Power System Dynamics

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Lecture - 23

Dynamic Modelling of Steam Turbines and Governors

Friends, today we will discuss dynamic models of steam turbines and governors.

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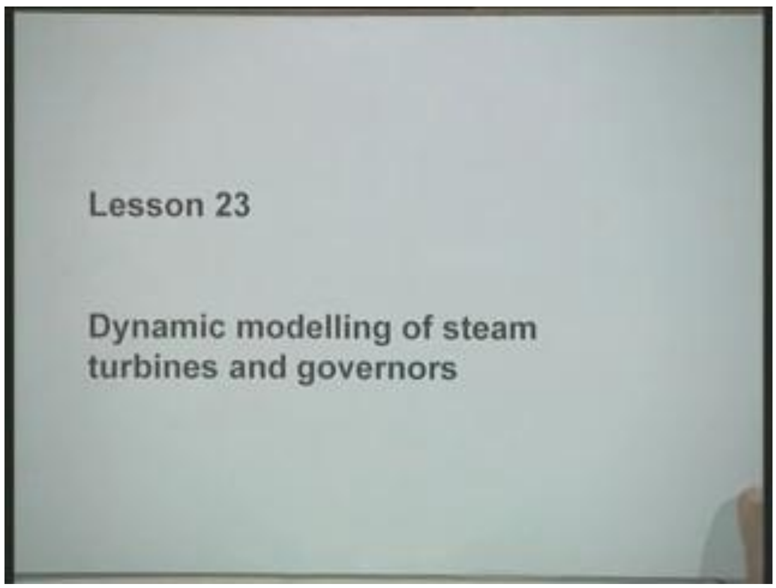

So far we have developed the model for synchronous generator and the associated excitation systems while studying the stability, we have made one assumption that mechanical input power remains constant right. Now while developing actually the model for transient stability analysis right we our swing equation our swing equation is written in the form 2H divided by omega s, d_2 delta by dt_2 equal to P_m minus P_e.

Now till now we have assumed that this mechanical power input is constant. Okay and the this is very valid assumption however whenever you want to do study involving a severe upsets in the power system and we want to know the long term midterm and voltage stability analysis of the system then the the turbine and associated governor models also required to be included and today, we will devote our studies to develop the models of steam turbines and associated governors before we developed this let us look at this block diagram.

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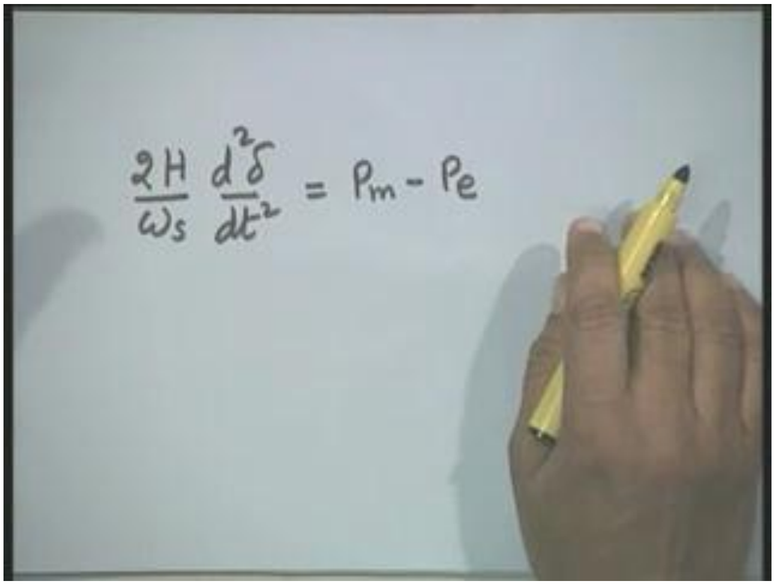

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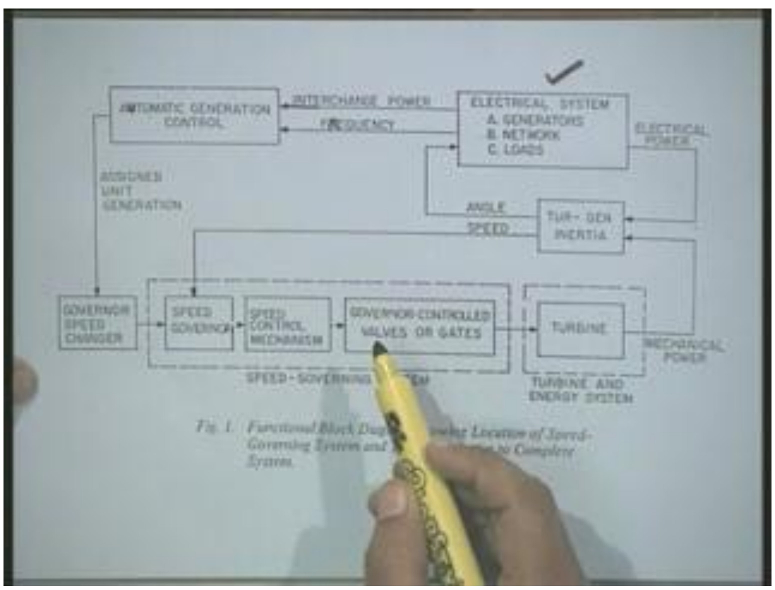

This block diagram shows the complete power system net power system. Now you can identify here the different blocks suppose you start with actually the power system network. This is the block which shows the power system networks which has which we represent the generators transmission line network and loads, okay. Now from this network we get output as electrical power and for the control of this power system as a whole we have different controls okay.

Now one control is actually the generation control and for controlling generation what is done is that we change the interchange power on various tie lines and find out the net interchange which has the system frequency this is processed in a controller which is called automatic generation control and the output signal which comes to the automatic generation control right. We will change the position of the speed changer. Okay, then when you look the major blocks you have the speed governor, speed controller mechanism and governor control valves and gates.

Now here we are writing valves and gates, the valves basically pertain to steam turbines and gates pertain to hydro turbines and the output or the position of the gates right control the input to the turbine and therefore this was the turbine here. Now we are while for for presenting the system dynamic model what we do is that we represent the turbine separately and then the output from the turbine will be represented as a mechanical power output and this mechanical power output will be used to write the swing equation that is we wild this, we will separate the turbine generator inertia and write the swing equation so that input to this block which we basically used to write the swing equation. We call it actually the turbine generator inertia input is electrical power and mechanical power the different of this is the accelerating power and the output from this block will give you the angle change in angular position and change in the speed.

Now the speed deviation signal is processed through a speed governor therefore the speed governor is a most important component in the control mechanism. It has two inputs, one coming through the coming from the terminal of the synchronous generator and that is the speed signal another is the a control signal coming through the AGC, we call actually the speed changer position, okay. Now these two signals when they enter through this governor governor will process it and we have a speed control mechanism and then ultimately the valves okay.

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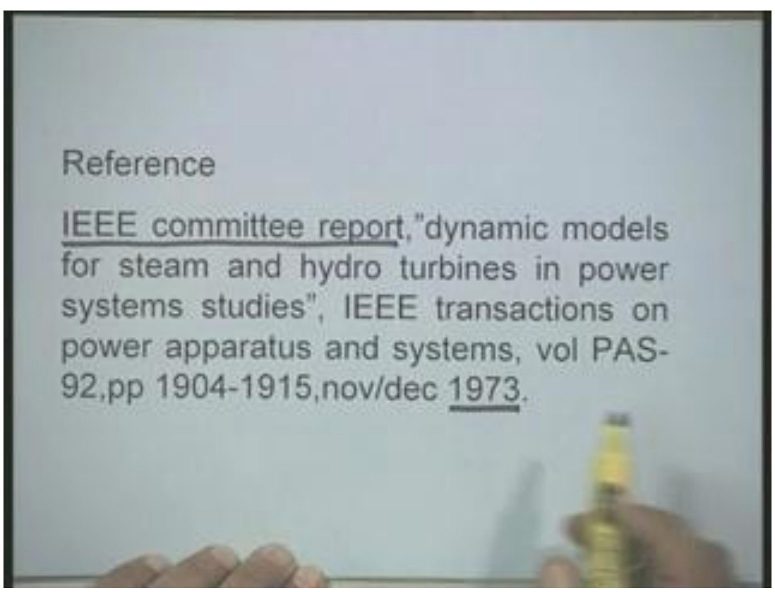

Now this is the complete schematic diagram which represents the location of steam turbine the governors with respect to the total system. Now our study will be confined to representing the steam turbine and the speed governing system okay. The reference material for steam turbine models and hydro turbine and associated governors is available in this IEEE committee report because when we discuss the excitation system models I have referred to a number of papers of published in IEEE transaction and IEEE ah standards. Okay similar to similar to the excitation system models the IEEE task force on power system dynamics has developed the models for steam turbines, governors and hydro turbines in associated governors.

This is published in the year 1973 and while developing these models, since this subject involves the mechanical system right along with the electrical system right and therefore this is written by by with the association of IEEE working group and American society of mechanical engineers right. Therefore, these two groups have contributed in developing the models which are published in IEEE transaction in the year 1973 this is the standard paper I advise all of you to take a copy and read it. Okay while developing these models there some assumptions which have been made because when we see the system as a whole right we have contingency controls for example fast valving right.

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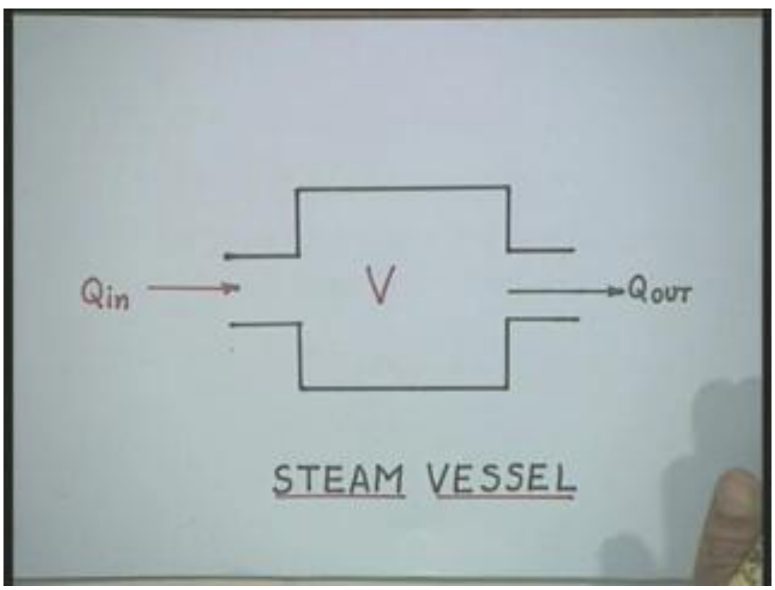

Now these type of controls have not been shown here in the models we will ah develop these models actually and discuss these models from beginning. Now to develop the model what we need is basically the relationship between the input and output. Now since here we will be dealing while developing the steam turbine model right where we know that the steam is generated in the boiler and then it flows through the various stages of steam turbine and then ultimately it is exhausted to the condenser. Okay now in order to develop the model let us start with a simple steam vessel, let us say that there is a steam vessel and volume V is the volume of this vessel. In this vessel the steam is entering and let us say that Q in is the steam in kilograms which is entering per second and Q out is the steam in kilograms leaving this channel.

We will develop actually a transfer function model relating the Q_{out} to Q_{in} and this basic model will be used to represent various stages of the steam turbine. Our basic objective is to develop a transfer function model relating the the Q_{out} that is the the steam coming out to the steam coming in to the vessel.

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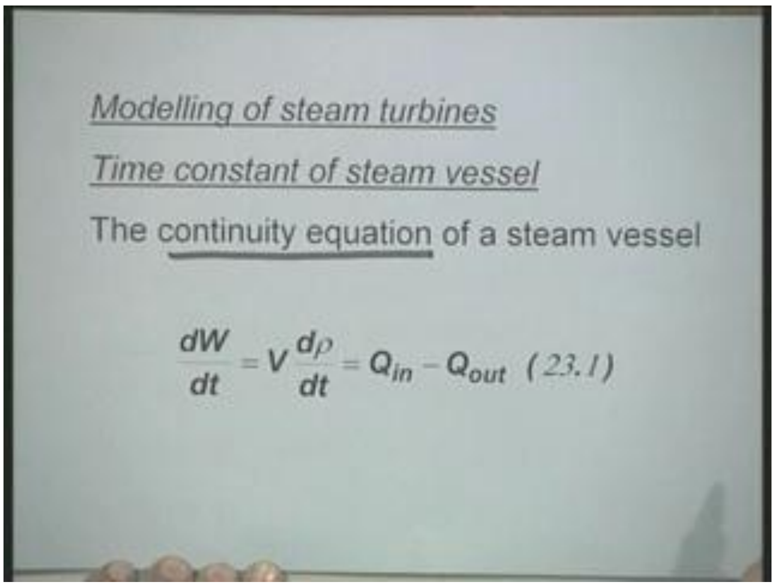

Here we can we make use of a basic equation which is called continuity equation, the continuity equation is written in the form d by dt of W, W is the weight of the steam W is the total weight of the steam which is inside the vessel. Okay this rate of change the d_W by dt is equal to V times d rho by dt. The rho here is the the density of the steam, okay we can say that it is the weight in kilograms per metre cube. Okay and V is the volume therefore V into rho is equal to total weight V into rho that is the total weight of the steam therefore rate of change of total weight of the steam content is equal to this difference Q_{in} minus Q_{out} a very simple mechanism that there is a vessel where steam is entering at a certain rate steam is leaving at certain rate right and this difference will represent the rate of change of way to the steam inside the vessel.

Now basic meaning of the terms here are W is the weight of the steam in the vessel in kilograms which is equal to V into rho, V is the volume of the vessel in metre cube, rho is the density of steam in kilogram per metre cube and Q is the steam mass flow rate, Q represent the steam mass flow rate kilograms per second, T represent time in seconds a very simple equation. Now here we will relate the the rate at which the steam is leaving the vessel to pressure right.

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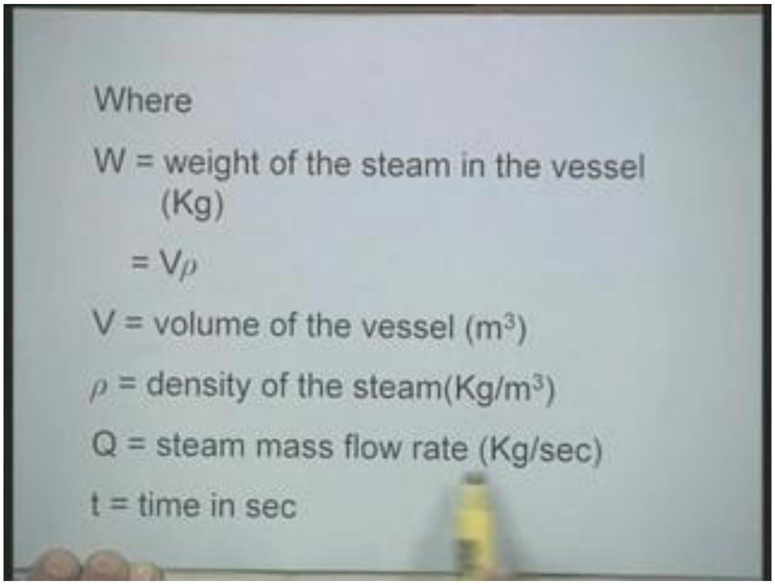

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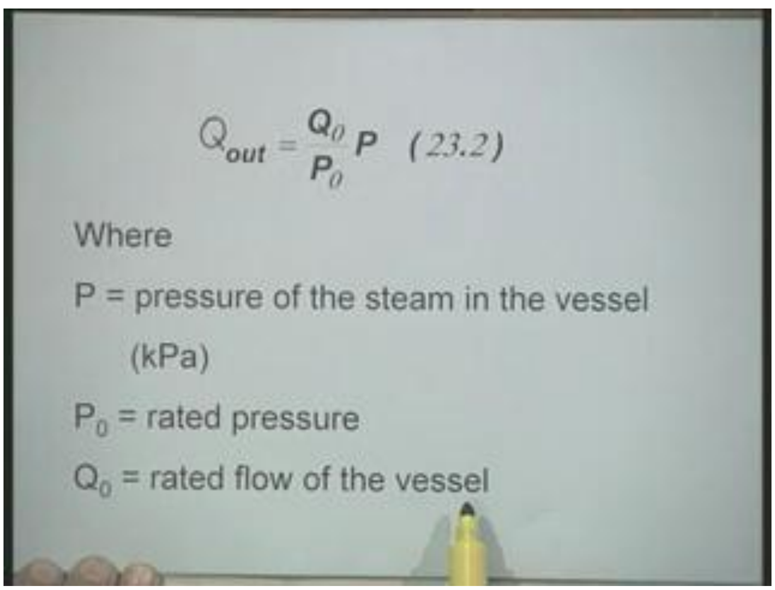

Now let us say that Q_o is the steam leaving the vessel per second when pressure is P_o right therefore at any other pressure the Q out will be equal to Q_o divided P_o into P where, P is the pressure which is different from the nominal pressure, okay P is the pressure of the steam in the vessel P_o is the rated pressure and Q_o is the rated flow of the vessel it means at a particular pressure the steam flow is Q_o and at any other pressure the rate of steam flow or steam flow is proportional to the pressure.

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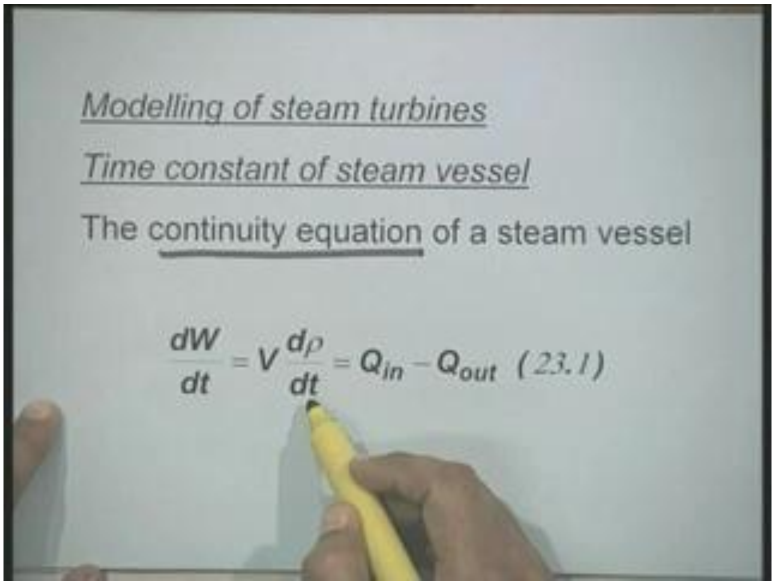

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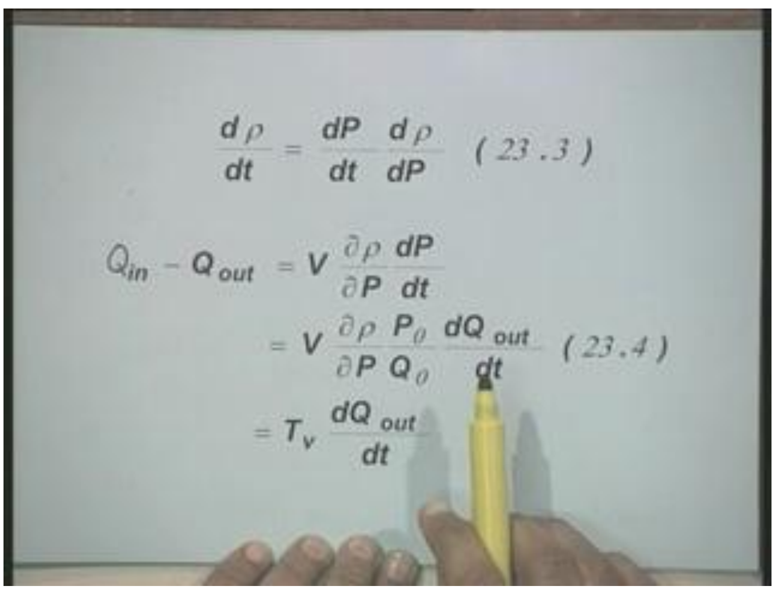

Now to develop the equation we need actually the expression for deer d rho by dt okay, Now to obtain the expression for d rho by dt. We can write like this d rho by dt can be written as dP by dt that is the derivative of pressure with respect to time or the rate of change pressure with respect to time into d rho by dP that this chain rule type of relation we have written that d rho by dt is equal to dP by dt into d rho by dP or you can put other way around d rho by dP into dP by dt that will be much better if you write down d rho by dt as d rho dP into dP by dt. Then, we substitute this expression in our continuity equation we get Q_{in} minus Q_{out} equal to volume into d rho by dP into dP by dt.

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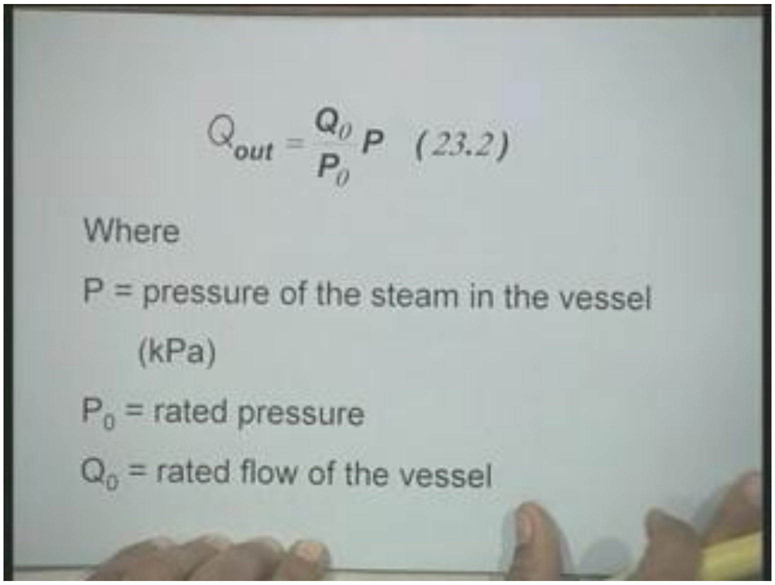

Okay, now here dP by dt can be replaced dP by dt can be replaced from this expression that is you can write down you can just take derivative of this equation. So we write down the dP by dt is equal to P_o by Q_o into dQ by dQ_{out} by dt. Okay use this expression so that I can write now Q in minus Q out equal to V into d rho by dP P_o by Q_o into dQ_{out} by dt. Okay here in this equation in this equation we will represent this total term V d rho by dP into P_o by Q_o by a term a constant called T_v dQ_{out} by dt.

Now here this term d rho by dP is a known quantity that is how the the density varies with the pressure this is the rate of change of steam density with pressure this can be this is a known quantity therefore all these terms are known P_o is known Q_o is known therefore this coefficient will be represented by a constant T_v at at right and ultimately you will see that this becomes the time constant of the vessel. Okay therefore, now I have a simple equation a first order differential equation this Q_{in} minus Q_{out} equal to T_v into d_Q out by dt you take the Laplace transform of this equation. Okay and then you can express the the Q_{out} in terms of Q_{in} right and you can write down the transfer function in this form Q_{out} by Q_{in} equal to 1over 1 plus s times T_v.

A simple first order transfer function which we have obtained here for this vessel, okay. Now this this is the these are the Laplace transform variables output input and this T_v is the time constant of the vessel. Okay now you understand actually the what are the parameters which determine this time constant T_v of the vessel okay because if you see it here again T, T_v depends upon the volume of the vessel these are the vessel right mode will be the time constant it will also depend upon these parameters what is the, what is the ah Q_o for a given value of P_o and this quantity that is the property of the steam okay therefore with with knowing these quantities or these parameters this T_v can be computed. Now let us come to the actual turbine representation or steam turbine representation. So far the steam turbines are concerned we have different configurations it all depends upon the rating of the machine right.

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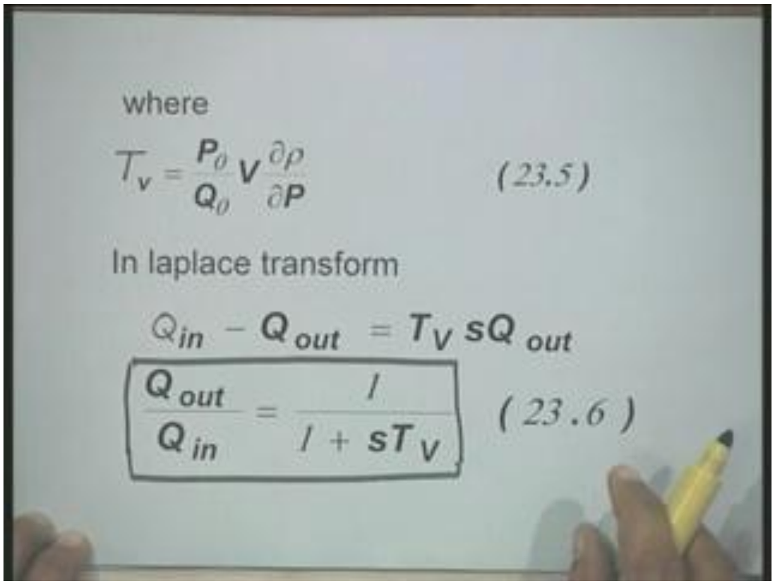

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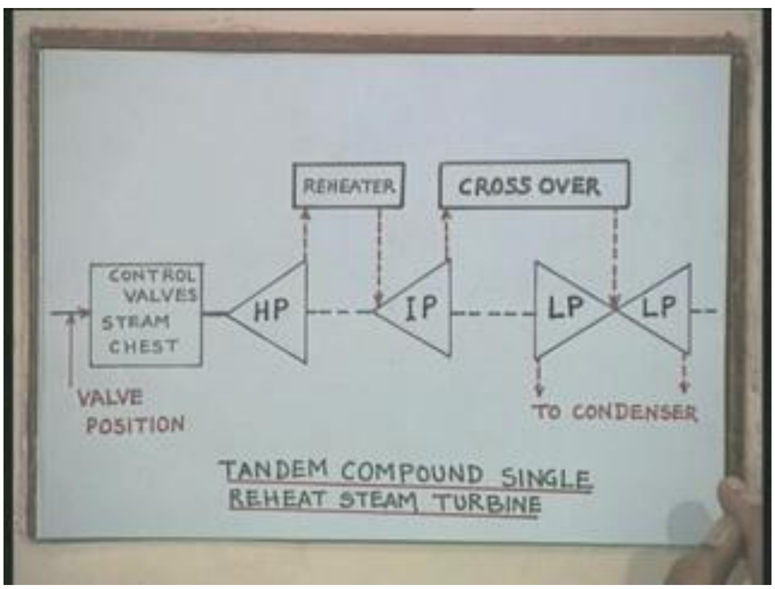

Now this block diagram represents the simple tandem compound single reheat steam turbine. Now here the basic blocks in this tandem compound single reheat steam turbine are that we will have control valves and steam chest that is that is the control valves right and the position of the control valve is adjusted by the governor, okay. The governor controls or speed control mechanism right they will be adjusting the position of the valves, okay. Therefore first block diagram which I can show here is h control valves and steam chest these valves are enclosed in an enclosure right which also houses some substantial amount of steam right therefore we call this is a steam chest.

The steam from this through this control valve enters the high pressure section of the turbine. After developing some power in the high pressure section the steam temperature and pressure reduces it gets expanded right therefore it is send to re heater after re heating the steam in the superheated condition again and then it enters the next stage of the turbine is called intermediate pressure turbine section, IP. The steam leaving from the intermediate pressure section enters the low pressure sections through cross over pipings okay and then it is exhausted to the condenser.

Now in this schematic diagram we have not shown certain valves which are provided in the system. For example I have not shown the interceptor valve there is a interceptor valve provided actually here in the reheater circuit that is the steam leaving the high pressure section there will be an interceptor valve we call IV. Similarly similarly we have here a control valve which we will be showing but along with the control valve there will be stop valves also therefore there will be always two valves stop valve which will be used to completely stop the flow of steam similarly along with the interceptor valve also we have a stop valve right.

Now in this models which we will be developing we will not be representing this stop valves. Similarly, I am not showing here the interceptor valve but they can also be represented okay further depending upon the size of the machine we may have a single stage reheating or two stage reheating. In case it is a two stage reheating we we will have one more section then the first section is normally called VHP which is a very high pressure turbine section, next will be called high pressure then intermediate pressure and so on that is the steam which leaves the very high pressure section and after working and when it leaves the very high pressure section will enter the reheater again it comes out enter the high pressure when it leaves again and enters into the re heater and so on.

Therefore it is called two stage sometimes we have other configurations which are called compound configuration there here you will find that all these sections are mounted on the same shaft that is high pressure interference, intermediate pressure low pressure and then generator but in the compound type of steam turbines they have two shafts right and but both this you know turbine sections are controlled simultaneously right they are not independent if they are independent then they become actually independent steam turbine sections okay.

Now our interest is to develop the transfer function model relating the power output from the turbine and the turbine output is denoted as mechanical torque or mechanical power okay and valve position that is what is the position of the valve right therefore, we will relate the relate the mechanical torque to the valve position that is suppose a time T equal to 0 if I change the position of valve right then how the output at the shaft will vary right.

Now you can easily see here now that we have control valve and steam chest therefore this is a steam vessel you can call it, high pressure section is also a steam vessel because here we have two types of blades stationary and moving right and the steam expands in the nozzles which are formed in the each section right therefore this also behaves like a vessel this also behaves like a vessel this also behaves like a vessel therefore the we can represent represent each of these by a time constant and the time constant will depend upon what is the volume of this what is the pressure and other parameters, okay. Further, suppose actually the total power is generated, the total say mechanical torque developed is say P_m.

Now this total mechanical torque is developed in these 3 sections okay a part of it is produced here in high pressure section half part in intermediate pressure section, part in the low pressure section right and generally generally you will find that around 70 percent to the power is produced due to the intermediate pressure and low pressure section and about 30 percent is produced in the high pressure section therefore we have to account while modeling the section of the power which is produced in each of the sections okay.

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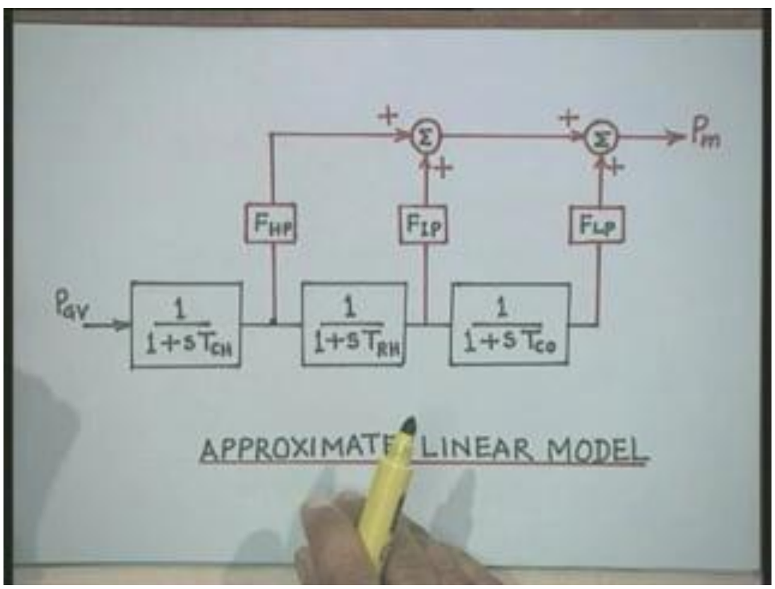

This is the simplest transfer function model of a single reheat tandem compound steam turbine. The configuration of that particular tandem compound single reheat steam turbine we have just now seen, the first block diagram this one this represents the steam chest and control valve the time constant associated with this is T_{CH}, CH is stand for the chest, okay. A certain amount of power is produced that is P_{GV} is stand for position of the governor valve P_{GV}, P stands for position P_{GV} define the position of the governor valve even this governor valve position is calibrated in terms of power right then whatsoever power is produced here in the, now this T_{CH} will also include the time constant associated with the high pressure section, high pressure section right.

Therefore this block diagram represents the the vessel that is the chest along with the high pressure therefore the total is represented by time constant T_{CH}, then when the steam enters through the reheater okay now the reheater pipings you can say the pipings are there and it has capacity to store a large amount of steam right and therefore associated with the heater is the time constant called T_{RH} right. Therefore we represent this reheater separately as one upon one plus S times T_{RH} and at the end the steam which leaves the intermediate pressure because this reheater along with the intermediate pressure is also that any time constant associated with the intermediate pressure is included in the re heater then at the end we have cross over pipings and the lower pressure section therefore we represent by one more time constant called T_{CO}, CO stand for the cross over pipings right.

Now at this point some power is generated in the high pressure section if I call this power as P_{HP}. Okay the power which is produced here in the intermediate pressure section I will call it as P_{IP} and power which is produced here in the low pressure section we will denote by P_{LP}. Okay now the total power which is going to be produced will be P_{HP} into F_{HP} plus P_{IP} into F_{IP} to P_{LP} into F_{LP} and the total is P_m. Okay this is what is the therefore now we have a complete transfer function relating the mechanical power P_m which is developed by the steam turbine and the governor valve position.

In case you have another configuration instead of having single reheat if you have a 2 stages reheat system right then we may have to add one more section right therefore depending upon actually the what is the actual configuration one can develop a transfer function relating the governor valve position to the mechanical power input and for each of these sections we can write down the differential equations because when we write the model right the model is to be written by writing a set of differential equations. For example in this particular case there are three time constants and therefore three differential equations will be required to describe the steam turbine.

Now the state variables state variables in this case will be P_{HP}, P_{IP} and P_{LP} these are the 3 state variables okay and in this particular arrangement if you want to study the small signal stability then there will be the incremental changes like the delta PHP will be the state variable, delta PIP will be state variable but when I am writing the complete non-linear model then these quantities as it is will become the state variables and therefore we will require the initial values to solve the problem. Therefore whenever I want to solve the stability problem I should know what is the initial value of this P_{HP}? initial value of P_{IP} and initial value of P_{LP} they are my state variable any doubt.

Now the the terms associated were explained I will just reiterate P_{GV} is the output power from the control valve or we can even represent the output position of the control valve but that is also expressed in terms of power calibrated in terms of power okay T_{CH} is the steam chest time constant T_{RH} is the re heater time constant T_{CO} is the steam storage or cross-over time constant.

Now here I wanted to just mention that out of all these time constants the T_{RH} the re heater time constant is the largest its value is around 10 seconds, 5 to 10seconds while this T_{CH} and T_{CO} the time constants are of the order of .2, .3 like that fraction of a second a small right and once when you see that the time constant T_{RH} a large time constant right then whenever you are trying to study the midterm or long term dynamics right then this model will have its effect on the stability.

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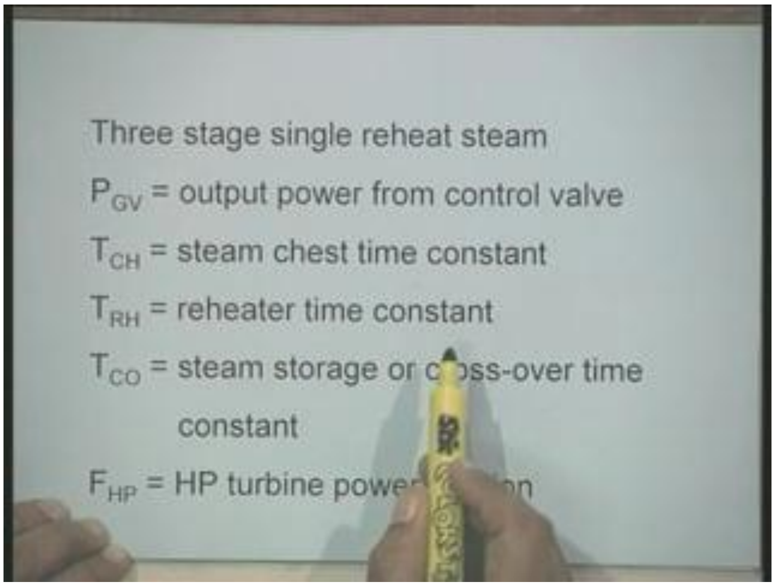

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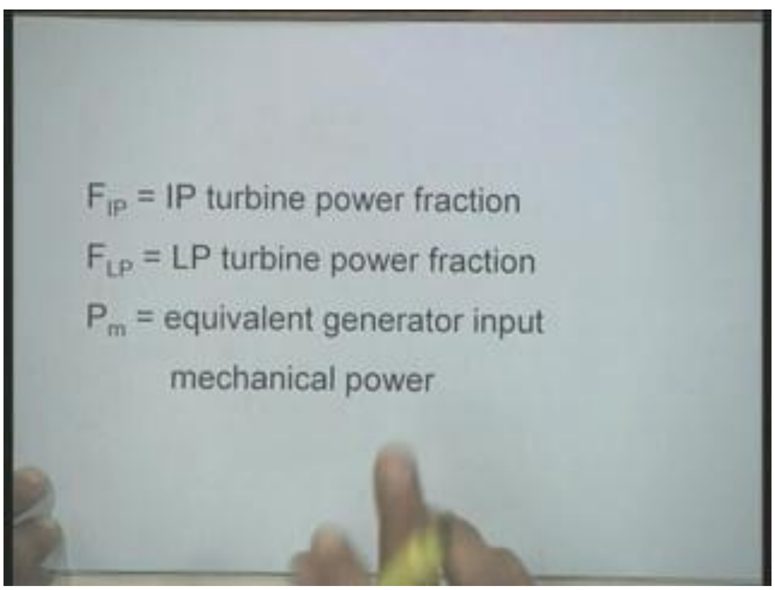

Now, similarly this FIP stands for IP turbine power fraction FLP is the LP turbine power fraction P_m is the equivalent generator input mechanical power, this is the mechanical power input which we have been talking about. Now the 3 differential equations which you can write can be written in the simple form, 3 differential equations are because there were 3 single order a first order transfer functions for each transfer functions you can write down one differential equation d by dt of P_{HP} as P_{GV} minus P_{HP} divided by T_{CH} similarly, d by dt of P_{IP} equal to P_{HP} minus P_{IP} divided by T_{RH}, d by dt of P_{LP} equal to PIP minus P_{LP} divided by T_{CO} and the mechanical power P_m is equal to P_{HP}, F_{HP} plus P_{IP}, F_{IP} plus P_{LP}, F_{LP} okay.

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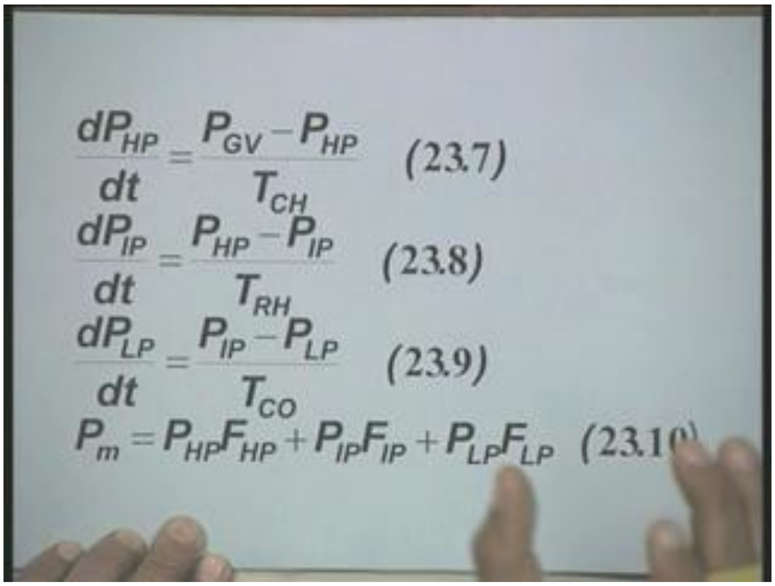

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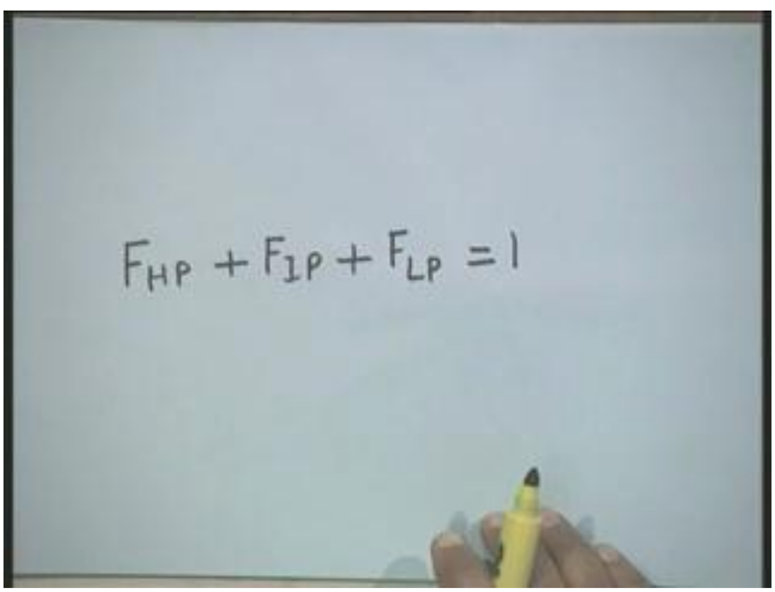

Now these 3 differential equations right we will will form the the model for the steam turbine and if you go for slightly you can say more detail not more detail but for different configuration you can write down the number of equations required to describe that particular configuration.

Now let us see what is the sum of these 3terms, now these 3 fractions that is the fraction of power which is generated in the HP section plus fraction of power which is generated in the IP section fashion ((00:34:47 min)) of power which is generated in the LP section, this sum should be equal to 1 okay.

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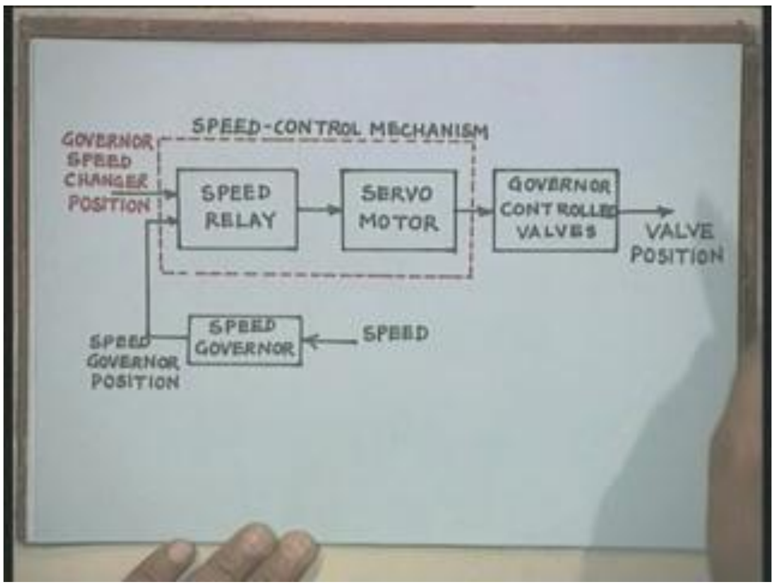

Now we will discuss the speed governor for steam turbine or we can say that speed turbine control, steam turbine control. Now before I go into details I wanted to specify here mention here that over the years there has been lot of development in the governing mechanism and the associated controls ah originally the mechanical hydraulic controllers are used they are still actually in operation but these days they have what we call electro hydraulic controllers or electro hydraulic governors but remember that in all these the hydraulic servomotor plays very significant role.

Now when we look into the control for the steam turbine the main function of this control is to open and close the steam turbine valves this is the end objective that we want to adjust the steam turbine valve position so that the required amount of steam flows this is what and these valves have to open against the pressure of the steam and they are are their inertia and their weight is very substantial NTPC engineers know actually that their weight may be in terms of few tons, am I right and therefore to make this valves to move, you require huge amount of torque or pressure right and therefore this pressure amplification is done in hydraulic servomotors, required amount of pressure amplification is done in hydraulic servomotors therefore here the basic components of speed control mechanism can be look like this.

We have a speed governor first block is the speed governor, input to the speed governor is the speed actual speed of the machine then the output of this governor will be the speed governor position. Okay depending upon the actually the speed there is some position of the governor this enters into the first block here. We call speed relay right I will discuss these three these components separately but there is a speed relay to this speed relay we have two inputs coming one is the one is the governor speed changer position, another is the speed governor position because as I have told in beginning in the first block diagram which had shown you therefore there were two inputs coming, one coming through AGC which is the speed changer position where you sometimes you can use that instead of speed changer position actually the the power output position your reference what the set point you can call it.

Okay and this set point can be adjusted by the AGC automatically otherwise it is done manually and another signal coming is through the governor these two signals enter the speed relay, speed relay is comprising of a pilot valve and a servomotor then there is one more servomotor hydraulic servomotor to amplify this power and then we have the governor control valves and output will be the valve position therefore you can easily see here that input to this control mechanism.

We have two signals one is a speed another is the speed changer position and the output is the valve position because when talked about the steam turbine models right the input to the model is the valve position right and now in this particular case the input will be speed and the set point these are the two inputs.

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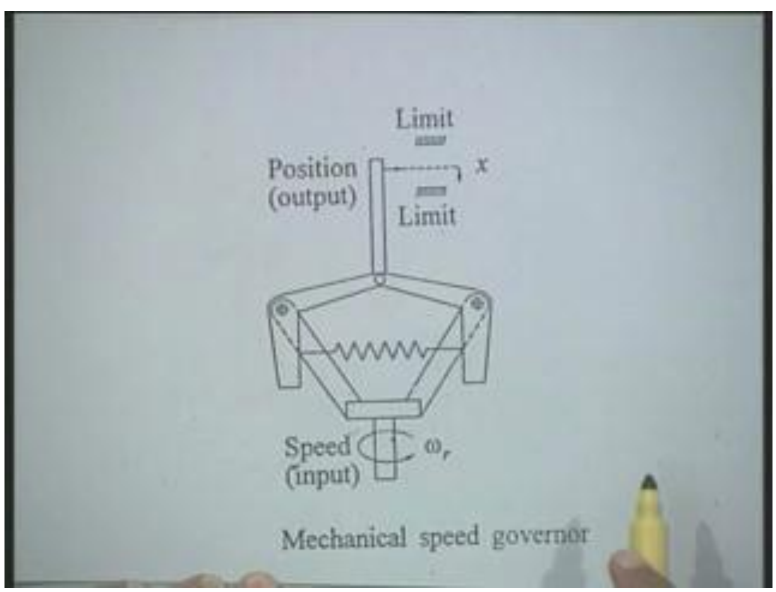

The governor which senses the speed right. This is the mechanical speed governor a flyball type of mechanism and although there is a lot of developments which have taken place in sensing the speed still flytype, flyball type speed governors are in operation these NTPC people is it operating in your system now or replaced therefore now the we use what is call actually the electric sensor, the speed sensors we call it for the speed sensing instead of using this mechanical flyball type of arrangement we use actually the electric speed sensors basic simple actually you can use a permanent magnet generator PMG and the speed can be sensed by knowing the voltage output of that okay.

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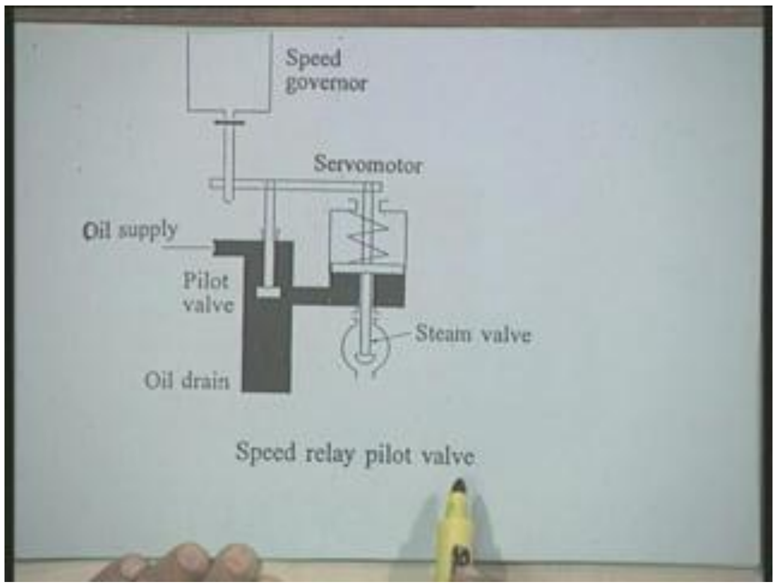

Now here irrespective what type of you can say the speed sensing you use right, we have a signal which is proportional to the speed okay. Now this diagram shows a simple speed relay pilot valve. Now when I talk electro hydraulic governor right the mechanical hydraulic governor or controller the M is replaced by E therefore basically the speed sensing mechanism is replaced but so far processing is concerned still we have this speed relay and servomotor, hydraulic servomotor right because the amount of power which is required is enormous the amplification is very high level, okay. Now in this arrangement I will just show you here actually this arrangement if you see this this rod which is coming here that represents the position of the speed governor.

Now when this rod actually will is attached to a lever like this and this lever is attached to a pilot valve and a spring loaded servomotor. Now here actually you will see a very interesting thing that always whether I talk of a hydraulic servomotor or a pilot valve right there will be linkage between the the valve piston and like the servomotor piston this linkage is basically to provide what is called negative feedback it is a negative feedback always. Now the arrangement is very simple here the high pressure oil is here you maintain right.

When the pilot valve suppose suppose actually the the pilot valve is made to move down okay then this high pressure oil will move into the servomotor and push the piston up the the the moment of this piston when it is moving up it is actually restricted by or controlled by the spring pressure, okay. Now you can easily see that when this is trying to move this will also come down while at the same time when this oil enters and tries to push it up through this same mechanism this pilot valve is also pushed up therefore this acts as a negative feedback.

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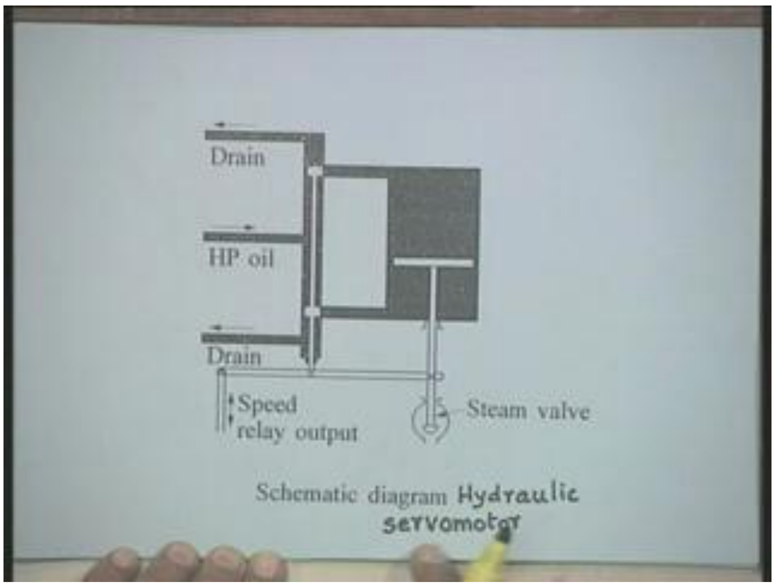

Now of course here in this diagram it is shown actually that as if this servomotor is controlling the steam valve but in case we need one more stage of amplification then this rod or this piston is going to control the hydraulic servomotor. In this hydraulic servomotor again the similar arrangement is there you have this pilot valves high pressure oil comes here right and the this linkage shows actually the connection to speed relay right and you can easily see actually that when this lever moves up right the this pilot valve moves goes up it opens this and the oil will can come down when it opens what happens is the oil will come down from this side and it enter from the top right, in the sense that is moving down that is actually when you move it down the oil will come from the from the the end, oil will leave from these two sides but enter through high pressure section only and it will move from the top push it down and oil will come out like this. Therefore through this mechanism the hydraulic servomotor actually you will be because of the high pressure oil which is maintained right therefore this power amplification takes place.

Okay and the amount of amplification will depend upon what is the what is the cross section area of the hydraulic servomotor or piston right and what is the pressure which is maintained in the high pressure oil right these are the parameters which will determine. Now when we try to develop the model for these devices you have to look into two aspects one is that the moment of this piston piston for a certain particular opening will depend upon the flow of oil at a certain pressure therefore this moment can be considered to be function of time as the time passes it increases therefore basically this can be represented by an integrator.

It will represent because when the oil is flowing at certain rate the piston will keep on moving right the position will keep on changing. Further further since in these all the devices there is always a negative feedback. So that output whatsoever is the output position here is fed back directly as a negative feedback, okay another thing which you have to see is the that there are two limits which we will be talking about one is called actually the rate limit that is the rate at which this valve is going to move up and down, another is the position limit, upper and lower position limits that is when the this can go to the top it will come down to the bottom there are two limits okay therefore there are two limits which will be shown one is called actually rate limit another is called the position limit. While when you talk about actually the speed relay these limits are normally not required to be shown.

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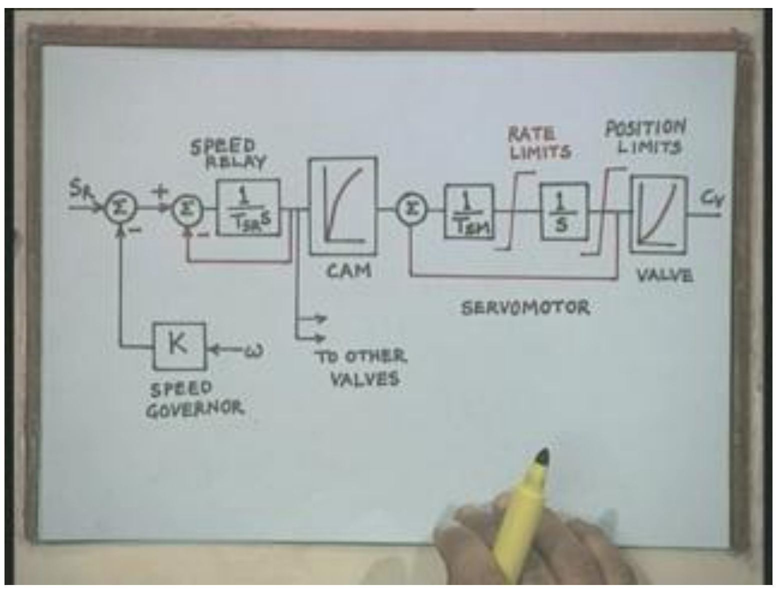

Now this block diagram represents the transfer function model of simple steam for a transfer function model of steam turbine governor. Now we can just start like this this is the speed governor, input to this is the speed okay therefore output of this will be a K times speed. They are basically it is a it is a speed sensor speed deviation is going to be sensed here. Now this is going to compared with the reference the error comes here.

Now this block diagram which I have shown here this block diagram it represents actually the transfer function of the speed relay, it is something like this. Speed relay we represent time constant of this as T_{RS}, T_{SR} not RS, T_{SR} I can put it we will call it T_{SR} speed relay an integrator this is basically integrator. The position is fed back there is a negative feedback loop here okay and this is the plus this is minus. Now this can be replaced by an equivalent transfer function one over 1 plus s times TSR that is this transfer function which has actually which represents the integrator and a negative feedback is represented by a first order transfer function of this form right.

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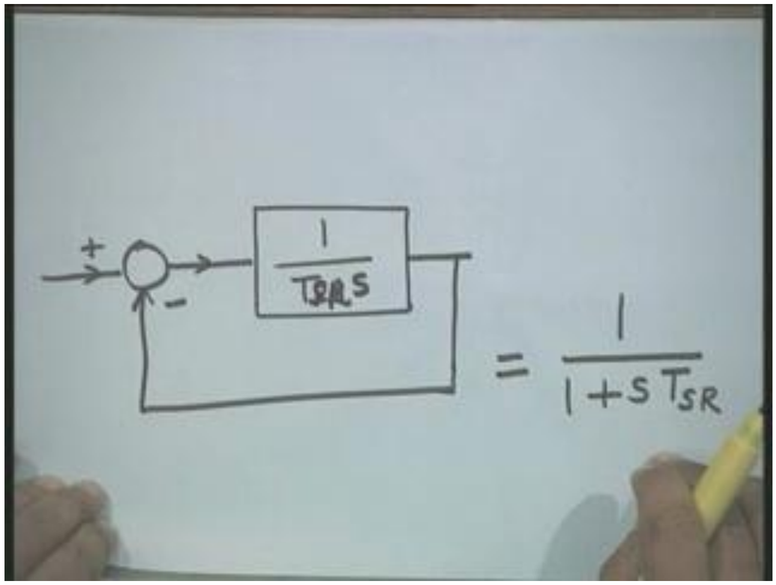

Similarly, here actually is the transfer function of the servomotor, while in the servomotor we try to represent the rate limit and the position limits and therefore these two this is this is the time constant one upon T_{SM} servomotor time constant, one upon T_{SM} at this point we can sense what is called the rate and after integrating we can sense the position right therefore these two are provided. Then the here you will find actually the there is a the control valve moment and actually the servomotor moment there is a non-linear relationship and therefore this is the valve characteristic.

Now in order to linearize this we actually a which will have a characteristic opposite to this. So that when we put together it will be linear characteristic now this is the complete transfer function model of a steam turbine governor. Now here I have not shown actually in this diagram but the speed relay output can be used to control other valves also because you may have for example interceptor valve, interceptor valve can also be controlled through this speed relay that is why it is shown other valves okay.

Now using because for stability studies, for stability studies we can model this non-linearity this non-linearity can be modelled and we can write down the transfer function or the differential equation relating the output of speed relay to the input. Similarly we can relate the output of the servomotor to the input and these relations are available therefore we can write the complete mathematical model of the and you can see really that this CV which I have shown here control valve position is basically the P_{GV}, P_{GV} the governor valve position or control valve position they are same.

Okay now with this ah let me summarize our presentation today. We have discussed today the the transfer function model of steam turbine and steam governor a steam turbine governor. We have also developed the differential equations which can be used to represent the steam turbine and the differential equations to represent the the steam turbine governor okay. Thank you!