Power System Dynamics

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Lecture - 24

Dynamic Modeling of Hydro Turbines and Governors

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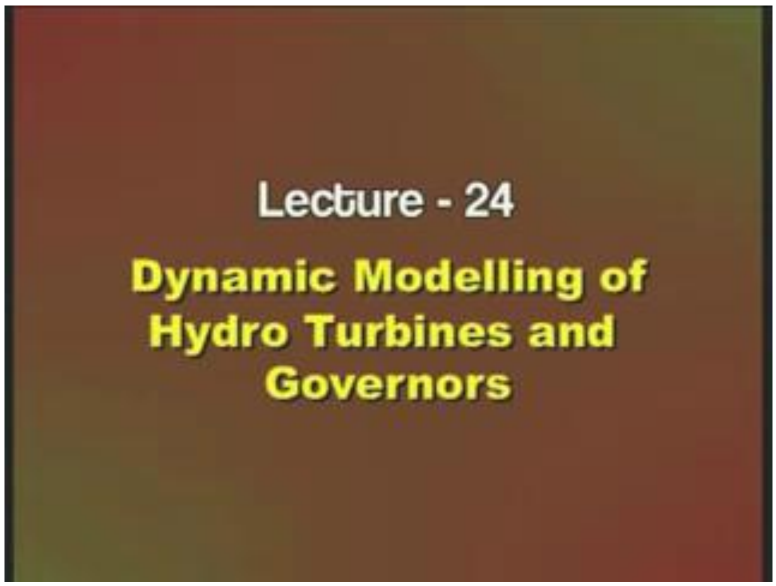

Friends, today we will study the dynamics modeling of hydro turbines and hydro governors. We have studied the dynamics models for steam turbines and a turbo governors, the characteristic of the hydraulic turbine are different from that of a steam turbine and therefore different dynamic models are required for hydro turbines the the physical arrangement for a hydro power plant is shown in this diagram.

This is the hydro turbine, this is the water storage tank, we will call it fore bay and this is the penstock through which the water flows from storage tank to the hydro turbine. The transient characteristic of the hydro turbine is determined by the dynamics of water flow in the penstock and we shall determine the transfer function of the hydro turbine. Now when we consider small perturbations about a steady state operating condition then we can relate the various parameters by linear equations.

Now this equation that is q equal to a_{11} h plus a_{12} n plus a_{13} g and another equation m equal to a_{21} h plus a_{22} n plus a_{23} g. Now this these two are the algebraic equations in this equation q stands for per unit deviation in flow, h stands for per unit deviation in head, n is per unit deviation in speed, g is the per unit deviation in gate position, m is the per unit deviation in torque.

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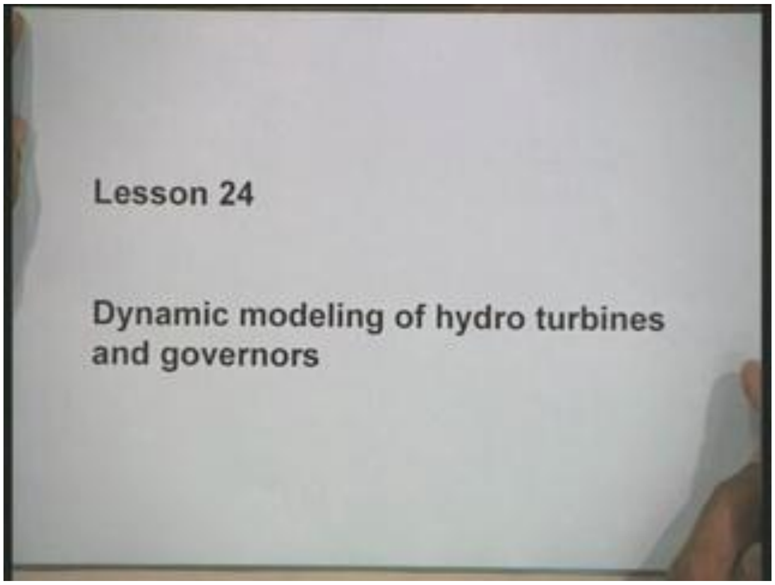

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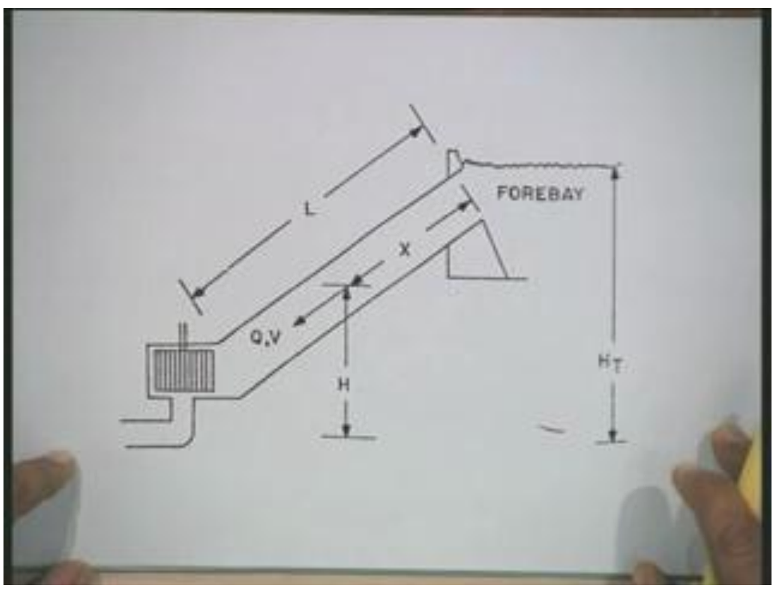

There we can say here therefore small perturbations we can relate the per unit deviation in flow to per unit deviation in head, per unit deviation in the speed, per unit deviation in gate position. Similarly the per unit deviation in torque is related to per unit deviation in head, per unit deviation in n that is the speed and per unit deviation in gate position. The now these are the two algebraic equations which relate the small change in the water flow water flow following following change in head speed and gate position.

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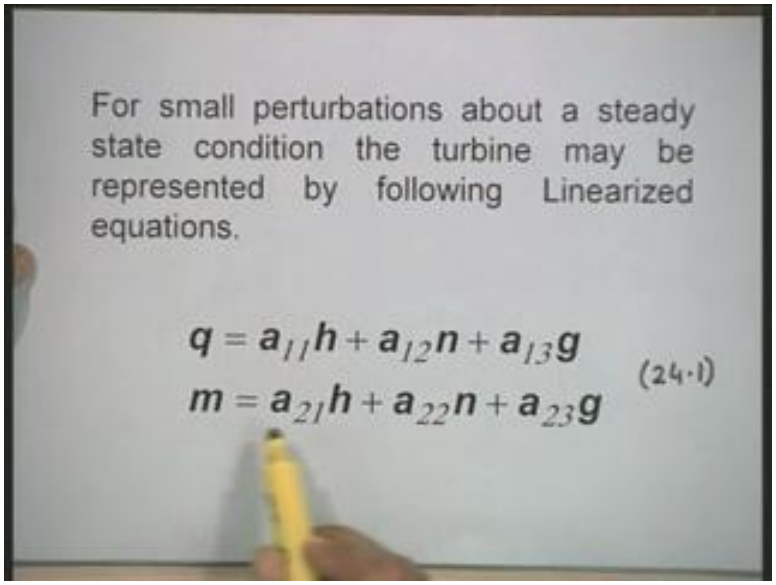

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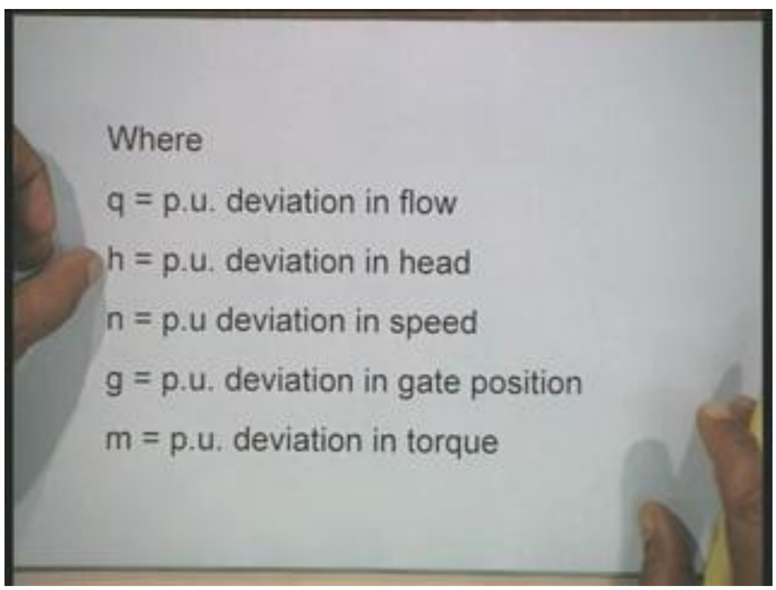

Similarly this is the change in torque produced following the small changes in head speed and gate. Now using these equations and using the dynamics of the water flow in the penstock a transfer function model for the hydro turbine is obtained. The transfer function relating the mechanical power output of the hydro turbine to the gate position or position of the gates that is P_{GV} is the position of the gates is related by these constants which were shown in those algebraic equations and an important term T_w.

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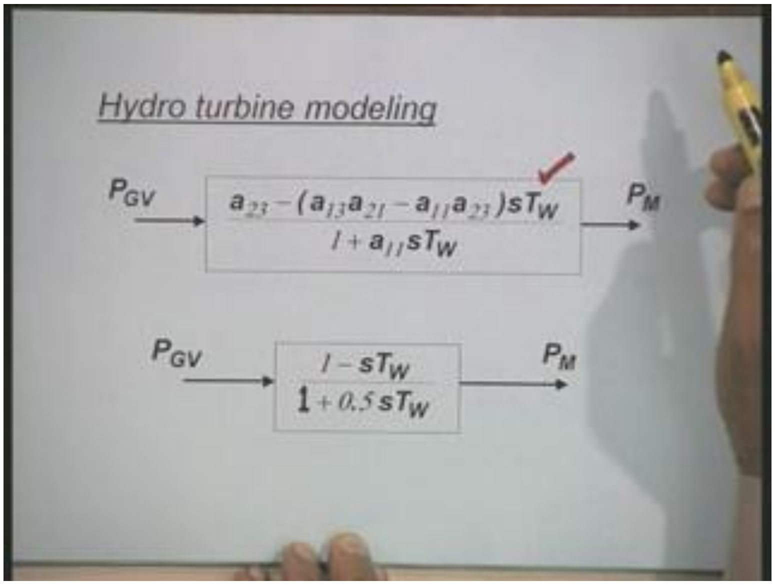

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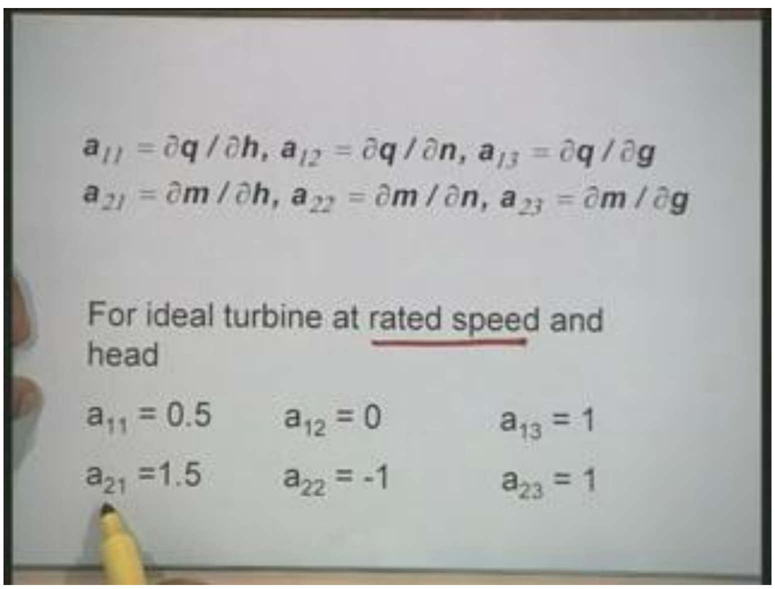

Now this T_w is the water time constant or water starting time constant of the hydro turbine. We will discuss about this time constant T_w in detail, further these coefficients a one one a $_{11}$, a $_{13}$, a_{21}, a_{22}, a_{23}. These can be interpreted as the partial derivatives of q with respective to head partial derivative of q with respect to speed deviation and so on now for ideal turbine which is normally considered to be a loss less turbine, the n for rated speed ideal turbine at rated speed these coefficients are having their values equal to a_{11} is .5, a1_2 is 0, a_{13} is 1, a_{21} is 1.5, a_{22} is minus 1 and a_{23} is 1. Therefore, if we make use of these values and obtain a transfer function relating the mechanical power developed to the valve position.

Now this transfer function comes out to be a very simple transfer function of the form one minus ST_w divided 1 plus 0.5 ST_w. Now let us understand what are the factors on which this water starting time or time constant T_w depends upon.

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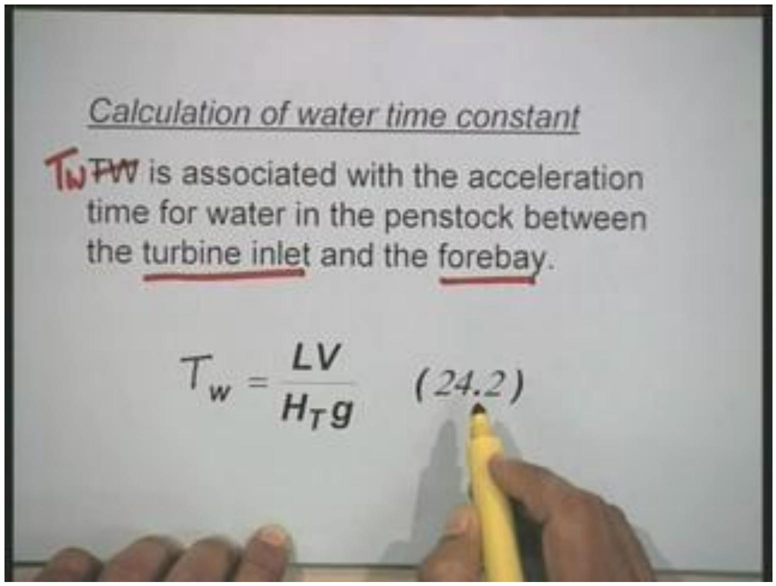

Now this time constant T_w is associated with in write T_w is associated with the acceleration time for water in the penstock between turbine inlet and forebay but basically represent the acceleration time. Now the equation for this time constant T_w is L into V divided by H_T into g, now here here L is the length of the penstock in feet, V is the velocity of the water in feet per second, H_T is the head in feet and g, g here is the acceleration due to gravity, g here is the acceleration due to gravity its value is feet per second square its units are like that that is if you put actually value of g it comes out to be 32.2 feet per second square 32.2.

Okay now what we do is that there exist a relationship between the power developed and the various parameters of the system therefore in this equation the velocity will be replaced by power and other terms that is the power generated is given by this equation V into H_T into A into e divided by 11.8, here P is the power in kilowatts, V is the velocity in feet per second velocity of the water in the penstock, H_T is the head, A is the cross sectional area of the penstock in feet square or square feet and e is the combined efficiency of the generator and turbine is the total efficiency divided by one therefore what we do the from this equation we express the value of V in terms of power, head, A and e and then substitute this value of the expression of V in this equation 24.2.

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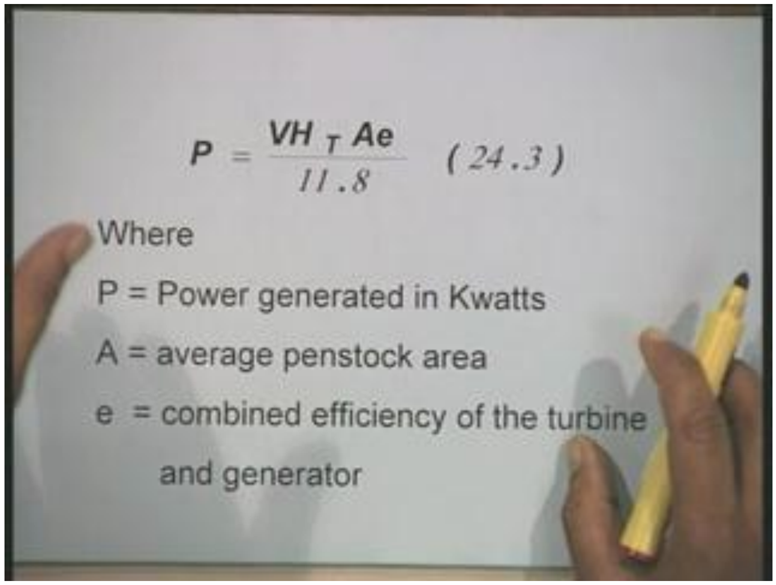

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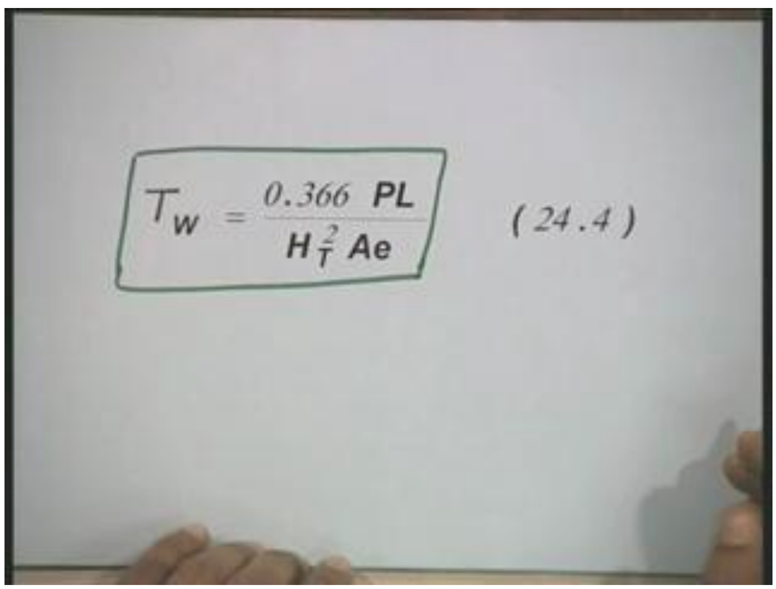

When we make this substitution we get the expression for water starting time constant T_w equal to 0.366 P_L divided by H_T square A into e. Here the value of g has been substituted as 32.2. Now this time constant T_w is a very important parameter. So for the model of the hydro turbine is concerned the hydro turbine the transfer function has some special characteristic and we will discuss the special characteristic of this hydro turbine transfer function.

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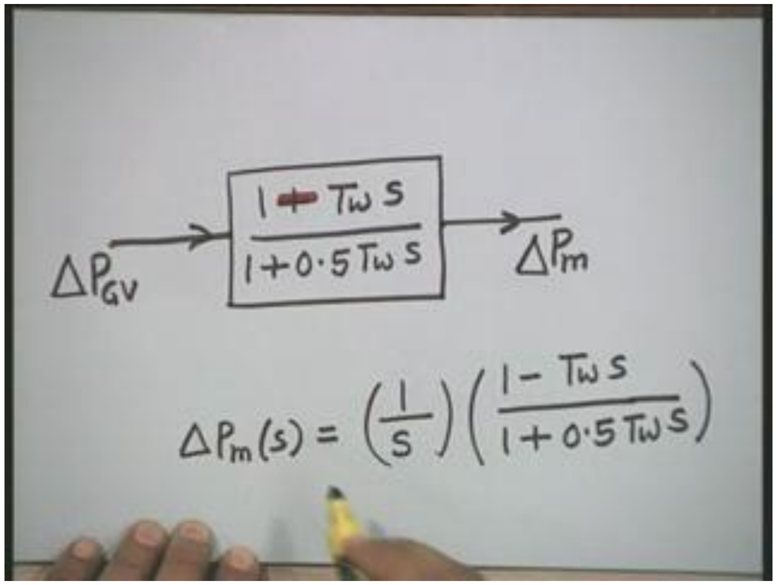

The transfer function of the hydro turbine which we have just now derived is 1 plus T_wS 1 plus 0.5 T_wS this is minus here, correct thank you, this is minus 1 minus T_wS 1plus 0.5 T_w okay is this, okay is minus. Now we can write down here mechanical power output P_m and the gate position P_{GV}.

Now this transfer function has one special characteristic that is the if I look at the poles in 0s of this transfer function then it has 10 in the right half of the S plane and a transfer functions or the systems the systems which have at least 10 or one pole in the right half of the S plane are known as the non minimum phase transfer functions or non-minimum phase systems.

We shall analyze the special characteristic of this turbine hydro turbine by considering unit step input to this turbine that is we change the valve position suddenly and once we give a any step input to this hydro turbine transfer function right then we can write down the expression for mechanical power developed.

Now here instead of considering a P_{GV}, we will prefer to consider this deviations deviations in the gate position okay and deviation in the mechanical power developed therefore when I consider the deviations I can write down the model in this form that is delta P_{GV} is the input and output is delta P, okay.

Now when we consider the unit step change in the position of valve or gate of this hydro turbine then delta PmS can be written as 1 by S 1minus T_wS over 1 plus 0.5 T_wS. Okay because we have considered the unit step change in gate position. So that the transfer function ah not the transfer function where the Laplace transform of unit step input is 1 by S.

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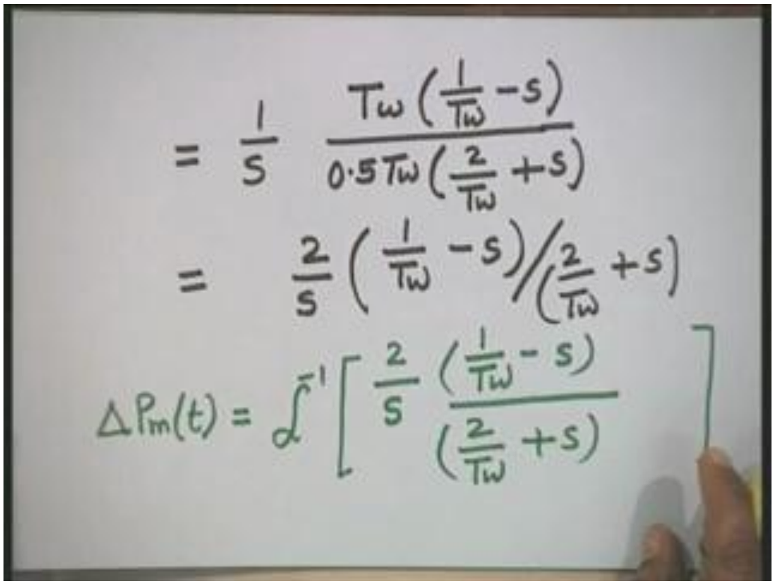

We shall write down this function in this form 1 by S take this T_w out, so that we can write here 1by T_w minus S divided by take the 0.5 T_w. So it write down 2 by T_w, okay plus S that is we are writing in the in the form S plus A or here actually is the S minus A this is the numerator directly it with not going to come actually in our expression for the response. This can be written as 2 by S 1 upon T_w minus S divided by 2 by T_w plus S.

Okay, we obtain the time response by taking the inverse transform of this transfer function that is we can obtain delta $P_m(t)$ by taking the inverse transform that is Laplace inverse of this whole function which I can write down here as 2 by 2 by S_1 by T_w minus S divided by 2 by T_w plus S, okay. Now we obtain the partial fraction of this and the partial fractions will come out to be like this and this will come out to be equal to Laplace transform of Laplace inverse of 1 by S minus 3over 2 by T_w plus S that is if you simplify this expression you will get this expression you can just check it.

Okay therefore now we can say that delta $P_m(t)$ is equal to 1 minus 3 to the power minus 2 by T_w into T this is the this is the response of the hydro turbine to step unit step change in valve position, okay. Now if I put t equal to 0 that is at time equal to 0 that is delta $P_m(o)$ is how much is equal to minus 2 and if I put now t equal to infinity in this equation I will get delta P_m infinity equal to 1. Now we can you can appreciate actually or the difference in the normal response which we get for the transfer function for a system suppose there is a system and we give a some input we except that the output should start following the input.

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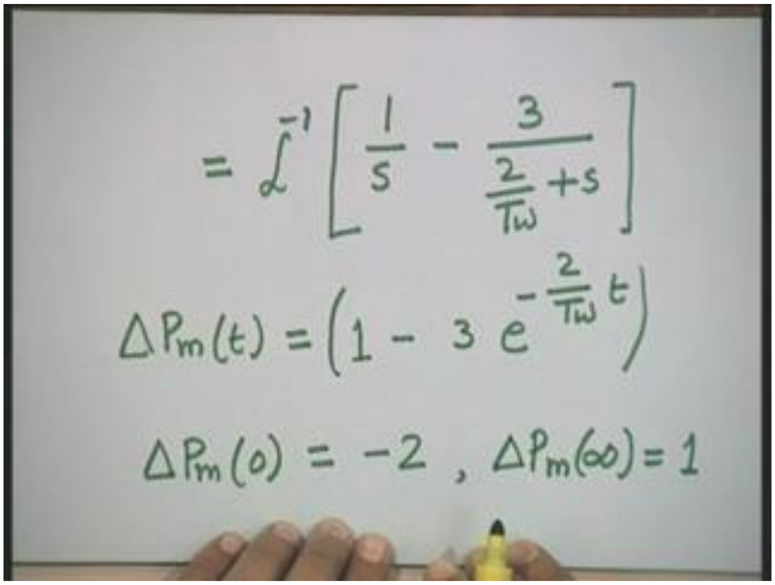

Now here you find that when at time t equal to 0 when I give a step change in valve position then immediately the change in mechanical power is minus 2. We have given a unit step input but the output is negative and this is as high as minus 2 and under steady state condition the output is same as input right. Now this is the main difference or many special characteristic of the hydro turbine.

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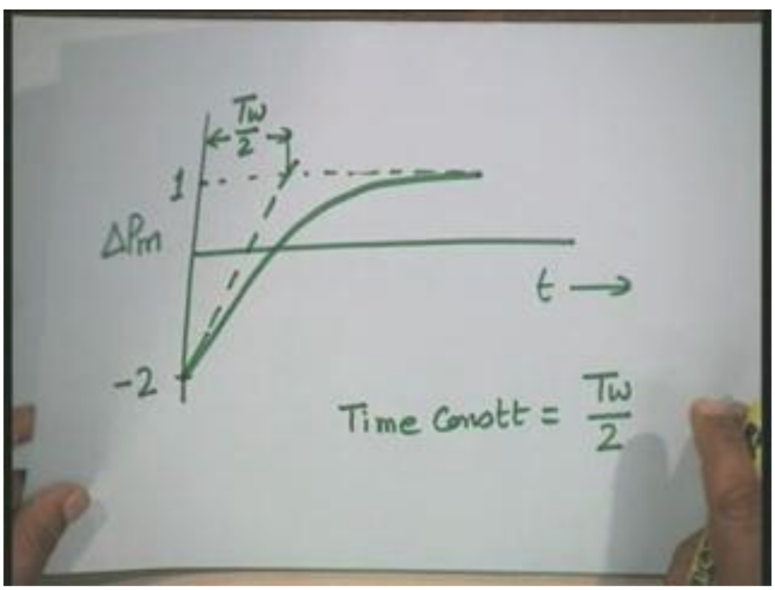

Now if I plot the response that is time t delta P_m, we start at minus 2 and t equal to 0 its value is minus 2 and it settles to value equal to 1and it is very exponentially, so that response is of this valve the time constant is time constant is T_w by 2 right that is if you if you draw a transient to this response curve at t equal to 0 then the curve will be the this transient will be like this and this time can be identified as T_w by 2, the meaning is that if the if the change in mechanical power changes at the initial rate then it will reach its steady state value in time equal to T_w by 2 right, otherwise it is very exponentially.

Now to understand what is the implication of this special characteristic of the hydraulic turbine on the type of governor which will be required. Now let us first consider that we use a simple governor no special features, a simple governor and let us see the what will be the requirement for stable operation for this system.

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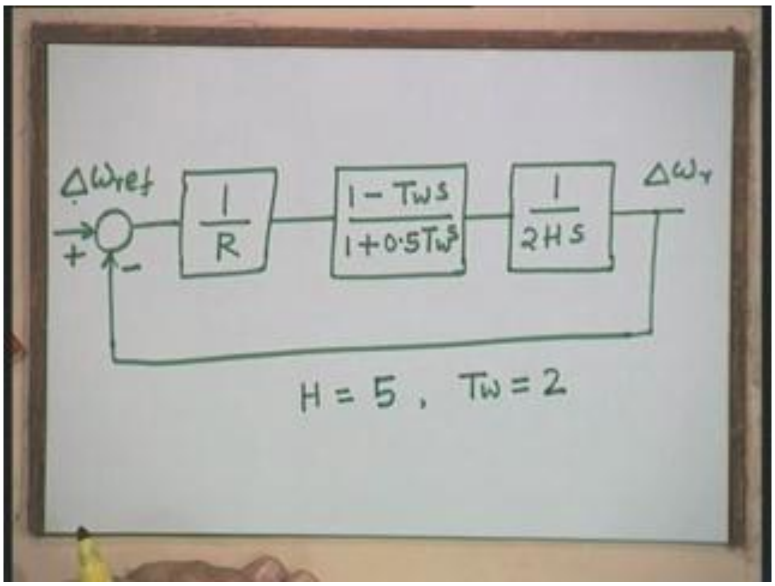

To understand this the a special requirement let us start with the simple governor we can represent the governor by a simple transfer function 1by R the transfer function of the hydro turbine or hydraulic turbine is 1minus T_wS, 1plus 0.5, T_wS, output of this hydro turbine will act on the inertia of the turbine generator system is 1 upon 2 H_S, I am neglecting the damping term this becomes my speed deviation delta omega R and here is a negative feedback. Okay this is negative this is change in reference this this term is delta omega reference I give as and is a plus.

Now to analyze the stability of this system what we will do is we will consider, we will consider the H equal to so let us say H equal to 5, okay. Let us take T_w equal to what was the taking 22. Okay now with this parameters we shall find out that what are the requirements on speed regulation parameter? Our basic requirement is it is a closed loop system and this system should have high degree of stability it should have a required stability margin.

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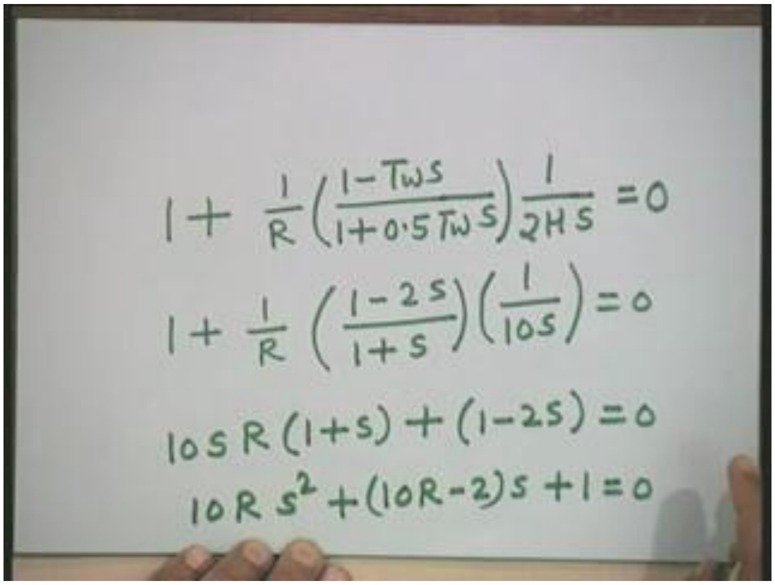

To analyze this requirement we write down the characteristic equation of this system, the characteristic equation can be written as 1 plus 1by R, 1 minus T_wS over 1 plus $0.5T_wS$ into 1 upon 2 H_S. Now here here this this is the forward loop transfer function 1 by R, 1 by R into this transfer function into this this is the forward loop transfer function and the the feedback is unity feedback and the of the characteristic equation is 1 plus gH which is the standard formula and it comes out to be equal to that is 1 plus 1 by R.

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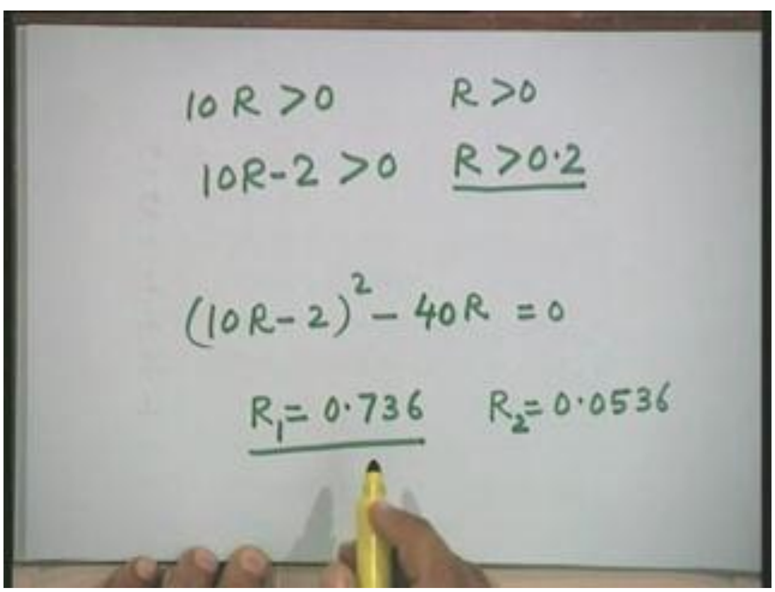

Now will let us substitute the value of T_w equal to 2 and H equal to 10 and let us see 1 plus 1 by R,1 minus 2S, 1 plus S, 1by 10s okay. We can write this as 10 SR plus is it okay or we can write this is in the form now 10 R S square plus 10 R minus 2 into S plus 1 equal to 0. Therefore this is a second order characteristic equation and for this second order characteristic equation to have its roots to lie in the left half of the S plane. Our requirement is that these coefficients should be positive therefore from this consideration that these coefficients to be positive one requirement is now the 10 R should be greater than 0 or we can say R should be greater than 0 the second requirement here is the 10 R minus 2 should be greater than 0 this puts the requirement that R should be greater than .2, it means from the consideration of stability the minimum value of R which we can choose for this governor is 20 percent.

Generally the the speed drop which we choose out or which is the governor parameter or 2 parameter of the governor is taken around 5 percent. Now if I take the R equal to 5 percent then this system is going become unstable, okay. Now suppose I want actually the response to be critically damped then for critically damped response our requirement is 10 R minus 2 whole square minus 10, 4, 40 R equal to 0 okay that is b square minus 4 ac should be equal to 0 and if you solve this equation the value of R which is required comes out to be .736 and another value of R is 0.05, what is the value 536 okay.

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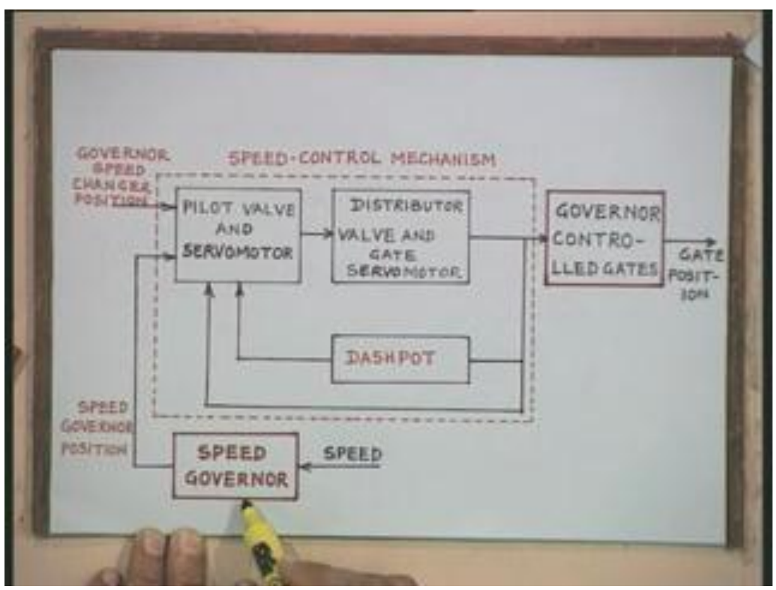

It means we get 2 roots of this equation one root says that the value of R or if I call it R_1 we call this as R_2 one root says that it should be R should be .736, the meaning of .736 means it is a 73.6 percent right and when I say R_2 equal to .0536 it is 5.36 percent but if you assume R_2 equal to .0536 then it does not made this requirement let R is greater than 0.2 and if you take this value of R equal to .0536 this will come out or this will result into a damping is so equal to minus 1 that is negative damping and with R_1 equal to .736 the it will have a critically damped response where will be equal to 1 right but this is too high and therefore in order to overcome this problem the the hydro governors which are provided have to have different characteristics.

Now we will discuss the characteristic of the hydro governor which is required for hydro turbines. Now this is the block diagram of a hydro governor that is the governor for hydro hydraulic turbine. The the building blocks of this governor or a speed control mechanism or the hydro governor is similar to that we use in a steam turbine, the only difference which we will see here is that this block dashpot okay.

Now let us just discuss what are the main blocks, the first block we can see here is the speed governor, the speed governor sensor the speed and it gives you a position which is which is proportional to the speed deviation or speed right there is the speed governor position. This first block pilot valve and servomotor, the input signal to this pilot valve and servomotor are the speed governor, speed changer position which is the signal which comes from AGC of the system and another is the position of the governor speed governor position. These two are the input signal to the pilot valve and servomotor, the output of this pilot valve and servomotor goes to another servomotor hydraulic servomotor which is named as distributor valves and gate servo motor.

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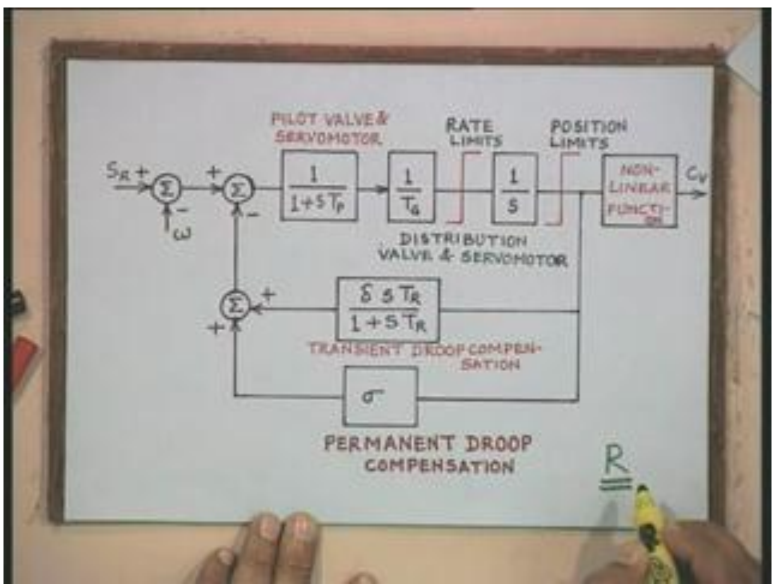

Now these 2 servo motors are required to amplify the power which is required to move the gates and the output of this hydraulic servomotor control the governor control valves or gates of the hydro hydraulic turbine and therefore output is the gate position, okay. Now this dashpot is to provide feedback signal and this feedback is a derivative feedback this dashpot is to realize if derivative feedback and you can see actually that there are 2 input signals coming one is directly coming from the position of the servomotor another is coming through dashpot right. Now these 2 these two feedback signals are required to obtain the required characteristic for the hydro governor.

Now this shows or this block diagram shows the transfer function of various building blocks of the hydro turbine governor or hydraulic turbine governor we start like this, this is the this is the transfer function of the pilot valve and servomotor this is the time constant of the distributor valve and servomotor TG stand for time constant of the distributor valve and servomotor. Here we show the rate limits then this transfer function one by S to represent the integration function and the another limits which we have is the position limit right, therefore these two limits are shown in this transfer function diagram and whenever we are studying the small perturbation dynamics or whenever the system is subjected to small perturbation then these these limits particularly may not be touched particularly the the position limit may not touch but the rate limits may have to incorporated. Again, you can see here there exist a non-linear function to relate the gate position to the hydraulic servomotor position that is when the hydraulic servomotor piston moves right it moves the gates and the movement of gates and the movement of the servomotor they are again related by a non-linear function. Therefore this show the nonlinear function the transfer function of the dashpot is delta STR over 1plus STR.

Now this transfer function you can see here that it is the derivative feedback, this is a derivative feedback because we have a a term S in the numerator that is STR or 1 plus STR this becomes the derivative feedback then this term delta delta is called transient drop delta is called transient drop then the another feedback which was shown in the block diagram is through this sigma.

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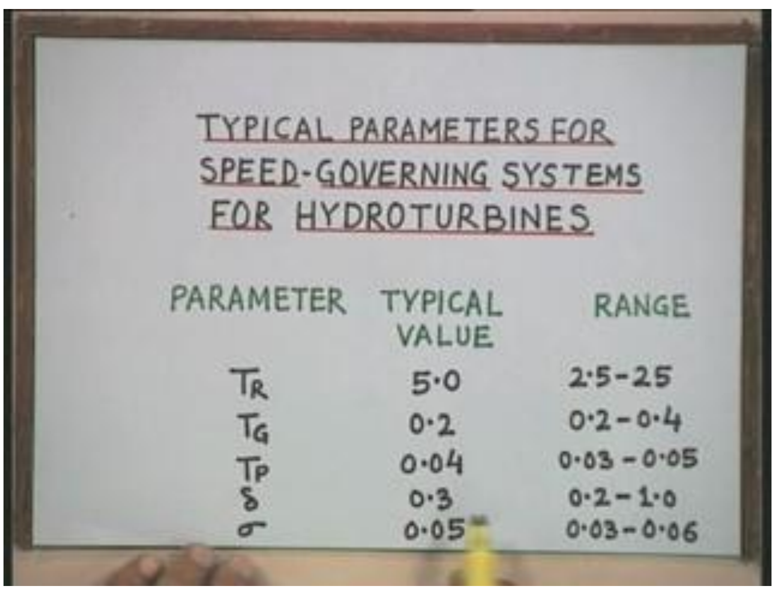

Now this sigma is same as R which we use actually in the models for the hydro for the governors. Now this sigma is known as the permanent drop, permanent drop the meaning here is that when the system is in dynamic condition right there will be output from the dashpot and the movement the system attain the steady state condition right there will be no output signal from the this transfer function and therefore the the net drop will be determined by the permanent drop sigma only, okay. The typical, the typical parameters of this hydro governor are this T_R is 5 seconds its it ranges in the range of 2.5 to 25 a wide range T_G, T_G is the time constant of the distributor distribution and valve and servomotor this time constant is small and its value is 0.2 second and its range is .2 to .4.

The T_P which is the time constant of the pilot valve and servomotor this time constant is very small of the order of .04 second and it is in the range of .03 to .05 second. The delta the temporary drop its value is .3 and its range is .2 to 1, the sigma or R its range is its value is .05 and it varies from .03 to .06 percent. Normally it is 2 percent or one in drop is considered and some places it may be lower than this or slightly higher than this but its the range is very narrow or is .03 to .06.

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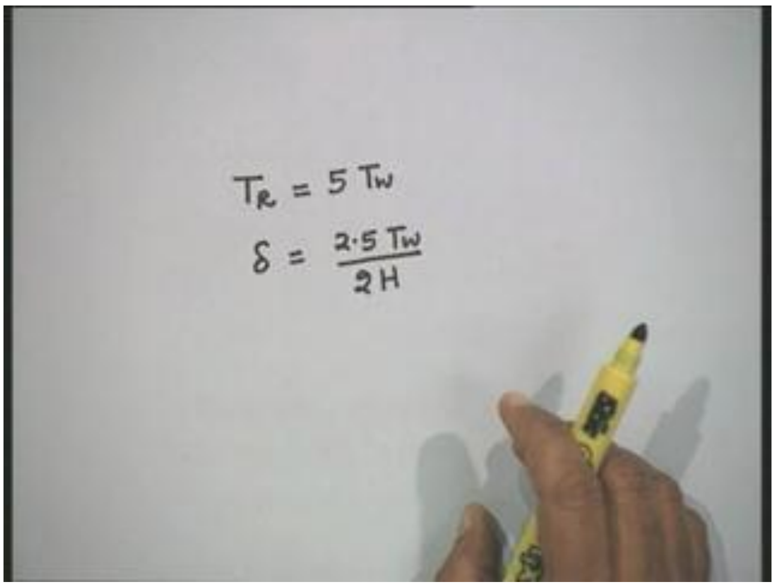

Further further this time constant T_R,T_R is depends upon the water starting time constant right, therefore the typical value is the T_R should be equal to 5 times T_w this is the thumb rule okay and suppose if T_w is 1then T_R is 5, suppose T_w is 2 T_R becomes 10 and so on similarly this temporary drop is 2.5 T_w divided by 2H. Therefore you can say that the temporary drop requirement depends upon the inertia constant of the turbine generator system and the water starting time right because as we discussed actually that this special feature that we have to provide a temporary drop compensation right particularly to take care of special characteristic of the hydraulic turbine and there is a relationship which relates a temporary drop to water starting time constant T_w and inertial constant H.

Now the question arises the how do we optimize the parameters of this hydro governor, one way is that okay you take this thumb rules that is you set the value of delta as given here in the range of .3 around .3, .221 or use this formula delta is 2.5 T_w divided by 2H. For example in this case when I put T_w equal to 1 and H is taken as 5 how much it comes out to be .25, 2.3 is one which we are talking about but however in any particular system particular system the procedure is that you you model the complete system take the hydro turbine, take the its associated governor right and you obtain the dynamic response of this system and we can use, we can use different techniques to set the parameters of these governors right.

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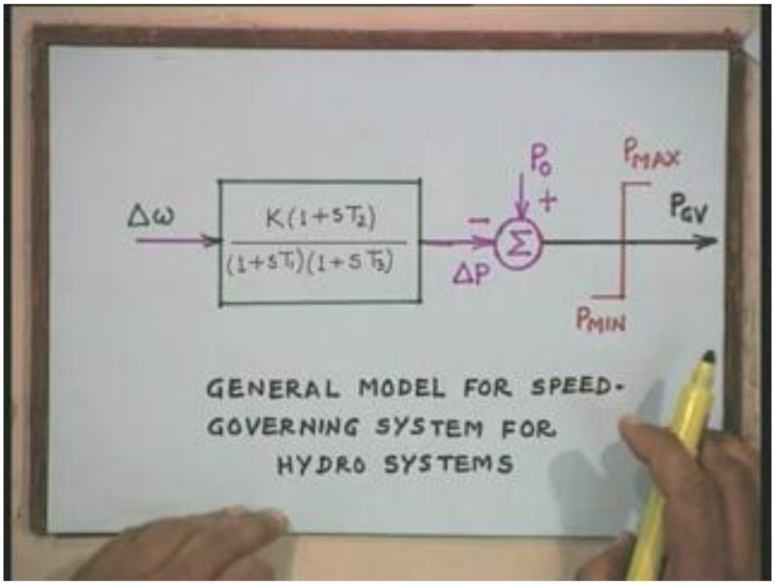

Generally the governor parameters are set under no load conditions the the general model for a speed governing system is developed and this is shown in a compact transfer function like this where input is delta omega the speed deviation signal in the transfer function is in the form K into 1plus S T_2 divided by 1 plus S times T_1 or 1 plus S times T_3. The output of this transfer function represents the change in power delta P, now this is added to the reference setting that is P_o which is the reference setting and this output which is the sum of P_o and delta P right is the gate valve or gate valve position okay.

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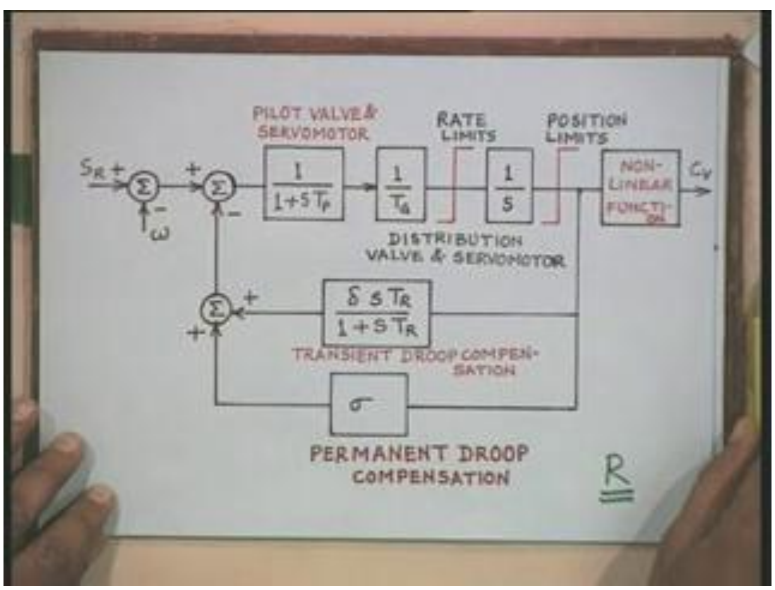

Now here as you know actually that this P_o is the position of the speed changer, in the AGC when we talk about this is the speed changer position. Now this time constants T_1, T_2, T_3 right. These time constants are can be obtained from the typical values which are given here for this T_P, T_R delta sigma and T_G so on that is these time constants T_1, T_2, T_1 and T_1, T_2 and T_3 right are related to the parameters of this governor and this is put in the simplified form for the purpose of simulation studies, okay.

Now another important point which we have to see here is that the there are different manufacturers of hydraulic governors, in they are hydraulic governors have been manufactured by the general electric company by a wasting house and so on right and therefore this manufacturers give the parameters of the model of the governors and developed by them right therefore the standard references are available where the parameters of different manufactures are given, if you look into the reference material which I have given to you last time that is the committee report right then in this report the parameters of different types of hydro governors are are given.

Now these parameters are generally the generally the typical values however however for a any utility for any utility has to set its own parameters by performing certain studies.
Now as we have studied actually that the excitation system and automatic voltage regulator parameters need to be set, similarly the parameters of the governors need be set. We are so far actually the turbine parameters are concerned they are constant only flexibility which we have is actually in setting the parameters of the hydro, hydro governors for hydro turbine and uh other governor for the steam turbine.

Now this constant K which I have shown here this K is the gain of the governor this gain is basically if the reciprocal of the permanent drop that is R if R is taken as 5 percent the gain will become 20 right and the standard techniques which are used for for setting the parameters are by either by time domain simulation or by frequency response analysis okay. Let me the sum up that we have studied the dynamic model for the hydro turbine.

We have also seen the special characteristic of the hydro turbine transfer function and to meet the requirement of the hydro turbine, the hydro governor is required to have a special feature and that feature is to have a temporary drop concept. Now when this hydro governor with the temporary drop is provided and is the parameters are properly set it will give the desired dynamic response for the system. Thank you!