delta_{cr} - \delta_1)$$

$$A_4 = \int_{\delta_{cr}}^{\delta_2} [2\sin(\delta/2) - P_m]dt = 4[\cos(\delta_{cr}/2) - \cos(\delta_2/2)] - P_m(\delta_2 - \delta_{cr})$$

Example10.1

Let an uncompensated SMIB power system is operating in steady state with a mechanical power input P_m equal to 0.5 per unit. Then δ_0 = 30° = 0.5236 rad and δ_{max}= 150° = 2.6180 rad. Consequently, the criticalclearingangleiscalculatedas(seeChapter9) δ_{cr}=79.56°=1.3886rad.

Let us now put an ideal shunt compensator at the midpoint. The pre-fault steady state operating angle ofthe compensated system can be obtained by solving 2 sin (δ/2) = 0.5, which gives δ_1 = 28.96° = 0.5054rad. Let us assume that we use the same critical clearing angle as obtained above for clearing a fault in thecompensatedsystemaswell.

The accelerating area is then given by A_3 = 0.4416. Equating with area A_4 we get a nonlinear equation oftheform

$$0.4416 = 3.0740 - 4\cos(\delta_2/2) - 0.5\delta_2 + 0.6943$$

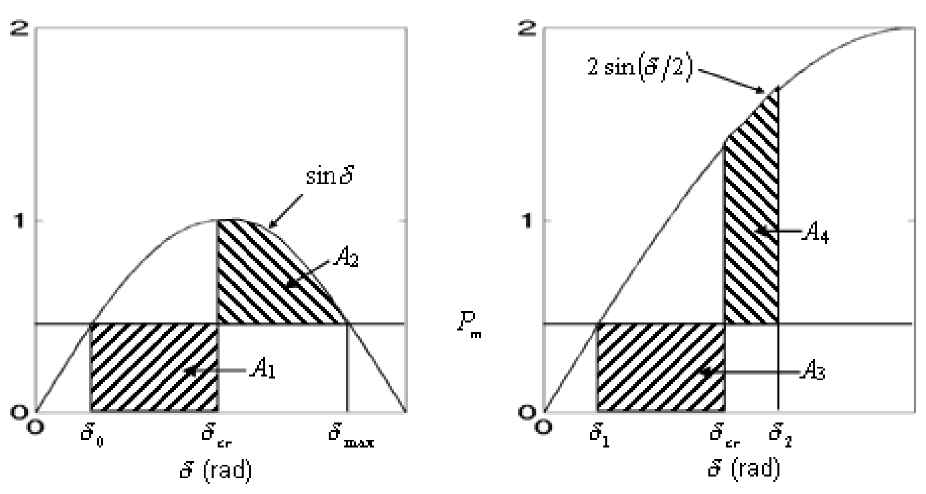


Fig 10.6 Power-angel curve showing clearing angles: (a) for uncompensated system and (b) forcompensatedsystem

Solving the above equation we get δ_2 = 104.34° = 1.856 rad. It is needless to say that the stability marginhasincreasedsignificantlyinthecompensatedsystem

ImprovingDampingtoPowerOscillations

The swing equation of a synchronous machine is given by (9.14). For any variation in the electricalquantities, the mechanical power input remains constant. Assuming that the magnitude of the midpointvoltage of the system is controllable by the shunt compensating device, the accelerating power in (9.14)becomes a function of two independent variables, $|V_M|$ and δ. Again since the mechanical power isconstant,itsperturbationwiththeindependentvariablesiszero.Wethengetthefollowingsmallperturbationexpressionoftheswingequation

$$\frac{2H}{\omega}\frac{d^2\Delta\delta}{dt^2}+\frac{\partial P_e}{\partial|V_M|}\Delta|V_M|+\frac{\partial P_e}{\partial\delta}\Delta\delta=0 \qquad (10.12)$$

WhereΔindicatesaperturbationaroundthenominal values.

If the midpoint voltage is regulated at a constantmagnitude, $\Delta|V_M|$ will be equal to zero.Hence theaboveequationwillreduceto

$$\frac{2H}{\omega}\frac{d^2\Delta\delta}{dt^2}+\frac{\partial P_e}{\partial\delta}\Delta\delta=0 \qquad (10.13)$$

The 2nd orderdifferentialequation givenin (10.13) can be writtenin the Laplace domain byneglectingtheinitialconditionsas

$$\left(\frac{2H}{\omega}s^2+\frac{\partial P_e}{\partial\delta}\right)\Delta\delta(s)=0 \qquad (10.14)$$

Therootsoftheabove equationarelocatedonthe imaginaryaxisof thes-planeatlocations$\pm j\omega_m$where

$$\omega_m=\sqrt{(\omega/2H)(\partial P_e/\partial\delta)}$$

This implies that the load angle will oscillate with a constant frequency of ω_m. Obviously, this solution isnot acceptable. Thus in order to provide damping, the midpoint voltage must be varied according to insympathywiththerateof change in$\Delta\delta$.Wecanthenwrite

$$\Delta|V_M| = K_M \frac{d\Delta\delta}{dt} \quad (10.15)$$

$$\frac{2H}{\omega}\frac{d^2\Delta\delta}{dt^2} + \frac{\partial P_e}{\partial|V_M|}K_M\frac{d\Delta\delta}{dt} + \frac{\partial P_e}{\partial\delta}\Delta\delta = 0 \quad (10.16)$$

Where$K_M$isaproportional gain.Substituting(10.15)in(10.12)weget

Provided that$K_M$is positive definite, the introduction of the control action (10.15) ensures that the rootsof the second order equation will have negative real parts. Therefore through the feedback, damping topower swings can be provided by placing the polesof the above equation to provide the necessarydampingratioand undammednaturalfrequencyofoscillations.

Example10.2

Consider the SMIB power system shown in Fig. 10.7. The generator is connected to the infinite busthrough a double circuit transmission line. At the midpoint bus of the lines, a shunt compensator isconnected. The shunt compensator is realized by the voltage source $V_F$that is connected to the midpointbus through a pure inductor X_F, also known as an **interface inductor** . The voltage source $V_F$is drivensuch that it is always in phase with the midpoint voltage V_M. The current $I_Q$is then purely inductive, itsdirectionbeingdependentonthe relativemagnitudesofthe twovoltages.Ifthe magnitude ofthemidpoint voltage is higher than the voltage source V_F,inductive currentwill flow from the ac system tothe voltage source. This implies that the source is absorbing var in this configuration. On the other hand,thesourcewillgeneratevarifitsmagnitudeis higherthanthatofthemidpointvoltage.

The system is simulated in MATLAB. The three-phase transmission line equations are simulated usingtheir differential equations, while the generator is represented by a pure voltage source. The second orderswing equation is simulated in which the mechanical power input is chosen such that the initial operatingangle of the generatorvoltage is (0.6981 rad). The instantaneous electrical power is computed from thedot product of the three-phase source current vector and source voltage vector. The system parameterschosenforsimulationare:

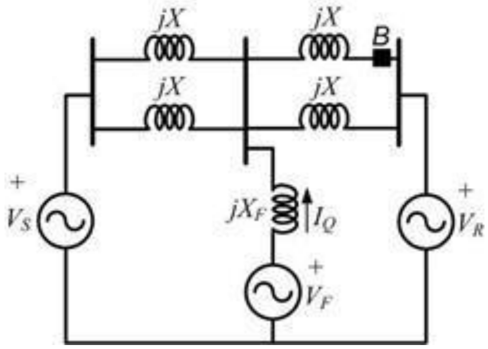


Fig.10.7SMIBsystemusedinthenumerical example.

Sending end voltage, V_S = 1 < 40° per unit,

Receiving end voltage, V_R = 1 < 0° per unit,

System Frequency ω_s = 100 π rad/s,

Line reactance, X=0.5 per unit,

Interface reactance, X_F per unit,

Generatorinertiaconstant,H=4.0MJ/MVA.

Two different tests are performed. In the first one, the midpoint voltage is regulated to 1 per unit using aproportional-plus-integral (PI) controller. The magnitude of the midpoint voltage is first calculated usingthed-q transformationofthe three phase quantities.Themagnitudeisthen compared with the setreference (1.0) and the error is passed through the PI controller to determine the magnitude of the sourcevoltage,ie,

$$|V_F| = K_P(1-|V_M|) + K_I\int(1-|V_M|)dt \quad (10.17)$$

$$V_F = \frac{V_M}{|V_M|}\times|V_F| \quad (10.18)$$

Thesourcevoltageisthengeneratedbyphaselockingitwiththemidpointvoltageusing

Fig. 10.8 depicts the system quantities when the system is perturbed for its nominal operating condition.The proportional gain (K_P) is chosen as 2.0, while the integral gain (K_I) is chosen as 10. In Fig. 10.8 (a)the a-phase of the midpoint voltage, source voltage and the injected current are shown once the systemtransients die out.It can be seen that the source and midpoint voltages are phase aligned,while theinjected current is lagging these two voltages by 90° . Furthermore, the midpoint voltage magnitude istightly regulated. Fig. 10.8 (b) depicts the perturbation in the load angle and the injected reactive power. Itcanbeseenthattheloadangleundergoessustainedoscillationandthisoscillationisinphasewiththe injected reactive power. This implies that, by tightly regulating the midpoint voltage though a high gainintegral controller, the injected reactive power oscillates in sympathy with the rotor angle. Therefore todamp out the rotor oscillation, a controller must be designed such that the injected reactive power is inphase opposition with the load angle. It is to be noted that the source voltage also modulates in sympathywith the injected reactive power. This however is not evident from Fig. 10.8 (a) as the time axis has beenshortenedhere.

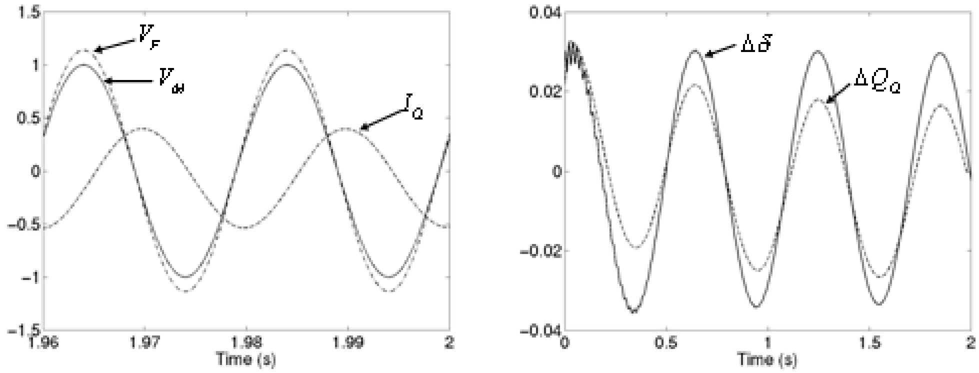


Fig.10.8Sustainedoscillationinrotorangledueto strongregulationofmidpointvoltage.

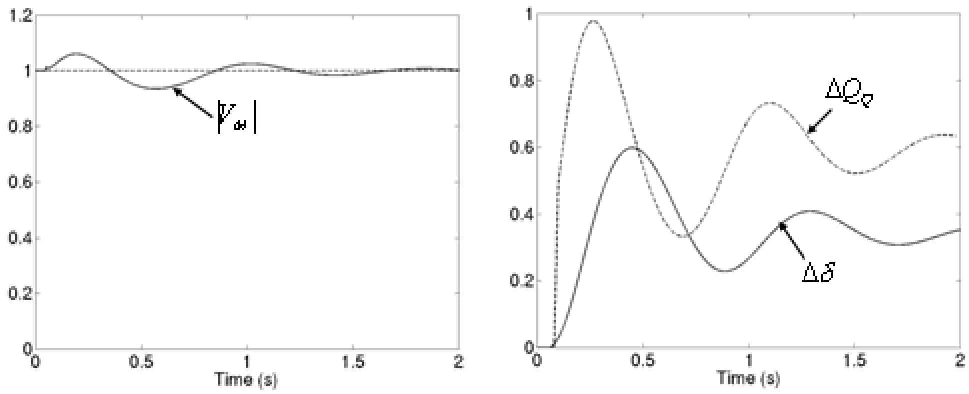
To improve damping, we now introduce a term that is proportional to the deviation of machine speed inthefeedbackloopsuchthatthecontrollawisgivenby

$$|V_F| = K_P\left(1-|V_M|\right)+K_I\int\left(1-|V_M|\right)dt + C_P\frac{d\Delta\delta}{dt} \quad (10.19)$$

Thevaluesofproportionalgain$K_P$andintegralgain$K_I$chosenaresameasbefore,whilethevalueofC_P chosenis50.Withthesystemoperatingonsteadystate,deliveringpowerat

a load angle of 40° for 50 ms, breaker *B* (see Fig. 10.7) opens inadvertently. The magnitude of themidpointvoltage isshowninFig.10.9(a).Itcanbeseenthatthe magnitudesettlestothe desiredvalue of

per unit once the initial transients die down. Fig. 10.9 (b) depicts perturbations in load angle andreactive power injected from theirPerrault steady state values. It can be seen that these two quantitieshaveaphasedifferenceof about90°andthisisessentialfordampingof poweroscillations.



(a) (b)

Fig 10.9Systemresponsewiththedamping controller

SectionII:IdealSeriesCompensator

- **ImpactofSeriesCompensatoronVoltageProfile**
- **ImprovingPower-AngleCharacteristics**
- **AnAlternate MethodofVoltage Injection**
- **ImprovingStabilityMargin**
- **Comparisons oftheTwo Modes ofOperation**
- **PowerFlowControlandPowerSwingDamping**Ide

alSeriesCompensator

Letusassumethattheseriescompensatorisrepresentedby anidealvoltagesource.Thisisshown inFig. 10.10. Let us further assume that the series compensator is ideal, i.e., it only supplies reactive power andno real power to the system. It is needless to say that this assumption is not valid for practical systems.However,for an introduction,the assumption ismore than adequate.It isto be noted that, unlike theshunt

Compensator, the location of the series compensator is not crucial, and it can be placed anywhere alongthetransmissionline.

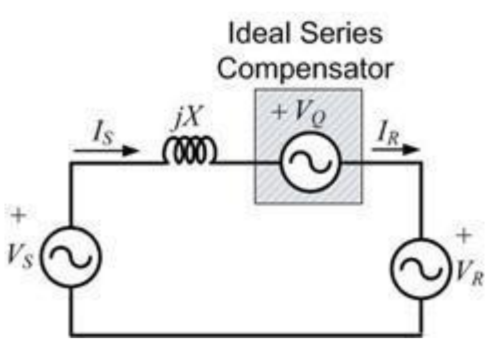


Fig.10.10Schematicdiagramofanidealseries compensatedsystem.

ImpactofSeriesCompensatoronVoltageProfile

In the equivalent schematic diagram of a series compensated power system is shown in Fig. 10.10, thereceiving end current is equal to the sending end current, i.e., $I_S = I_R$. The series voltage $V_Q$is injected insuchawaythatthemagnitudeoftheinjectedvoltageismadeproportionaltothatofthelinecurrent. Furthermore,thephaseofthe voltageisforcedtobeinquadraturewiththelinecurrent.Wethenhave

$$V_Q = \lambda I_S e^{\mp j90°} \quad (10.20)$$

The ratio λ/X is called the **compensation level** and is often expressed in percentage. This compensationlevel is usually measured with respect to the transmission line reactance. For example, we shall refer thecompensation level as 50% when $\lambda = X/2$. In the analysis presented below, we assume that the injectedvoltagelagsthelinecurrent.Theimplicationofthevoltageleadingthecurrentwillbediscussedlater.

ApplyingKVLweget

$$V_S - V_Q - V_R = jXI_S \quad \Rightarrow \quad V_S - V_R = \mp j\lambda I_S + jXI_S$$

$$I_S = \frac{V\angle\delta - V}{j(X \mp \lambda)} \quad (10.21)$$

Assuming$V_S = V<\delta$and$V_R = V<0°$,wegetthefollowingexpressionforthelinecurrent

Whenwechoose$V_Q = \lambda I_S e^{-j90°}$, thelinecurrentequationbecomes

$$I_S = \frac{V\angle\delta - V}{j(X - \lambda)}$$

Thus we see that λ is subtracted from X . This choice of the sign corresponds to the voltage source actingasa purecapacitor.Hence wecallthisasthe**capacitivemodeofoperation**

In contrast, if we choose $V_Q = \lambda I_S e^{+j90°}$,$\lambda$ is added to X , and this mode is referred to as the **inductivemode of operation** . Since this voltage injection using (10.20) add λ to or subtract λ from the linereactance, we shall refer it as voltage injection in **constant reactance mode**. We shall consider theimplicationofseriesvoltageinjection onthetransmissionlinevoltagethroughthefollowing example.

Example10.3

Consider a lossless transmission line that has a 0.5 per unit line reactance (X). The sending end andreceivingendvoltagesaregivenby1<δand1<0°perunitrespectivelywhereδischosenas30°.Let us choose λ = 0.5 and operation in the capacitive mode. For this line, this implies a 30% level of lineimpedance compensation. The line current is then given from (10.21) asI_S= 1.479 7 < 15° perunit andthe injected voltage calculated from (10.20) is V_Q= 0.2218 < - 75° per unit. The phasor diagrams of thetwo end voltages, line current and injected voltage are shown in Fig. 10.11 (a). We shall now consider afewdifferentcases.

Let us assume that the series compensator is placed in the middle of the transmission line. We then definetwovoltages,oneateitherside oftheseriescompensator.Theseare:

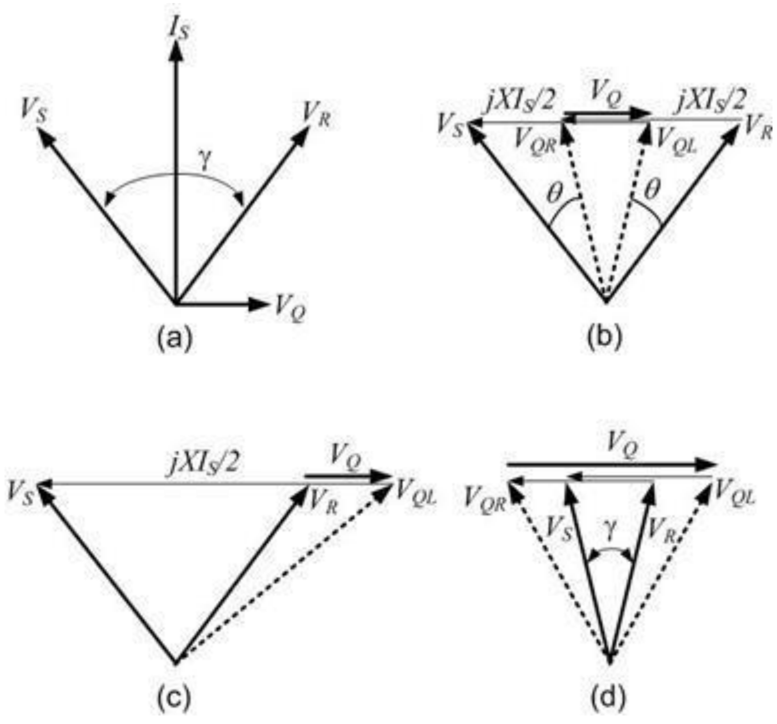
Voltage on the left: V_{QL}= V_S- jXI_S/ 2 = 0.9723 < 8.45° per unitVoltageontheright:V_{QR}=V_R+jXI_S/2=0.9723<21.55° perunit

The difference of these two voltages is the **injected voltage**. This is shown in Fig. 10.11 (b), where theangle θ = 8.45° . The worst case voltage along the line will then be at the two points on either side of theseries compensator where the voltage phasors are aligned with the line current phasor. These two pointsare equidistant from the series compensator. However, their particular locations will be dependent on thesystemparameters.

As a second case, let us consider that the series compensator is placed at the end of the transmission line,justbeforetheinfinitebus.Wethenhavethefollowingvoltage

Voltageontheleftofthecompensator:V_{QL}= V_R+V_Q= 1.0789 <-11.46°perunit

This is shown in Fig. 10.11 (c). The maximum voltage rise in the line is then to the immediate left of thecompensator, i.e., at V_{QL}. The maximum voltage drop however still occurs at the point where the voltagephasorisalignedwiththelinecurrentphasor.



As a third case, let us increase the level of compensation from 30% to 70% (i.e., change λ from 0.15 to0.35). We however, do not want to change the level of steady state power transfer. The relation betweenpower transfer and compensation level will be discussed in the next subsection. It will however suffice tosay that this is accomplished by lowering the value of the angle δ of the sending end voltage to 12.37° .Let us further assume that the series compensator is placed in the middle of the transmission line. We thenhaveV_{QL}=1.0255<-8.01°perunitandV_{QR}=1.0255 <20.38°perunit.Thisisshownin Fig.10.11(d).Itisobviousthatthevoltage along theline risesto amaximumlevel ateithersideoftheseriescompensator.

ImprovingPower-AngleCharacteristics

$$P_S + jQ_S = V_S I_S^* = V\angle\delta\left[\frac{V\angle-\delta - V}{-j(X \mp \lambda)}\right] = \frac{V^2 - V^2\angle\delta}{-j(X \mp \lambda)}$$
$$= \frac{V^2 \sin\delta}{X \mp \lambda} + j\frac{V^2(1-\cos\delta)}{X \mp \lambda} \qquad (10.22)$$

Notingthatthesendingendapparentpoweris$V_S I_S$*,wecanwriteSimilarlythereceivingendapparentpowerisgivenb y

$$P_R + jQ_R = V_R I_S^* = V\left[\frac{V\angle-\delta - V}{-j(X \mp \lambda)}\right]$$
$$= \frac{V^2 \sin\delta}{X \mp \lambda} + j\frac{V^2(\cos\delta - 1)}{X \mp \lambda} \qquad (10.23)$$

$$P_S = P_R = P_e = \frac{V^2}{X \mp \lambda}\sin\delta \qquad (10.24)$$

Hencetherealpowertransmittedoverthelineisgivenby

The power-angle characteristics of a series compensated power system are given in Fig. 10.12. In thisfigure the base power is chosen as V^2 / X . Three curves are shown, of which the curve P_0 is the **power-angle curve**when the line is not compensated. Curveswhich have maximum powers greater than thebase power pertain to capacitive mode of operation. On the other hand, all curves the inductive mode ofoperation will have maximum values less than 1. For example, in Fig. 10.12, the curve P_1 is for capacitivemodeandthecurveP_2 isforinductive mode of operation.

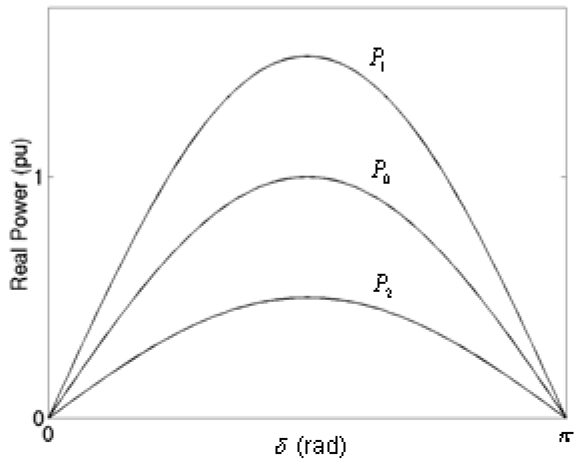


Fig. 10.12Power-anglecharacteristicsinconstantreactancemode.

Let us now have alook at the reactive power.Forsimplicity let us restrict ourattention to capacitivemode of operation only as this represents the normal mode of operation in which the power transfer overthelineisenhanced.From(10.20)and(10.21)wegetthereactivepowersuppliedbythecompensatoras

$$Q_Q = V_Q I_S^* = -j\lambda \frac{V\angle\delta - V}{j(X-\lambda)} \times \frac{V\angle-\delta - V}{-j(X-\lambda)}$$

Solvingtheaboveequationweget

$$Q_Q = -j\frac{2\lambda V^2}{(X-\lambda)^2}(1-\cos\delta) \qquad (10.25)$$

In Fig.10.13, the reactive powerinjected by the series compensatoris plotted againstthe maximumpower transfer as the compensation level changes from 10% to 60%. As the compensation level increases,the maximum power transfer also increases. However, at the same time, the reactive injection requirementfrom the series compensator also increases. It is interesting to note that at 50% compensation level, thereactive power injection requirement from a series compensator is same that from shunt compensator thatisregulatingthe midpointvoltageto1.0perunit.

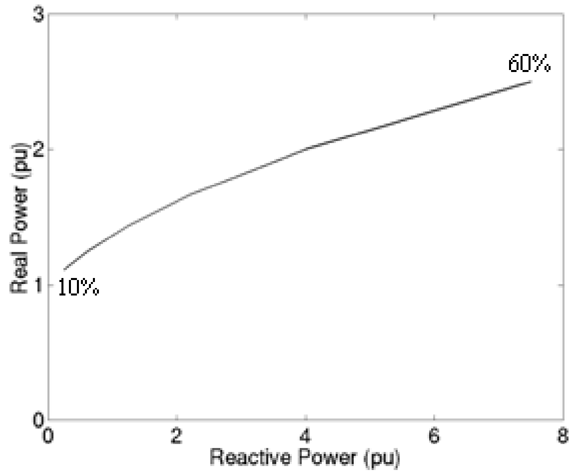


Fig. 10.13 Reactive power injection by a series compensator versus maximum power transfer as thelevelofcompensationchangesinconstant reactancemode.

AnAlternateMethodofVoltage Injection

So far we have assumed that the series compensator injects a voltage that is in quadrature with the linecurrent and its magnitude is proportional to the magnitude of the line current. A set of very interestingequations can be obtained if the last assumption about the magnitude is relaxed. The injected voltage isthengivenby

$$V_Q = \lambda \frac{\vec{I}_S}{|I_S|} e^{\mp j90^\circ} \quad (10.26)$$

Wecanthenwritetheaboveequationas

$$\frac{V_Q}{I_S} = \frac{\lambda}{|I_S|} e^{\mp j90^\circ} = \mp jX_Q \quad (10.27)$$

i.e., the voltage source in quadrature with the current is represented as a pure reactance that is eitherinductive or capacitive. Since in this form we injected a constant voltage in quadrature with the linecurrent,weshallreferthisas**constantvoltage injectionmode**.

$$X_{eq} = X \mp X_Q$$

Thetotalequivalentinductanceofthelineisthen

$$P_e = \frac{V^2}{X_{eq}} \sin \delta = \frac{V^2}{X(1 \mp X_Q / X)} \sin \delta$$

DefiningV_S= V<δandV_R< 0°,wecanthenwritethepowertransferequationas

$$P_e = \frac{V^2}{X(1 \mp |V_Q| / |I_S| X)} \sin \delta$$

Since$|V_Q|$ /| I_S|

=X_Q,wecanmodifytheaboveequationasConsiderthephasordiagramofFig.10.14(a),whichisforcapacitiveoperat ionoftheseriescompensator.Fromthisdiagramweget

$$|I_S| X = |V_Q| + 2V \sin(\delta/2)$$

$$|I_S| X = -|V_Q| + 2V \sin(\delta/2)$$

SimilarlyfromtheinductiveoperationphasordiagramshowninFig.10.14(b),weget

$$P_e = \frac{V^2}{X} \sin \delta \frac{|I_S| X}{|I_S| X \mp |V_Q|} = \frac{V^2}{X} \sin \delta \frac{\pm |V_Q| + 2V \sin(\delta/2)}{\pm |V_Q| + 2V \sin(\delta/2) \mp |V_Q|}$$

$$= \frac{V^2}{X} \sin \delta \frac{\pm |V_Q| + 2V \sin(\delta/2)}{2V \sin(\delta/2)} = \frac{V^2}{X} \sin \delta \pm \frac{V}{X} |V_Q| \cos(\delta/2) \quad (10.29)$$

Substitutingtheabovetwoequationsin(10.28)andrearrangingwegetwherethepositivesignisforcapacitiveoperation

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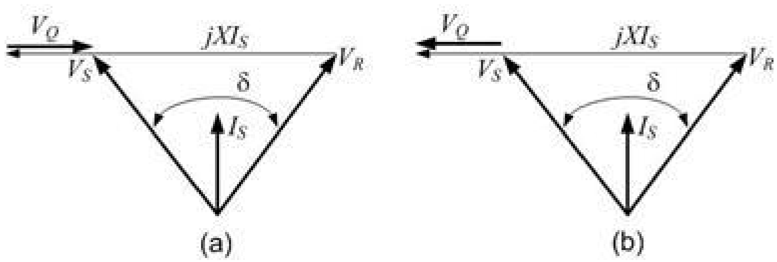

Fig. 10.14 Phasor diagram of series compensated system: (a) capacitive operation and (b) inductiveoperation.

The power-angle characteristics of this particular series connection are given in Fig. 10.15. In this figurethe base power is chosen as V^2/X . Three curves are shown, of which the curve P_0 is the **power-anglecurve**when the line is not compensated. Curves which have maximum powers greater than the basepower pertain to capacitive mode of operation. On the other hand, all curves the inductive mode ofoperation will have maximum values less than 1. For example, in Fig. 10.15, the curve P_1 is for capacitivemodeandthecurveP_2 isforinductive mode of operation.

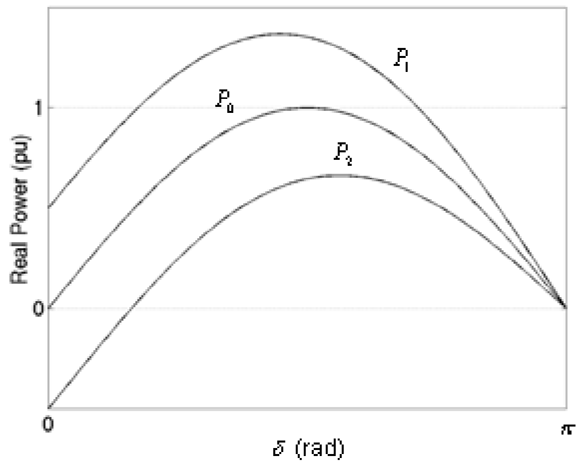

Fig.10.15Power-anglecharacteristicsforconstantvoltagemode

$$Q_Q = |V_Q||I_S| \quad (10.30)$$

Thereactivepowersuppliedbythecompensatorinthiscasewillbe

ImprovingStabilityMargin

From the power-angle curves of Figs. 10.13 and 10.15 it can be seen that the same amount of power canbe transmitted over a capacitive compensated line at a lower load angle than an uncompensated system.Furthermore,anincreaseintheheightinthepower-anglecurvemeansthatalargeramountofdecelerating area is available for a compensated system. Thus improvement in stability margin for acapacitiveseriescompensatedsystemoveranuncompensatedsystemisobvious.

Comparisons oftheTwo Modes ofOperation

As a comparison between the two different modes of voltage injection, let us first consider the constantreactance mode of voltage injection with acompensation level of 50%.Choosing V^2/X as the basepower, the power-angle characteristic reaches a maximum of 2.0 per unit at a load angle $\pi / 2$. Now $|V_Q|$in constant voltage mode is chosen such that the real power is 2.0 per unit at a load angle of $\pi / 2$. This isaccomplishedusing(10.29) where weget

$$|V_Q| = \frac{2 - \sin 90°}{\cos 45°} = 1.4142 \text{ Per unit}$$

The power-angle characteristics of the two different modes are now drawn in Fig. 10.16 (a). It can be seenthat the two curvesmatch at$\pi / 2$. However, the maximum powerforconstant voltage case is about 2.1perunitandoccursatanangleof 67° .

Fig. 10.16 (b) depicts the line current for the two cases. It can be seen that the increase in line current ineithercaseismonotonic.Thisisnotsurprisingforthecaseofconstantreactancemodesinceastheload angle increases, both real power and line currents increase. Now consider the case of constant voltagecontrol. When the load angle moves backwards from π /2 to 67°, the power moves from 2.0 per unit to itspeak value of 2.1 per unit. The line current during this stage decreases from about 2.83 to 2.50 per unit.Thus,eventhoughthepowerthroughthe lineincreases,thelinecurrentdecreases.

PowerFlowControlandPowerSwingDamping

Oneofthemajoradvantagesofseriescompensationisthatthroughitsuse realpowerflow overtransmission corridors can be effectively controlled. Consider, for example, the SMIB system shown inFig.10.17 in which the generatorand infinite bus are connected through adouble circuittransmissionline,labeledline-1andline-2.Ofthetwotransmissionlines,line-2iscompensatedbyaseriescompensator.Thecompensatorthencanbeutilizedtoregulatepowerflowovertheentiresystem.

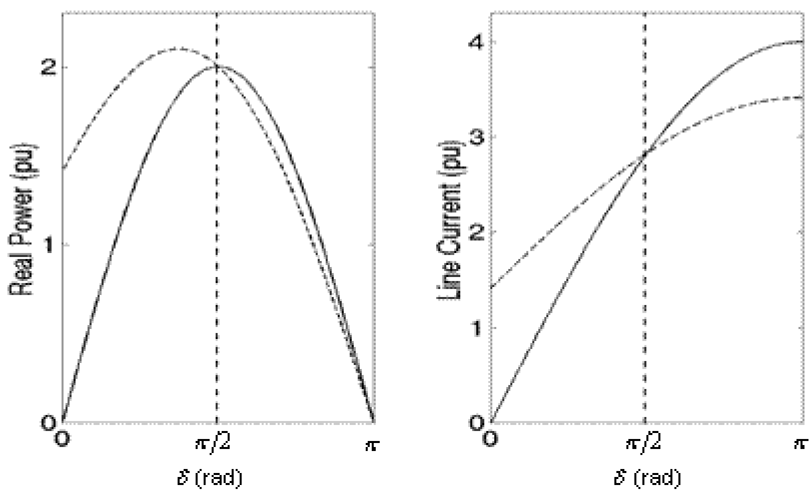

Fig.10.16Power-angleandlinecurrent-anglecharacteristicsofthetwodifferentmethodsofvoltage injection: solid line showing constant reactance mode and dashed line showing constantvoltagemode.

For example, let us consider that the system is operating in the steady state delivering a power ofP_{m0}at aload angle of δ_0 . Lines 1 and 2 are then sending power $P_{e1}$and P_{e2}respectively, such that $P_{m0}= P_{e1}+ P_{e2}$.The mechanical power input suddenly goes up to P_{m1}. There are two ways of controlling the power in thissituation:

- **Regulating Control**: Channeling the increase in power through line-1. In this case the seriescompensator maintains the power flow over line-2 at P_{e2}. The load angle in this case goes up insympathywiththe increaseinP_{e1}.
- **TrackingControl:** Channeling the increase in powerthrough line-2. In this case the seriescompensator helps in maintaining the power flow overline-1 at P_{e1}while holding the load angletoδ_0 .

Let usillustratethesetwoaspectswiththehelpofanumerical example.

Example10.4

LetusconsiderthesystemofFig.7.8wherethesystemparametersaregivenby

SystemFrequency=50Hz,|*VS*|=|*VR*|=1.0perunit,X=0.5perunitand$d$0=30°/

Itisassumedthattheseriescompensatoroperatesinconstantreactancemodewithacompensationlevelof30%.Wethenhave

P_{e1}=1.0perunit,P_{e2}=1.43perunit,P_m=2.43perunit

The objective of the control scheme here is to maintain the power through line-2 to a pre-specified value,P_{ref}. To accomplish this a proportional-plus-integral (PI) controller is placed in the feedback loop of P_{e2}.Inaddition,toimprovedampingaterm thatisproportionaltothedeviationofmachinespeedisintroducedinthefeedbackloop.Thecontrollawisthengiven by

$$C_L = K_P\left(P_{ref} - P_{e2}\right) + K_I\int\left(P_{ref} - P_{e2}\right)dt + C_P\frac{d\Delta\delta}{dt} \qquad (10.31)$$

Where $C_L = \lambda / X$ is the compensation level. For the simulation studies performed, the following controllerparametersarechosen

K_P=0.1,K_I=1.0andC_P=75

RegulatingControl: Withthesystemoperatinginthenominalsteadystate,themechanicalpowerinputis suddenly raised by 10%. It is expected that the series compensator will hold the power through line-2constant at line-2 at P_{e2}such that entire power increase is channeled through line-1. We then expect thatthe power P_{e1}will increase to 1.243 per unit and the load angle to go up to 0.67 rad. The compensationlevelwillthenchangeto13%.

The time responses for various quantities for this test are given in Fig. 10.18. In Fig. 10.18 (a), the powerthrough the two line is plotted. It can be seen that while the power through line-2 comes back to itsnominal value following the transient, the powerthrough the otherline is raised to expected level.Similarly,theloadangleandthecompensationlevelreach theirexpectedvalues,asshowninFigs.10.18 (b) and (c), respectively. Finally, Fig. 10.18 (d) depicts the last two cycles of phase-a of the line currentandinjectedvoltage.Itcanbeclearlyseenthatthesetwoquantitiesareinquadrature,withthelinecurrentleadingthe injectedvoltage.

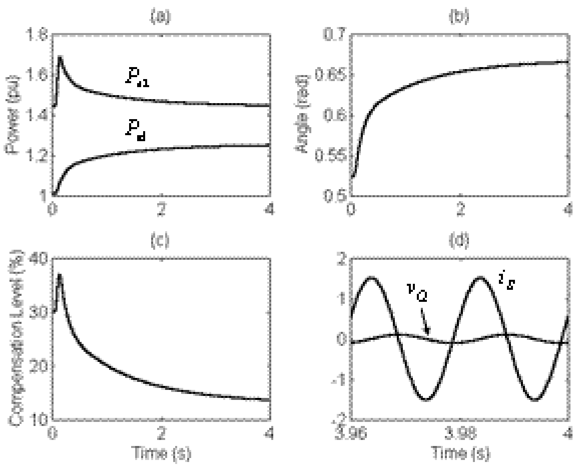

Fig.10.18Systemresponsewithregulating powerflowcontrollerTrackingControl

With the system operating in the nominal steady state, the mechanical power input is suddenly raised by25%. It is expected that the series compensator will make the entire power increase to flow through line-2such that both $P_{e1}$and load angle are maintained constant at their nominal values. The power P_{e2}throughline-2willthenincreasetoabout2.04perunitandthecompensationlevelwillchangeto51%.

The time responses for various quantities for this test are given in Fig. 10.19. It can be seen that while thepower through line-1 comes back to its nominal value following the transient, the power through the otherline is raised to level expected.Similarly,the load angle comes back to its nominal value and thecompensation level is raised 51%, as shown in Figs. 10.19 (b) and (c), respectively. Finally, Fig. 7.19 (d)depictsthelasttwocyclesofphase-aof thelinecurrentandinjectedvoltage.

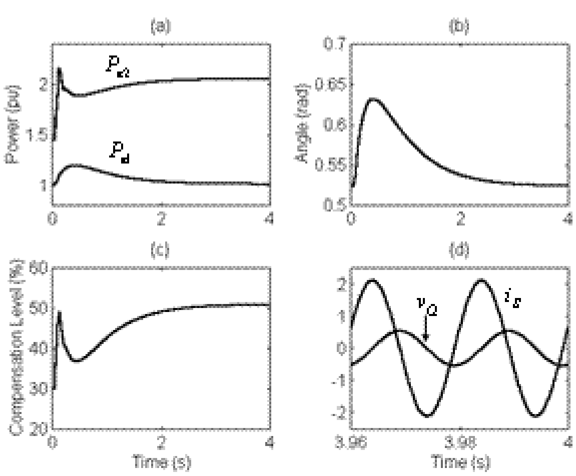

Fig.10.19Systemresponsewithregulating powerflowcontroller