Economic Operation and Control of Power System

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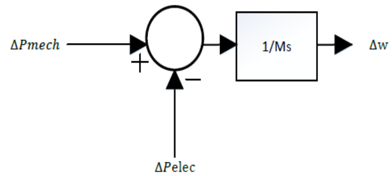
Week - 01

Lecture - 03

The important aspect of power system is control engineering where we need to control the power outputs and also is specific to automatic generation control we are expected to restore the system frequency when it deviates from either 50 or 60 hertz. It is also important to relocate generation to keep it at economic dispatch point. Also keep interchange with other control areas as scheduled megawatts. Monitor and control generators as they ramp up and ramp down. So, if you see the power system is a very dynamic one which has to increase its power output. Sometimes, it has to reduce its power output sometime and then we are supposed to transmit x mega watt of power from one area to other area. And then the operating economic operating point which is let us say x mega watt that has to be generated at that given point of time and the frequency need to be very close to 50 or 60 hertz always. Though it is next to impossible to achieve exactly 50 or 60 all the time but the attempt to have it same because if you can have a same frequency throughout the day then your system become very big. Now first of all try to understand the basic turbine generator mechanism what exactly happens. So as you could see, you know there is a rotating device where you give mechanical energy and the turbine actually rotates and that drives your generator and then you have electrical energy as an output. Now frequency directly related to the speed of rotation. So whenever there is a rotating device then you have frequency. So the frequency become constant when the rotation become constant. Now similarly, it is also expected that the mechanical energy and the electrical energy output they must be equal. Whatever the mechanical energy you provide it is expected to deliver same amount of electrical energy with different forms. So the mechanical torque which is very important factor which is negative of electrical torque in the speed remain constant. So you could see the direction of rotation of the turbine and the generator they are opposite to each other so negative to each other. Electrical load changes are uncontrolled because we consumers behave differently so no one can control the load to a particular value. So the load has to oscillate every second every milliseconds so they are uncontrollable. So we must control the mechanical energy input to match. Very interesting. So now what is happening the electrical energy requirement is keep on oscillating. So we cannot make it constant because it is impossible because it depends on many customers behavior. However, the mechanical energy input that we are providing to generate electricity that need to be controlled as per the variation being seen through my electrical energy requirements. So that is the challenge. So for that we need to have control mechanisms to control your operation and you could see that there is a general control system which receives many signals from different corridors. That is signals through turbine generating unit and if you have many turbine generating units then each and every turbine generating unit must communicate to your generation control systems and you must be also having tie power flow, tie line power flow to neighboring system. For example, let's say there is a power transmission between Uttarakhand to Rajasthan. So if there is an agreement that this amount of power has to be exchanged so probably you have to make sure that all the time the tie line flow is as per your desired commitment. So that is another interesting point and then you have to measure the generator electrical output, you have to measure the generator system frequency and also you need to measure the neighboring output.

So all those signals we have to collect and then give to your generator control system every second or every millisecond. Now let us get into the mathematics of it. Now when you try to carry out mathematical analysis of generation control what exactly happens that the I alpha which is the net torque and the m which is omega I, I will explain you the variables slowly. So the Pnet, Net power which is omega t net, the top net which is omega times I alpha because t equal to I alpha and which is nothing but my m alpha because omega I equal to m. So what is omega which is rotational speed, alpha is rotational acceleration, delta phase angle of rotating machine, T net is the net accelerating torque in the machine, T mechanical is the mechanical torque exerted on the machine by the turbine, T electrical is the electrical torque exerted on the machine by the generator and P net is the net accelerating power and similarly P mechanical which is mechanical power output and P electrical is the electrical power output and I is very well known moment of inertia and M is the angular momentum of the machine.

So these are the standard basic background and based on which we will try to develop some of the important equations in due course of time. Now if I have to model a generator because generator is a physical device and that generator need to be modeled. So what happens in a generator we give mechanical energy and there is a negative feedback signal which is coming from the change in electrical signal. So what is happening we detect the change in electrical power requirement and hence we change our mechanical power input so that the delta omega will be as per the desired one.



So that is what the relation is all about. So how do you get into this block diagram?

$$A = \pi r^2 \Delta P_{mech} - \Delta P_{elec} = \omega_o I \frac{d}{dt}(\Delta\omega)$$

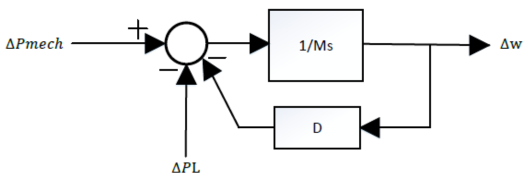
$$= \mathrm{M} \frac{d}{dt}(\Delta\omega) \ \ldots \ (3.2)$$

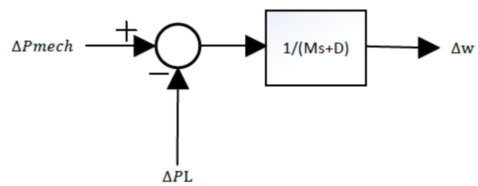
Now further expanding this equation you will come to know the generator which is being actually represented in mathematical form because this mathematical representations will help you to carry out certain analysis or derive certain expressions for your real time analysis. So that means if I do a computing program for example so I cannot take my physical machine and say that this is the device you measure the speed of it. So you have to represent each and every variable or component in a power system in a mathematical form before we create the whole control loop.

Now similarly we will try to model the load mathematically. So how do we do that?

$$\Delta P_{elec} = \underbrace{\Delta P_L}_{\text{Nonfrequency-sensitive load change}} + \underbrace{D\Delta\omega}_{\text{Frequency-sensitive load change}}$$

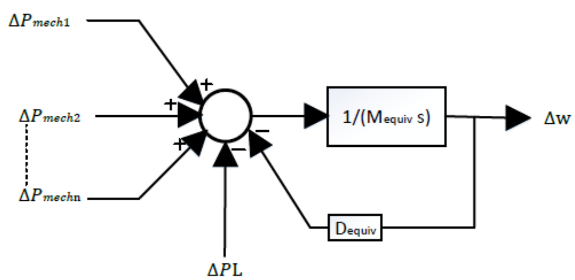
So when you talk about change in load that is delta p electrical we say change in electrical power. So there are two different components who decides the change in power. So because we behave differently. So one component which is non frequency sensitive load changes. So, that means there are few load changes they are not going to they are not frequency sensitive non frequency sensitive irrespective of frequency they will disturb. Now one more component which is frequency sensitive load changes. That means if you change the load then the frequency will be disturbed.





Because of that, the change in P, delta P which is given as two different component one is delta PL direct load change and the other one is actually frequency dependent which is D delta omega. So if you see the equation it is just compared to the previous diagram that I have given to you what will happen? The delta P mechanical, delta P electrical and the P load and the delta omega is in its place but you could see that the delta P electrical will also add another component which is D times of delta omega will now be injected in the place of actually delta P electrical. So instead of delta P electrical this equation as you could see which is being replaced by these two components. So from the above equation delta p electrical is being replaced by delta p load and d delta omega. Hence my original block diagram is now being replaced with this. Now I can make further simpler because as you could see it is one upon Ms and then there is D you can combine these two blocks and by combining you can get one upon Ms minus D. So my new block diagram now will be delta P mechanical with a positive input and then negative feedback of delta PL and the output is delta omega with a block of one upon Ms minus D.

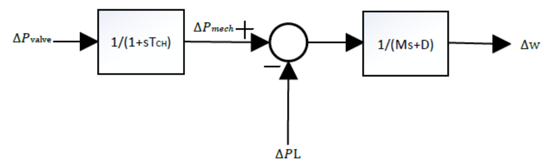
So this is what the current position. Further we will make it more clearer with other variables. Now if I go back to my generator model now so if because it may so happen that you may have a power plant with many generators. So now assuming there are n number of generators placed in a power system so you could see that the input may come from because there is a change in load I like to meet through n number of machines. So the mechanical power input from the machine one, machine two and machine n may contribute to achieve your load change. So if that is the case then the diagram is now being extended to this form:



Multi Turbine Generator Model

where you have delta P mechanical from generator one, two and from n and delta PL was there as it is and then you have D equivalent because when you have many machines one machine means one D. But if there are n number of machines then you have n Ds so you have to have D equivalent and then you can have one upon M equivalent into s and this delta omega. So it is now important for a multi turbine generator model it is as same as my single machine excluding the mechanical change in mechanical power inputs has to be different and also the D and M need to be not based on a single machine but it is multi machine based so you need to determine what is D equivalent and M equivalent for n number of machines. Now if you see that way then further you can change the system to a simpler diagram. So the delta P mechanical which is available to you so this is basically a model where you can see so let us fix it here.

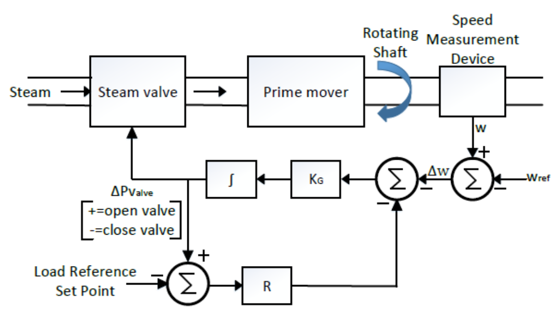
We have prime mover model as:

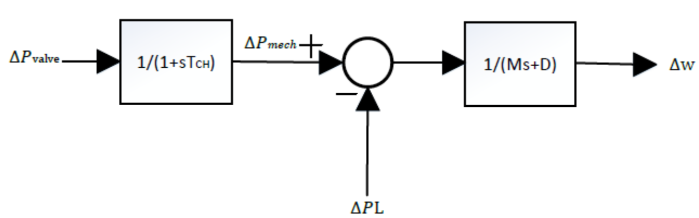


Prime Mover Model

So this is exactly similar that you have already discussed so this could be either for a single machine or it could be n machine system but the structure of the block diagram of the generator remain same excluding few of the variables that make up this model.

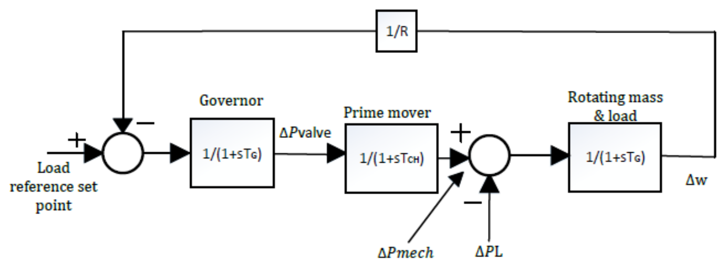
So let us move to what is governor model with droop speed. So governor model actually as you all know this is quite interesting so for the governor model the first of all this section we have already discussed but the governor model will help me to understand how this mechanical power that is being injected. So what we do basically we provide steam for the machine to run and that get into the steam valve and that rotates my rotating shaft and then we can measure the speed and then you can feedback mechanism to the valve. So this is what my delta P valve which is appearing here which decides that how much steam has to be given to the steam valve to rotate the prime mover so that my required frequency is being met. So this is very critical I request everyone to concentrate and focus here.





So we do have a low difference point here am I right and then this is basically your omega reference which is we let us say we like to operate at 50 hertz for an example or maybe 60 hertz whatever it is. So and you could experience some change in delta and that delta being actually managed and further feedback mechanism has gone to my steam valve so that in due course of time the frequency can actually be achieved. So this is the overall governor model actually with speed shared droop and what is speed droop try to understand. Speed droop characteristic is very simple where it talks about your frequency versus the power, frequency versus the output. Now one thing is very clear if the load is high and if you are drawing maximum power then your frequency is expected to drop.

How do I explain? If you are riding a cycle and if you allow your friend to sit or ride along with you or someone jumps into your back seat then the load become very very high then it is expected that you slow down the speed will slow down. So similarly when the load increases probably the frequency drops. So similarly when the load is low if there is the weight reduces then you ride faster when the weight is more then you ride slower so that is true characteristic to me and this is basically the power versus frequency changes and you could see that for different you know power variation that is if you move from P1 to P1 dash so that means there is increase in power so that has forced my frequency to drop from this level to this level. This is the mechanism to understand. Now what happens the droop characteristic will be different for different machines for different systems so unit 1 you could see by increasing this much of power the frequency drop this way and the other one actually by changing the power the frequency drop but one thing is very important if you fix the frequency drop remain constant in both the machines then the change in power need not be same. Either if you fix the power where power variation same then your frequency variation become different and if you fix the frequency then your power variation will be different if there are two different machines or two different systems. Now we will get into the model of the generation governor prime mover and rotating inertia so now it is a club system so this portion we have already seen where there is a mechanical power input and we have P load and this equation is known and delta omega. Now what we are doing actually because this prime mover up to the P valve we have seen now slowly we merge the first section to the second section now we are adding the governor one actually and finally you could see the overall block diagram of the whole system is captured starting from the load reference point so you have to have the load reference point and then whatever the practical delta omega you get that need to be reversed as a feedback mechanism to know whether you further need to change your valve or change your speed and then change your frequency so this is keep on changing so every second the frequencies keep on oscillating the valve is keep on changing its injection and the prime mover is keep on moving in a different way and hence the we always try to reduce the gap of delta omega so the delta omega is expected to be zero in a practical circumstances where whatever the desired frequency you are able to achieve by managing all these changes. Now if you solve this block diagram:



We get,

$$\Delta\omega = \frac{-\Delta P_L}{\frac{1}{R_1} + \frac{1}{R_2} \dots + \frac{1}{R_n} + D} \dots 3.3$$

If you go for tie line model actually tie line model, I already told you that you have two different areas and connected through a tie line. And this is one area you can control your change in load. If there is load change, you know how to manage. This is another area if there is load change you know how to manage both the machines, you can manage but if there is a tie line and you are committed to allow some X megawatt of power to flow so then this X megawatt power become a load to this generator and become an injection to this generator. So now because there is a tie line due to tie line now the each modeling of area 1 and area 2 become different so the whatever the modeling we have done in the past will change if there is a tie line attached to that area if there is no tie line you are perfect but if there is a tie line then that variation need to be accommodated. So what is tie line power flow which is 1 upon x tie theta 1 minus theta 2 because it decides based on the angle variation between two terminals or they will have the power flows. The flow model using linear power flow model can be also mentioned as:

$$P_{tieflow} = \frac{1}{X_{tie}}(\theta_1 - \theta_2) \dots (3.4)$$

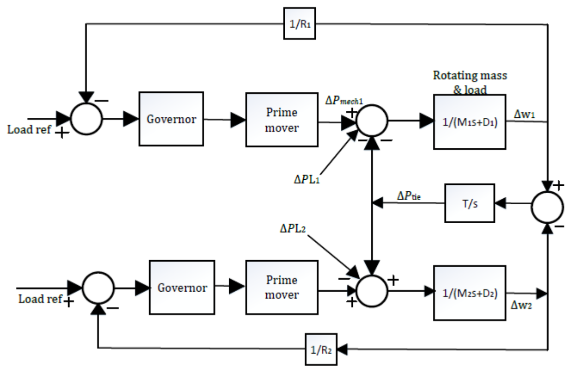
The flow modeled using linear power flow model

$$P_{tieflow} = \frac{1}{X_{tie}}(\Delta\theta_1 - \Delta\theta_2) \dots (3.5)$$

$$P_{tieflow} = \frac{T}{s}(\Delta\omega_1 - \Delta\omega_2) \dots (3.6)$$

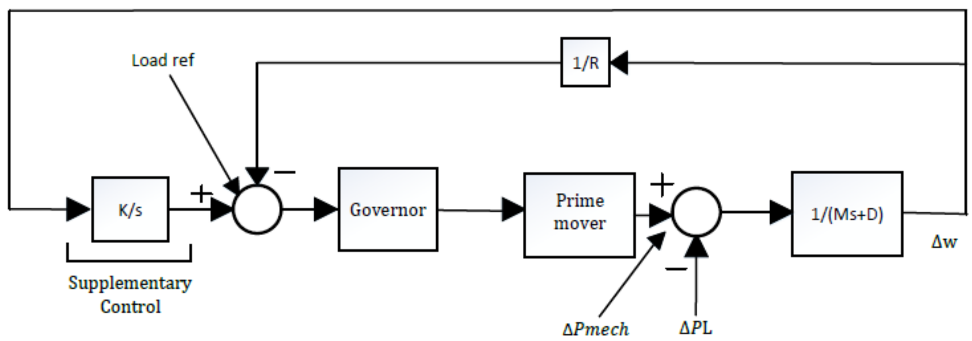
So the power flow in a tie line depends on the frequencies of both the area 1 as well as 2.

Now again the same system, I like to model with the tie line so if you look at this diagram very carefully so what we have done.



This is what you know the tie line power flow which is we mentioned delta P type the change in tie line power flow and this is what the exchange that takes place the interconnection between two areas so this is my one area and this is area 1, this is area 2 and there is a tie line so absolutely same system with two different R1s, R1 and R2 different variables and there is a load connected to first line the first area which is delta P L1 for the area 2 this delta P L2 but they are also interconnected. So what has happened now the change in load in the area 1 change in load in the area 2 and the change in tie line flow they are now interconnected. Now how does the frequency response to load changes. I have already discussed, but I am repeating it again so what exactly happened if there is a load change. You know there is a load, there is a you know step change in my load so when there is a step change in load, so you could see the frequency that start dropping, load increase, the frequency drops but this happens actually there is no governor action that means load increases. This drops imagine that you are riding a cycle someone joined you or try to you know capture this backseat of yours and the load increases. So, the speed reduces but if there is a mechanism to increase the speed based on the load increases then probably your speed become constant even though there is a variation in load. So, exactly happens in your machine where even though the load changes, the frequency is expected to drop but it not drop continuously. If you can accommodate governor action to that so you could see in the first case it drops but in the second case it drops. But finally it control to the desired frequency and the change in frequency delta omega is given by:

$$\Delta\omega=\frac{-\Delta P_L}{\frac{1}{R_1}+\frac{1}{R_2}+D_1+D_2} \quad \ldots 3.7$$



Now what do you understand by supplementary control because this is don't get confused here because this is for USA model you can also write it down 50 Hertz for rest of the country or maybe for India for example all right so supplementary control is necessary to drive frequency back to normal so if the frequency drops then you have to bring back to normal so that type of additional control is known as supplementary control so you could see this segment which is responsible for bringing back the frequency change due to load changes. Now there are a few basic rules that we follow in case of Tie line control so these are standard regulations:

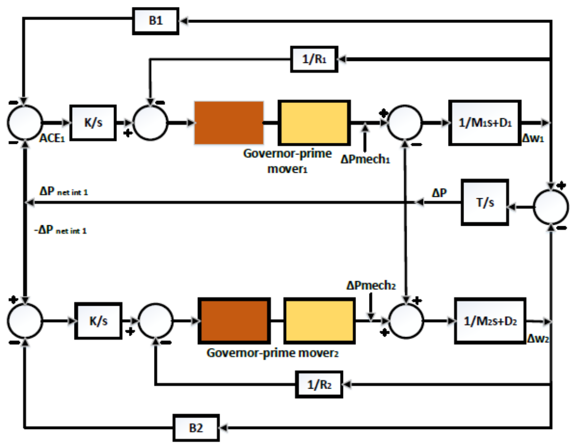
$\Delta\omega$	$\Delta P_{net\ int}$	Load change	Resulting control action
-	-	ΔP_{L1} + ΔP_{L2} 0	Increase P_{gen} in system 1
+	+	ΔP_{L1} − ΔP_{L2} 0	Decrease P_{gen} in system 1
-	+	ΔP_{L1} 0 ΔP_{L2} +	Increase P_{gen} in system 2
+	-	ΔP_{L1} 0 ΔP_{L2} −	Increase P_{gen} in system 2

What happens, there is load change:

Delta PL 1 is positive and Delta PL 2 is 0 means there is no change in load in my area 2 so this is my area 1 this is my area 2 or you can say this is my machine 1 and this is my machine 2 so there is no change in load in my machine 2 but there is change in load in my machine 1 that shows that increase speed generation in system 1 so because there is no change in the second system ok there is no change so don't disturb if there is a change in load in your area 1 so you have to increase the generation of the area 1 to make the load. Similarly, if there is a reduction in load in your area 1 no change in area 2 then you have to decrease the generation in that system ok the same thing applicable your area 2 also and subject to you can also imagine that the Delta Omega which is negative and Delta P net which is negative one segment I will clearly explain to you so that you don't have any confusion now let's say when Delta PL 1 is positive ok so that means there is a frequency drop is load increase so that means Delta Omega become negative and the

Delta P net interchange which is negative all right so because the load increased here so that means this flow will be negative and there is no change here and to balance the system now you have to increase the generation of the system. A similar rule is applicable to different whether increase and decrease for both area 1 as well as area 2.

Now what is area control error?



It is an important factor because when there are two different areas so there is an area control error which has been calculated for area 1 as well as area 2 so given by:

$$ACE_1 = -\Delta P_{netint1} - B_1 \Delta\omega$$

$$ACE_2 = -\Delta P_{netint2} - B_2 \Delta\omega$$

Now let us move to a very important logic known as the generator allocation using participation factor given by:

$$P_{ides} = P_{ibase} + pf_i \times \Delta P_{total}$$

$$\Delta P_{total} = P_{newtotal} - \sum_{all\ gen} P_{ibase}$$

P_{ides}= new Desired Output from unit i

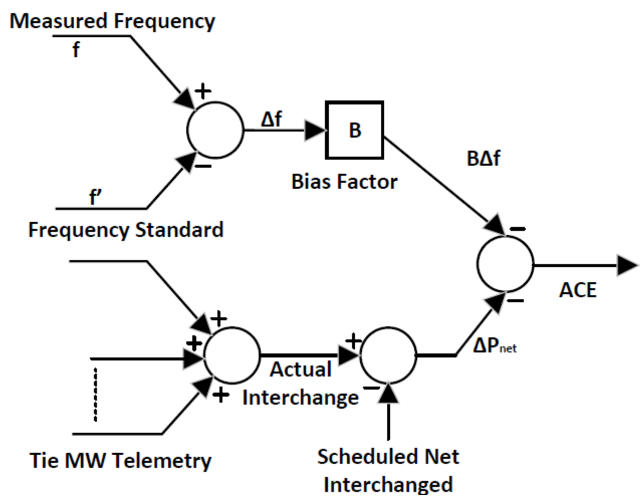
P_{ibase}= base-point generation from unit i

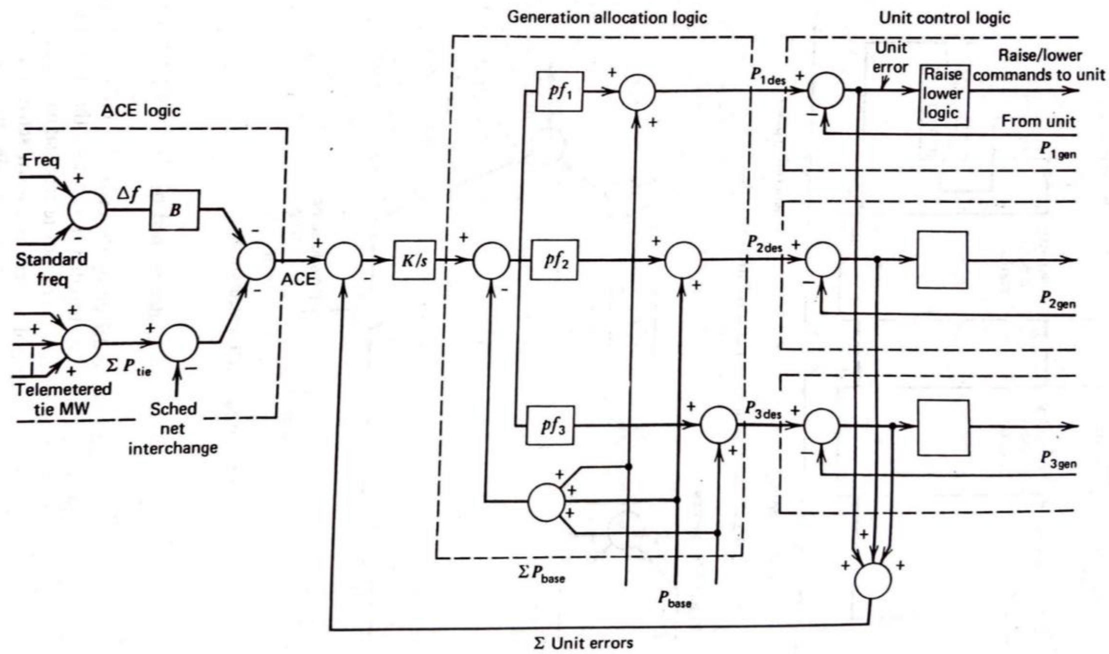
pf_i= participation factor for unit i

ΔP_{total} = Change in total generation

$P_{newtotal}$ = New total generation

This is a very important concept so first you know the total power requirement and you know how much all the generators are providing at this point of time. So, if the your desired power is increasing the new total so there is a gap between what you required and what is available to you. So, one challenge here how do you calculate PF1 that I haven't told so probably it will be slowly clear so please rethink you need to know the PF1 of each unit to calculate for a given change how much desired power can be achieved by a given system okay now one more important concept which is generator control room which is as I told you is desired output that need to be managed because you have the load set points and you have the load set points and the desired outputs can be achieved for any system and there could be one unit two units and n units so there is a closed loop mechanism among all the generators to achieve the desired output from n number of systems finally there is one important point known as AGC calculations and that also can easily be calculated so this is my measure frequency and this is the standard frequency that I want to have and there is a change in frequency that is Delta F and that will lead to the bias vector and probably through telemetry mechanism you can understand the tie line flow and that will let me know the actual interchange and the schedule interchange and that will help me to understand:





If you look very carefully it will look like this the whole system what we have already discussed now this is the system we have actually and these are the mechanisms where you get all the control logic that has or overall control of the last now there are a few features of AGC it assist action move more unit to speed up control of AC filtering AC don't try to follow in the noise telemetry failure logic don't take wrong actions when telemetry fails unit control detection monitor generators to be sure they are responding control units ramp control control rate of unit ramping rate limiting keep unit changes within its rate limit unit control modes example of manual base load base load and now not control performance standards you know this is being defined like you know for a given situation up to what extent we can tolerate the deviations now let's say you have n number of systems they're a tie line control if one misbehaves that will impact the whole system so you have to be very careful and follow the guidelines.

For example, if you remember if someone keep on consuming energy in a particular state which has been tie-line with let's say another state let's say Rajasthan and Uttarakhand they are connected and one state is keep on drawing power and if there is a tie line the power will go from the other state to let's say the Uttarakhand consume more power then all the power from Rajasthan will move to Uttarakhand and that will disturb the whole mechanism of Rajasthan state okay so you have to be because when you see experience more load through tie line means your frequencies keep on dropping okay and hence you are extracting power from others so you cannot perhaps do that to disturb another system which has been controlled through a tie line okay so we all have to expect our frequency and manage our own required load energy system so that the tie line commitment can be met so if you see the first controlled performance standard:

CSP1: $AVG_{Period}\left[\left(\frac{ACE_i}{-10B_i}\right) * \Delta F_1\right] \leq \ \varepsilon_1^2$

Where,

ACE_i is the one minute of ACE for the minute indexed as I

B_i is the average frequency bias in effect over that minute

ΔF_1 is the one minute average of the interconnection's frequency error

ε_1^2 is a constant determined by each interconnection to meet a specified frequency bound

$$\boldsymbol{CSP2}\ AVG_{10-minute}\ (ACE_i) \leq L_{10}$$

ACE for at least 90% of the ten-minutes periods during a calendar month

$$L_{1o} = 1{,}65\varepsilon_{10}\sqrt{(-10B_i\,)(-10B_1\,)}$$

ε_{10} is the RMS of the ten minute average frequency error over a given year and is the same for all control areas in the same for all control areas in the interconnection.

Now by doing that, what we are achieving if you have not control performance standards it allows control areas to minimize by allowing maximum allowance for value of its or if your area control error is perfect then you will be given allowances the larger allowed ACE the less two generation unit need to reverse and maneuver now lower maneuvering means less wear and tear on gears and control means if you pressurize your generators to behave in a ramp way that you know suddenly you give me 100 megawatt suddenly you reduce your generation by another 50 megawatt this is not practical acceptable though theoretically it is true so we don't allow based on this ramping capability only a minor change is acceptable so to do that to make my machines robust to make my system operational and reliable we can allow a certain variation may see and that is governed by certain standards so with this note we come to an end of this section thank you very much for your kind attention.