Economic Operation and Control of Power System

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Week - 11

Lecture – 51

Hello and good morning everyone, welcome you all for the NPTEL online course on Economic Operations and Control of Power Systems. Today's lecture will discuss about Control of Generations. So the optimal dispatch and scheduling of generation establish the best operation point with respect to economics right. So based on economic load dispatch, economic dispatch we will be getting the best operation point which is economical and OPF will also help us understand that ultimately whatever the generation that we are planning it should be also economical including the system constraints. So the operating point must be implemented via generation control. Let us say you give a command this is a generation output that need to be achieved.

So how do you achieve it actually at the end of the day there should be some control loops acting together such that you would be able to manage that specific generation from a particular generator. Also if there is a change in load conditions these generators would be able to adjust the generator output such that the change in load will not have any effect in change in frequency. So this is the objective. So local generator control for each individual generator because ultimately in the root level each generator output will be changed such that you will not feel any change in system frequency.

Energy control center for the control of a large utility and the flow of power across interconnections to other utilities. So like there are multiple utilities they are connected together during using tie lines. So you should ensure that the frequency will be managed here also but ultimately if there is any tie line power exchange that need to be taken place that will be also be done such that even in that case the frequency will be managed properly maintained at a nominal value. So regional control over several utilities and the independent power producers IPPs that is ISO independent system operator will be playing a crucial role in power exchange and RTO original transmission system operator will ensure that proper control action is taken place at the regional level at the national level such the interstate power control will be proper. So many generators supply power to the transmission system in reality it is not one single generator which is managing the entire power so it is a multiple generators.

So consumer loads are constantly changing the power level because you keep on changing the loads in your home switching on the lights switching off ACs and all these things perturbations will be always there from the distribution load side. So some control means are needed to allocate the load changes to the generator there should be some means where you reflect the changes in the load on the generator side. So a governor in each unit maintains a mechanical speed basically the governor is meant to maintain the speed this one is called a speed governor if you maintain speed then automatically you also maintain the frequency. So basically ultimately what you need to do if there is a change in load you need to adjust the speed by using speed governors. So you see here this is what a simple block diagram you can see there is a entire power So there are multiple generators connected let us say here we are giving an example generator 1 and generator 2 the turbine generator unit combination is there and you are sensing the power output of individual generator and you are also measuring the system frequency.

If there is a change in system frequency you would take an appropriate control action there is a common control system is there from there you would dispatch individual control signal is a common control system is there from there you would dispatch individual control signal to individual generator such that a change in system frequency will be managed by all the generators. Otherwise let us say you can take a control action and push one single generator couple of generators to manage then it will be overburden it will not be a justice for sharing change in load. So ultimately the change in frequency which is occurring due to change in load need to be managed by all the generators hence both individual control signal is being generated from the main control center and the appropriate action is being taken place. And also measurement of tie line flows to neighboring system is also managed by this generation control system. We need to define different models so first we will start with generator model.

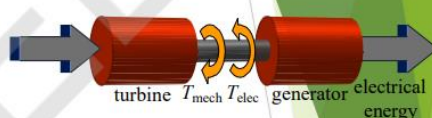
So here is a turbine so the input could be steam or you know whatever the water or could be gas or whatever anything renewable energy also you can take renewable energy also. So whatever is the input there is a force which is making the turbine to rotate and that is coupled with a generator through a shaft and ultimately we are getting electrical energy. So the turbine is producing mechanical energy so let us say this is a mechanical torque that is seen but if there is a load connected let us say this is a utility there is a load connected there will be opposite torque being applied which is due to the effect of Lenz law you can say. So the electromagnetic torque is being reflected such that it would try to reduce the speed if there is more load so then there will be change in frequency. So that we will discuss how in spite of there is a load we will keep manage the frequency at nominal value.

So these are some of the parameters:

- ω = rotational speed
- α = rotational acceleration
- δ = phase angle of a rotating machine
- T_{net} = net accelerating torque in a machine
- T_{mech} = mechanical torque exerted on the shaft by the turbine
- T_{elec} = electrical torque exerted on the shaft by the generator
- P_{net} = net accelerating power
- P_{mech} = mechanical power input
- P_{elec} = electrical power output
- I = moment of inertia for the machine
- M = angular momentum of the machine

So these are the parameters which are important for generator model. So basic relationship we will start with the basic so acceleration principle is T net.

- Basic relationships
  - acceleration principle: $T_{net} = I\alpha$
  - momentum principle: $M = \omega I$
  - power equation: $P_{net} = \omega T_{net}$

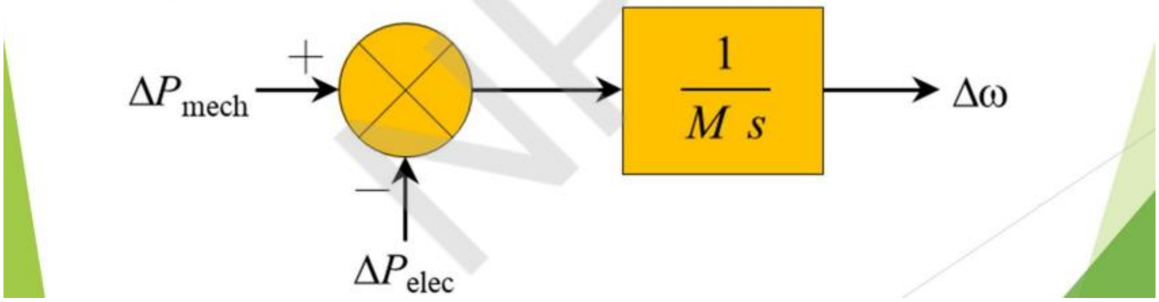


- Phase Angle deviation
  - general shaft equation: $\omega = \omega_o + \alpha t,\ \delta = \delta_o + \omega_o t + \frac{1}{2}\alpha t^2$
  - deviation from nominal: $\frac{d}{dt}(\Delta\delta) = \Delta\omega = \alpha t$
  - relationship to torque: $T_{net} = T_{mech} - T_{elec} = I\alpha = I\frac{d^2}{dt^2}(\Delta\delta)$
  - deviation of power: $P_{net} = P_{mec} - P_{elec} = \omega T_{net} = \omega I \frac{d^2}{dt^2}(\Delta\delta)$
  - the resulting swing eq.: $P_{mech} - P_{elec} = M\frac{d^2}{dt^2}(\Delta\delta) = M\frac{d}{dt}(\Delta\omega)$

Now apply Laplace transform this is during steady state mechanical torque is equal to electric delta that is:

- $T_{mech_O} = T_{elec_O}$
- $T_{net} = T_{mech_O} - T_{elec_O} + \Delta T_{mech} - \Delta T_{elec} = \Delta T_{mech} - \Delta T_{elec}$
- $P_{net} = \omega T_{net} = \omega \Delta T_{mech} - \omega \Delta T_{elec} = \Delta P_{mech} - \Delta P_{elec}$
- $\Delta P_{mech} - \Delta P_{elec} = M \frac{d}{dt}(\Delta\omega)$
- $\Delta P_{mech} - \Delta P_{elec} = Ms(\Delta\omega)$

Block diagram model

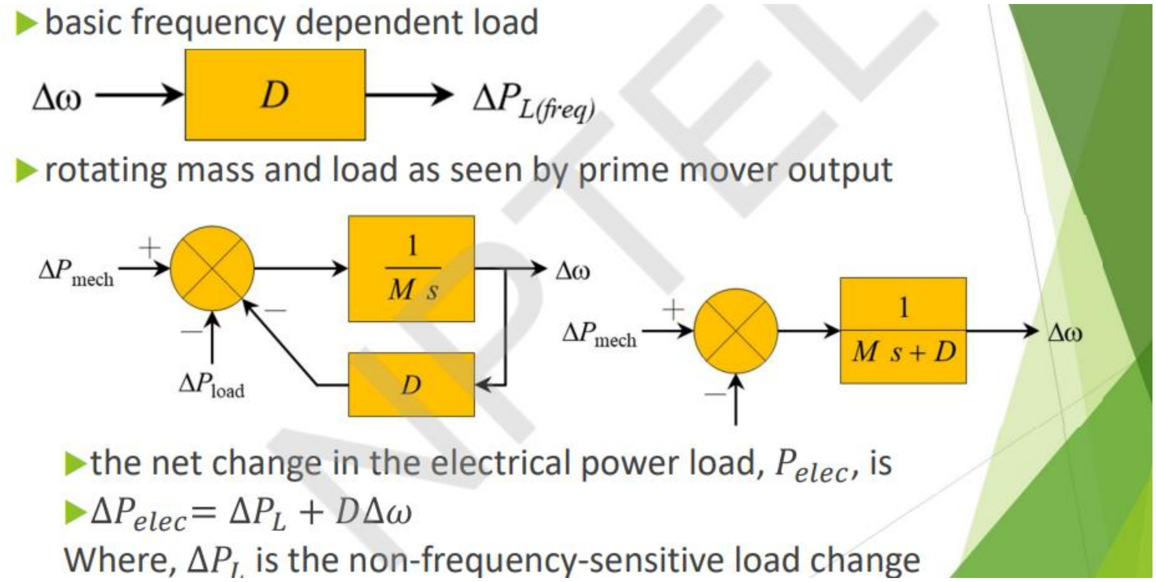


Now we will go to load model. Electrical load consists of varieties of devices purely resistive load, nowadays power electronics loads are also there which are non-linear loads and motor loads dynamic loads rotating machines. So motor loads dominates the mix of loads basically because most of the industrial loads are motor loads. Motors exhibit a variable power frequency characteristics, model of the effect of a frequency change on the net load drawn. That means if there is a change in frequency that is also reflected in terms of change in power output from this machines.

So that need to be also taken care in the control loop, frequency dependent loads, their performance depends upon the change in frequency. So

$$\Delta P_{L(freq)} = D.(\Delta\omega)$$

So D is expressed as that factor as a percentage change in load per percentage change in frequency. So percentage change in load means actually delta PL here, percentage change in load with respect to percentage change in frequency. Due to some reason if there is change in frequency because of that there will be change in power output from these loads.



So this is nothing but your delta P load, delta P load and you will get this overall control loop. So the net change in electrical power load is P electrical is delta P electrical is equal to delta PL plus d delta omega. D delta omega is due to frequency dependent loads. There will be some loads also which are not frequency dependent loads. Even though there is change in frequency these loads will not have any impact.

So the special effect due to change in frequency is not seen here. So henceforth the total net electrical power load changes, effect due to change in load due to frequency dependent loads and just normal loads which are not frequency dependent loads. So let us take an example. Consider an isolated power system on a 1000 mega volt ampere base. So 600 MVA generator is considered where moment of inertia momentum is 7.6 per unit mega watt per unit frequency per second on the machine base and 400 MVA is the load which is considered. So the load changes by 2 percentage for a 1 percentage change in frequency. So here we are getting an idea about what is d. d is equal to 2 percentage by 1 percentage change in load with respect to change in frequency. So d is equal to 2 basically. Suppose that the load increases by 10 MVA. What is the transient response of the system frequency? So change everything to the per unit level now that will be easy for our analysis. M is equal to we have given 7.6 mega watt means is 600 by base is 1000.

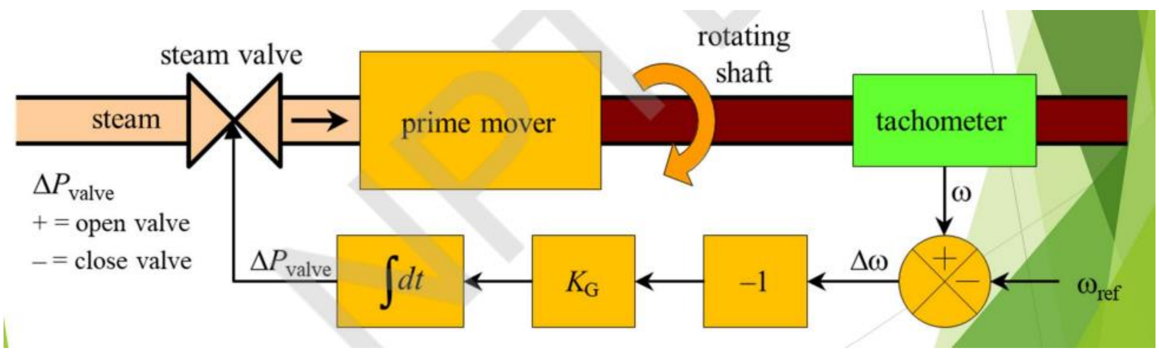
So you will get 4.56 per unit. d is equal to 2 into we just calculated 2 this into this is at 400 MVA this is the load and divided by 1000 you will get 0.8 per unit and delta P L is the change in load which is increasing load this is 10 MVA with respect to base this is 0.01 by S. Because this is changing with respect to time so 0.01 by S. That is delta omega S is equal to delta P L into 1 by M S plus d according to our control loop that is 1 by M is 4.56 and d is 0.8. So this is your delta P L and then sorry this is your delta omega and then this is in Laplace domain change to time domain.

So you will get this term. So the change in frequency with respect to time is indicated here as a transient response. Next we will move to prime mover model. The prime mover drives the generating unit. It could be steam turbine or hydro turbine whatever. So there is a steam input and that is regulated using a steam valve.

That is regulated using a steam valve. Either you can even though if there is steam input you can close it so that prime mover may be may not be getting any input at all so that control is there. So again then based on how much you open based on that you will get the mechanical power output. So modelling must account for control system characteristics. Example boiler and steam supply. You see a model of the non reheat turbine.

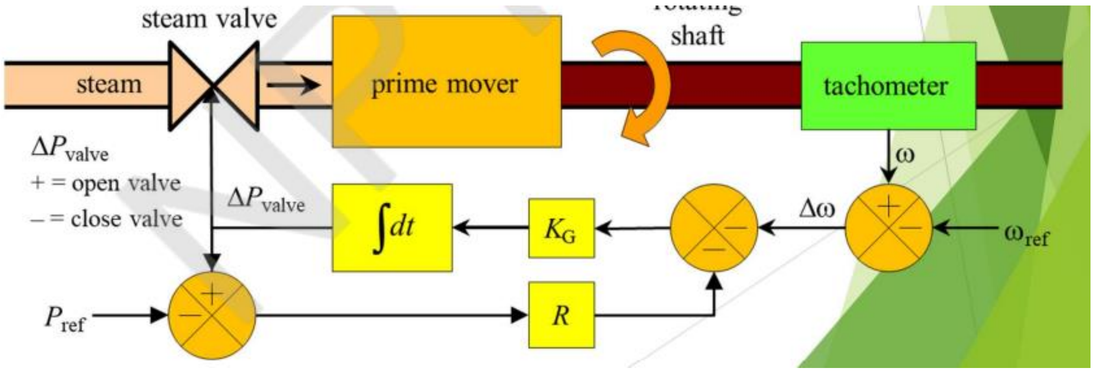
So delta P wall into 1 by 1 plus S TCH is delta P mechanical. That means the mechanical power output will be indirectly depending upon how much steam valve proportionately will open. So that is expressed in terms of this action. Delta P mechanical is equal to this is the transfer function 1 by 1 plus S TCH because there will be a charging time, time constant is involved when we open it and per unit change in valve position from nominal value delta P valve.

So now this is your prime mover model.

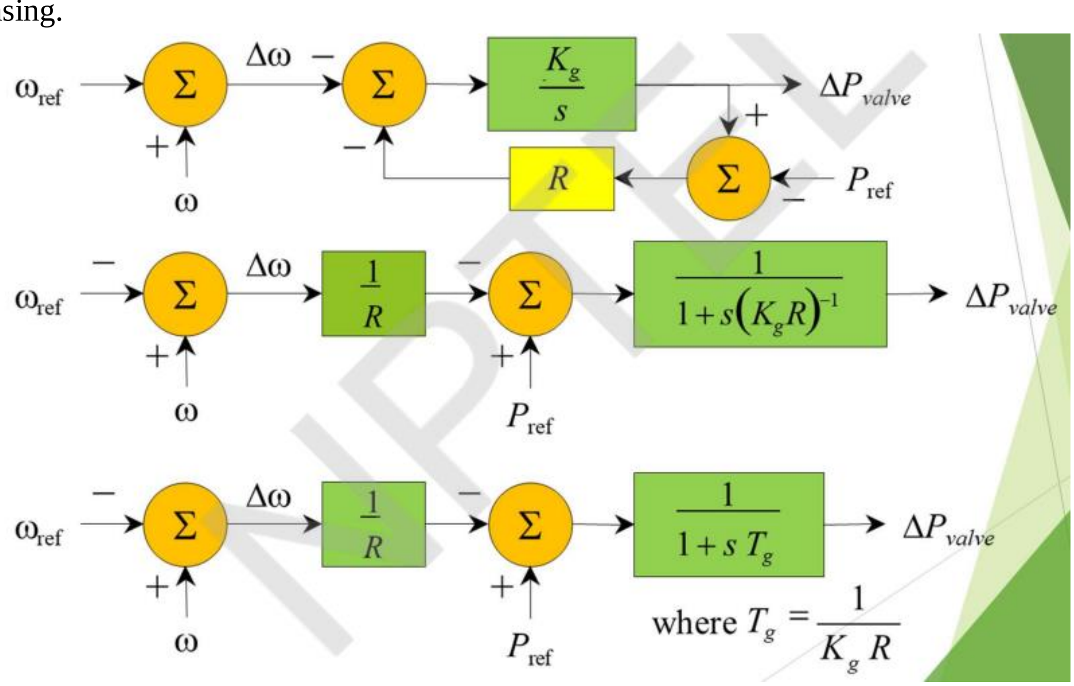


The delta P mechanical is coming and it is dependent on the P valve. So that also we need to be included when you consider the overall control function. So delta P valve into 1 by 1 plus S TCH will give delta P mechanical and this subtracted by delta P load multiplied by 1 by MS plus D. This is due to the swing equation that we are getting this and dependent loads, frequency dependent loads.

You are getting delta omega ultimately. Now governor model.



The governor compensates for change in shaft speed. Changes in load will eventually lead to change in shaft speed basically. Change in shaft speed is also seen as a change in system frequency. So simplest type of control is the isochronous governor. Isochronous means there is only one generator connected to the system where there are loads present. Now how it works? Now there is a steam input which is regulated through steam valve through a prime mover and there is a rotating shaft. Let us say there is a generator and all is there. Now you use a tachometer to measure the speed and there is a nominal frequency. Let us say it is 50 hertz for India that need to be regulated and let us say there are so many loads which are connected here in actual system. So the output of this may be connected to a generator. This is generator and generator output is connected to various loads. If there is a load which is connected to this generator output, so because there will be electromagnetic torque opposing torque, it will try to pull the frequency down because speed is decreasing now. If there is increasing load, speed will decrease because of which there is a difference which is created from the nominal value. There is a difference and this is being minus omega w reference because frequency speed is decreasing.



So this output is negative basically and you are again multiplied by negative that means it is positive here. So there is a gain just to increase the control action. Basically this is PI controller. This is integral controller. This is what is called as steady stator and ultimately what is the action? Action is your change in load will have to be reflected as change in steam wall output because of which the input will be increasing now.

So the entire thing is positive. Positive means what is there? Open the valve, you open it even wider so that more steam can go inside. Let us suppose the speed is increased because load has decreased. So this output will be positive. This is positive here. This is positive and this is negative and ultimately you will close the wall.

So this is with respect to one single generator. It can manage it quite comfortably. What will happen if there are multiple generators because in actual power system and they are connected to infinite grid, there are multiple such generators which are running in parallel. So you can either just put a bird on one single generator, take the control action, just keep one generator to cater to the requirement, change in load that will not be possible actually in real sense. No one single generator can is having sufficient capacity to manage to the entire system. So you need to change, this reflection of change in load has to be distributed across different generators.

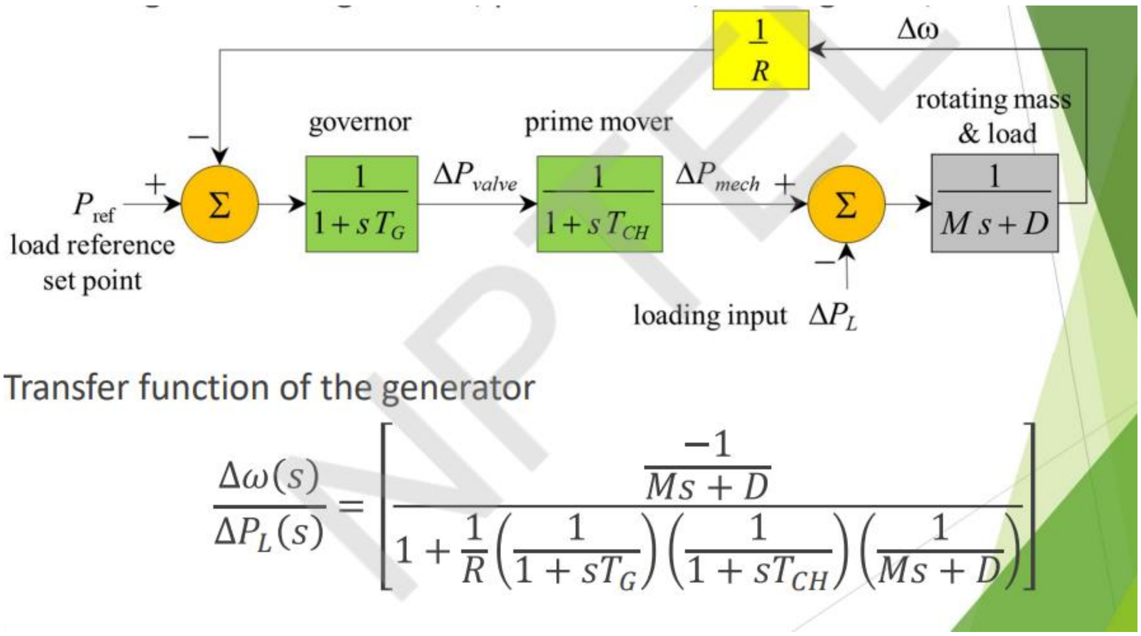
So to force frequency error to 0 requires the use of an integration that we have discussed. The isochronous governor cannot be used when two or more generators are electrically connected to the same system. What will happen is there will be, there is a fighting between generator governors for system frequency. Everyone wants to pull actually. So this will lead to system instability and problems with load distribution between generators and also you are not judiciously distributing the change in load among different generators.

So these are the two issues. So a load reference control provides settings for both the frequency and the desired power output basically. So a new input, the load frequency signal controls the desired power output. A feedback loop contains a gain R that determines a speed loop characteristics. So basically a speed loop characteristics, the governor or a loop characteristics will help to ensure that during normal and transient conditions the load is shared among the multiple generators. I will explain you in detail. So the speed loop function handles the load sharing between generators. There will always be a unique frequency at which the system loading will be shared among the generators. The gain R is equivalent to the per unit change in frequency for a one per unit change in power. This is what is droop coefficient. Change in frequency with respect to change in power and individual generator has its own droop coefficients that depends upon its size and capacity. Now what is happening? This is a general control loop characteristics. So we are adding this extra term now. There is a load reference set point or it is also considered to be governor set point. So because at this load reference set point you will be able to appropriately generate a rated frequency, a nominal frequency.

So now there is a summation block as you can see here. There is a summation block. So delta P valve, the valve position output is again checked with the load reference set point and this output is connected to the droop coefficient and this is again connected to the main summation block here. So what is happening? So let us say there is a decrease in load or let us say there is an increase in load. The frequency is decreasing, speed is decreasing.

So that means this output is negative, this is what I told. In case of single generator the entire burden was on one single generator. That is what we have discussed in the last slide. Now what will happen? Because of the presence of the droop this need to be divided. That means you cannot have 100% shearing on one single generator. That means whatever is the sign that you are getting here, this is negative. So negative into negative, this will be positive here. At this side this is positive. But here what you are getting is this is a negative. So positive negative that means earlier let us say it was for example 100% in the first case without this droop characteristics included, let us say it was 100%. 100% in the sense, 100% reflection on one single generator. Now because of the droop this will reduce the shearing on individual generator. It could be 80%, 50% or 30%, 20% it could be any number. But it will be less than the previous number and that will be shared based on their capacity. So again this will be applied to integrator control. So appropriate valve opening is being catered such that all the generators which are running in parallel will share the change in load and the frequency will be adjusted with a cumulative effect basically. So the same block diagram is being simplified here. So this is P reference, this is load reference set point and then there is a droop coefficient and delta omega minus this and this is the integrator control and is applied to the valve position basically.

This is the same thing which is represented in a different manner. You can change the, you can shift this basically block diagram reduction techniques so that you will be able to obtain a transfer function ultimately. So we are just using block diagram reduction techniques.



So R is shifted here, this is 1 by R then you will get this term 1 by 1 plus S kg R whole inverse and ultimately this is what you are getting where 1 by kg R is reflected as 1 by S 1 plus S tg. So this is what I was interested to show actually speed droop characteristics. So if there is a change increase in power output by generator you can say here there is a change in frequency, drop in frequency basically. So if there are two generators which are sharing the power unit 1 power output is unit 2 power output. So you can see here this is the nominal frequency let us say this is 50 hertz. So for that the power shared by the first generator is P1 and the power shared by the second generator is P2. They have different droop characteristics. So if the load is increased then the power output from the first generator is changed from P1 to P1 dash and power output from the second generator is changed from P2 to P2 dash such that P1 dash plus P2 dash will be is equal to change in load.

But as a result of this now both of these generators are agreeing to operate at a different frequency which is different from nominal frequency. Earlier it was F0 now they are operating at F dash. This is a primary control action, primary frequency control loop. The secondary frequency control loop will ensure that ultimately you need to restore the frequency to the 50 hertz nominal value so that the further change in the valve output should be taken place by each of the generators such that they will contribute and maintain the frequency at 50 hertz. Otherwise what will happen there are so many frequency dependent loads that is what we have told.

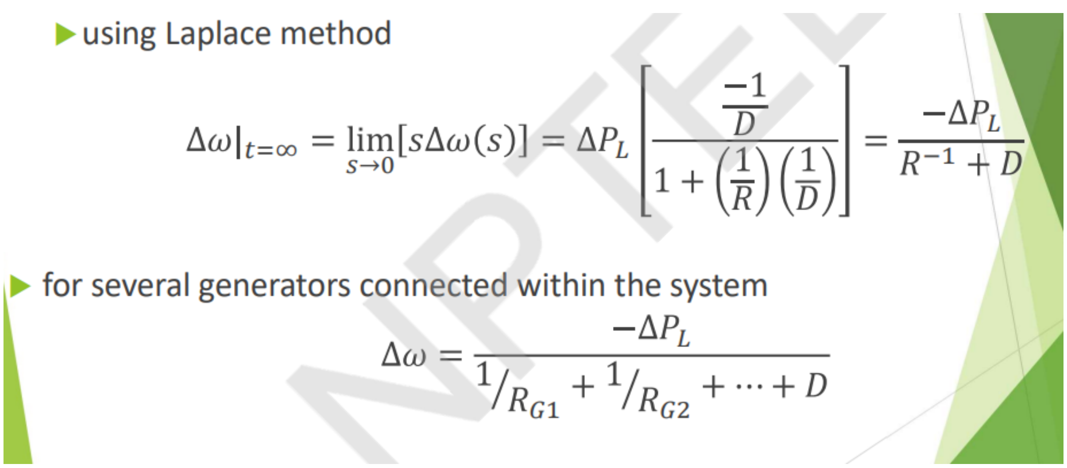
The frequency dependent loads could able to operate at better, could able to show a better performance at F0 rather than at F dash because F0 is what a rated frequency at which this motor is also designed for. So you need to bring back the frequency from F dash to F0. So for that you need to again change the governor output that is what we have done in the previous here. This is what is taking care of that secondary control action. Frequency 50 hertz need to be restored and that need to be also again you see here that need to be shared among the generators.

How much valve need to be changed proportionately based on the capacity. So speed changes settings this is what load reference for nominal speed, load reference set points. This is for nominal speed at no load, load reference for nominal speed at 50% loading. This is at 50% loading. You are just changing the governor set points basically from here to here. Load reference for nominal speed at 50% loading you can see this is also there. So this is the overall block diagram. This is the overall block diagram. You can see this is a P reference, this is a load reference set point and then there is a governor. First thing that will come is governor. From governor this valve is adjusted such that the prime mover is rotated and at individual level there is a different control transfer function that is been added.

This is a transfer function of the governor, this is a transfer function of the prime mover. The output of prime mover is mechanical power output that is compared with the loading input that is load basically and this is the rotating mass and the frequency dependence load. Finally there is a change in frequency then that is connected with the droop characteristics and is reflected back to the first summation block. So the transfer function is output by input that means delta omega s by delta p L s.

So you will get this transfer function ultimately. If you do the transfer function analysis you will get this. What is the steady state behaviour?

So final value of the transfer function that means t tends to infinity that means s is equal to 0. This is the final value theorem.



So for several generators connected within a system change in frequency is reflected in terms of cumulative effect of all the droop characteristics. This is with respect to one single generator. So multiple generators have their own droop characteristics and there is also a term which is relevant to frequency dependent loads D. So this will decide the effect of the change in frequency with respect to change in load. So with this we will conclude today generator control. Thank you very much.