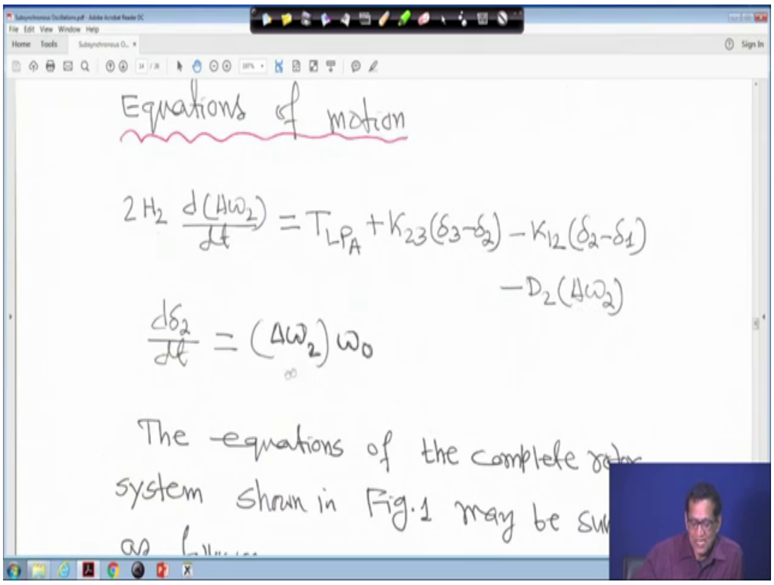
Power System Dynamics, Control and Monitoring
Prof. Debapriya Das
Department of Electrical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 60
Subsynchronous oscillation, Windup and non windup limits

Ok. So, we are back again, right. So, next is actually equations of motion, right and this is the last part of this course, right.

(Refer Slide Time: 00:31)

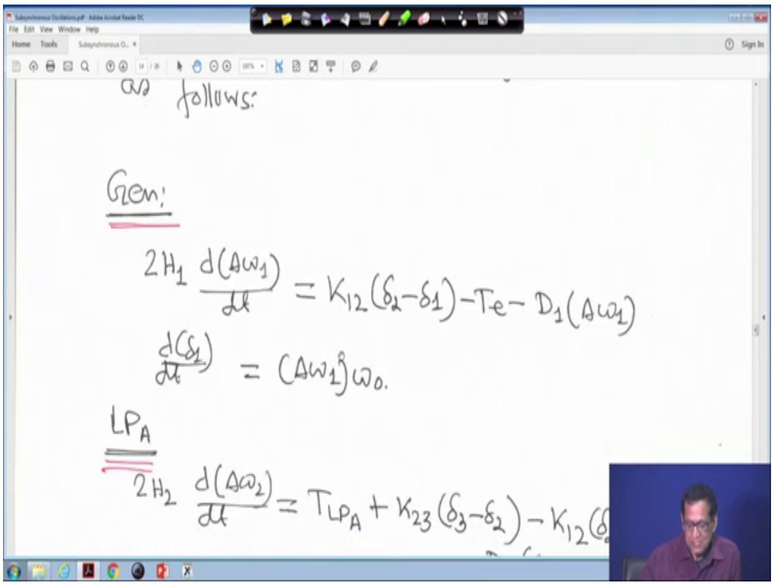


So, next is the equation of motion for the section 2. So, it will be 2 H 2 d dt of delta omega 2 is equal to T LP A plus K del K 23 delta 3 minus delta 2, then minus K 12 delta 2 minus delta 1 minus D 2 delta omega 2 because these are the input torque, right and this is your equation of motion. And similarly, your d delta 2 by dt will be delta omega 2 omega 0. This type of equation already we have derived and here you are considering separate several subsection, so you have to write this you are what you call equation of motion like this, right.

So, these two are input torque then you make it minus K 12 delta 2 minus delta 1 this is output torque and this was damping minus delta 2 into delta omega 2, right D 2 into delta omega 2. And this is your d delta T upon dt is equal to delta omega 2 omega 0, right.

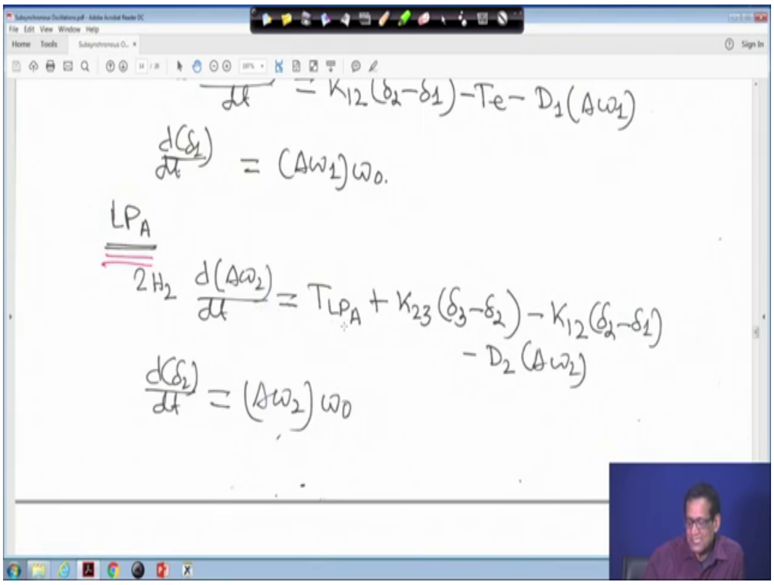
Now, equations of the complete rotor system shown in figure 1 may be summarized. Now, similarly you have your in figure one we have section 1, section 2, section 3, section 4 and section 5. So, similarly one after another you proceed and the way I showed the first two section, 3 sections similarly you can write down the equation from the inspection, right.

(Refer Slide Time: 01:57)



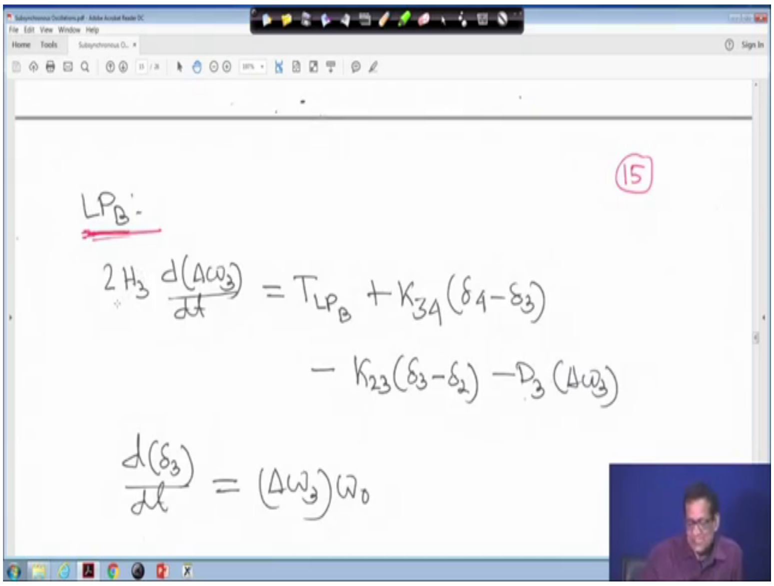
So, for the your what you call for therefore, for generator now we summarized this. Now, rewriting this equation for generator 2 H 1 d dt of delta omega 1 is equal to K 12 delta 2 minus delta 1 minus Te minus D 1 delta omega 1. Now, d dt of delta 1 delta omega 1 into omega 0.

(Refer Slide Time: 02:15)



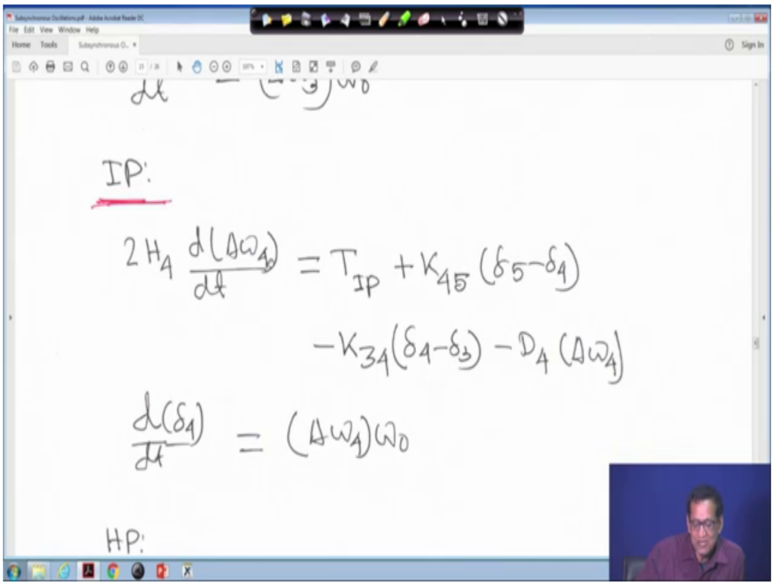
Similarly, for LP a section 2 H 2 d dt of delta omega 2 is equal to T LP A plus K 23 delta 3 minus delta 2 minus K 12 delta 2 minus delta 1 minus D 2 delta omega 2 and d dt of delta 2 is equal to delta omega 2 omega 0. These two we have seen that how to make it, here and here also here also how to make it; now we are summarizing this.

(Refer Slide Time: 02:40)



Similarly, for section 3 same way you will write 2 H 3 which will be d dt of delta omega 3 is equal to this is the input torque, right that it T LP B that is that is the section b that low pressure turbine, right. T LP B plus K 3 4 into delta 4 minus delta 3 minus K 23 delta 3 minus delta 2 minus D 3 delta omega 3. This is for the section 3, right. And d dt of delta 3 is equal to delta omega 3 into omega 0, right.

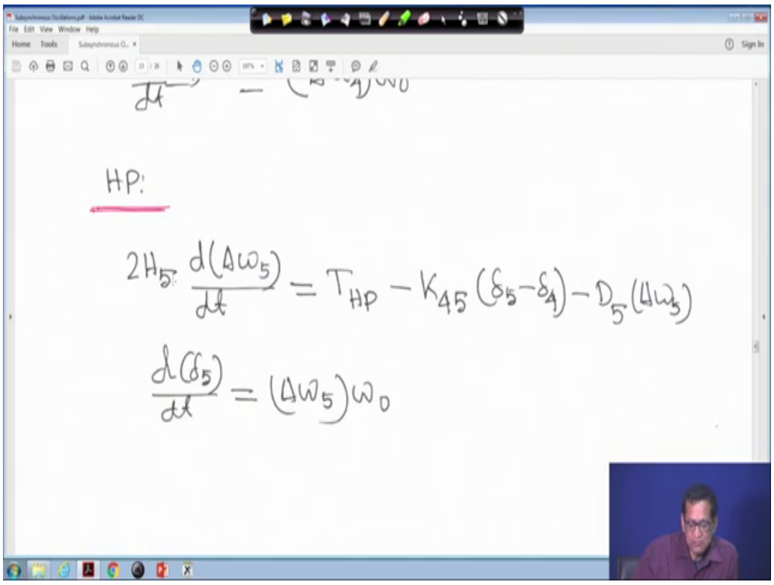
(Refer Slide Time: 03:13)



Similarly, for intermediate pressure just from your inspection you can write that 2 H 4 d dt of delta omega 4 only their inertias are different, right because you are considering your what you call different section, is equal to T IP plus K 45 into delta 5 minus delta 4 minus K 3 4 delta 4 minus delta 3 minus D 4 delta omega 4. And d dt of delta 4 will be delta omega 4 into omega 0, right. So, this is your; what you call that is intermediate section.

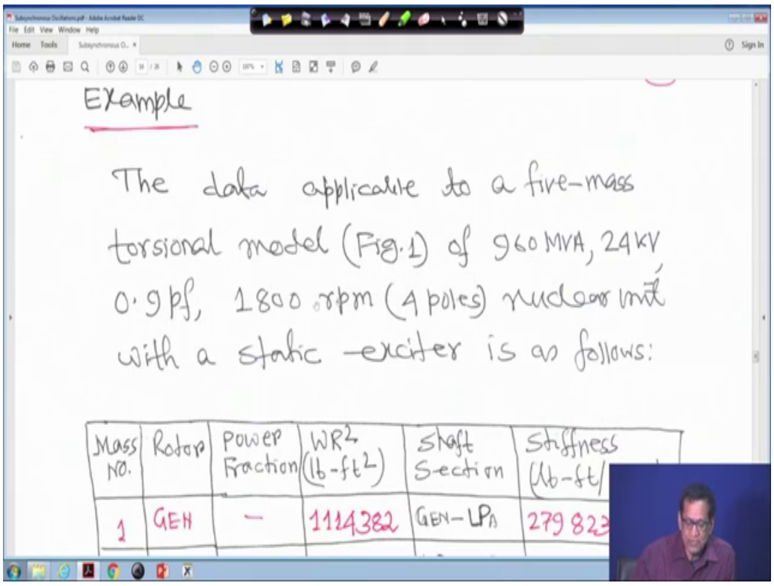
Now, in your then high pressure, that is intermediate pressure that is high pressure.

(Refer Slide Time: 03:50)



Now, for high pressure this section 5. It is 2 H 5 d dt of delta omega 5 is equal to T HP that are the input torque minus K 45 into delta 5 minus delta 4 minus D 5 delta omega 5. This is for the high pressure portion, section 5. And d dt of delta 5 will be delta omega 5 omega 0. This is how we have to represent that each section, right.

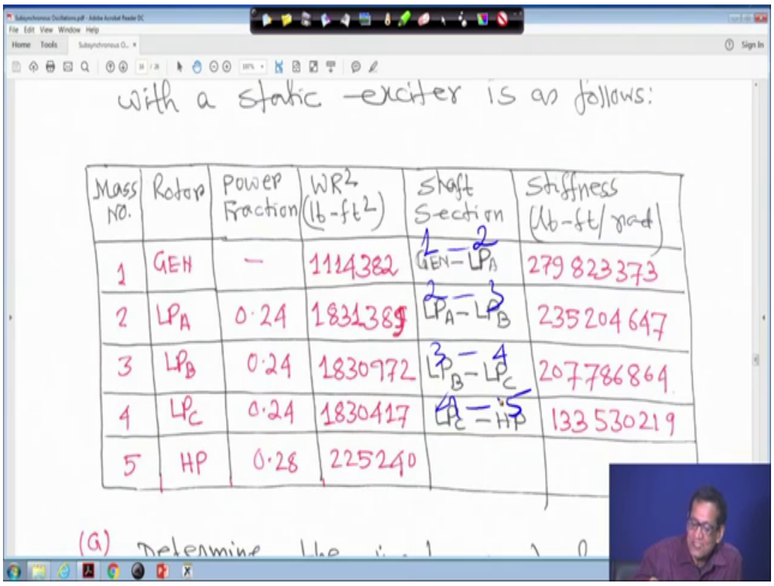
(Refer Slide Time: 04:22)



So, now we will take one example, right, we will take one example. The data applicable to a 5 mass torsional model that is your figure 1, right; figure 1 also you have considered 5 mass of 960 MVA, 24 KV and 0.9 power factor, 1800 rpm 4 poles 60 Hertz, so it is

1800 rpm, right, nuclear unit with a static exciter is as follows; so these are the data given, right.

(Refer Slide Time: 04:50)



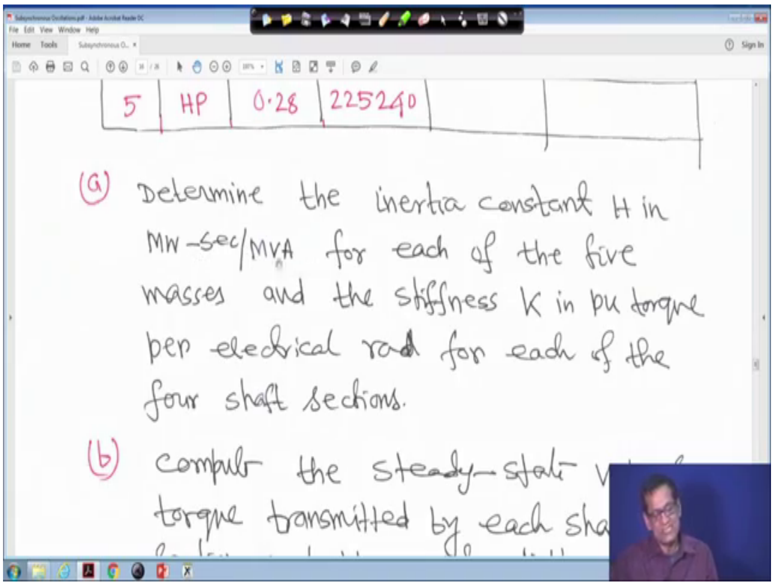
So, in this example only one thing I will not calculate for you. I will give the final answer, but I request you to compute that one, right. So, that is there are 5 sections, so 1 2 3 4 5, so there is different mass is there. The 1 is generated, 2 is the low pressure turbine, the section a section b it is LP B and your intermediate pressure that is LP C and this is a high pressure, right.

The power fraction generator is nothing but other turbine fraction it is 0.24, 0.24, 0.24 and this is high pressure side is 0.28, if you add all in it will be 1 because our representing is fraction that is per unit, right fraction. And this is your you moment of inertia in pound feet square. It is a huge figure it is given, right. So, it for example, this is 1114382 like this, so these are huge data, so that is pound feet square is given.

And these are the shaft section this is generator this is actually your generator to LP A. So, this is actually section 1 to section 2, right and this is section 2 to section 3, this is section 3 to section 4 and this is section 4 to section 5, right. So, 1 to 2, 2 to 3, 3 to 4 and 4 to 5. So, there are 4 4 section, right 5 masses so 4 section, so 4 shaft, right.

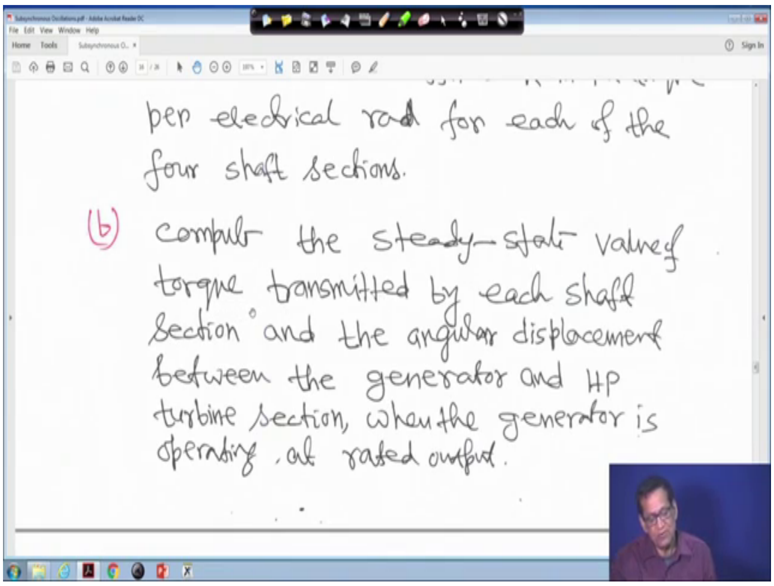
And your these are these are your what you call these are the stiffness that is its given pound feet per radian. So, it is a huge day I mean these figures are very large, right, but this stiffness is given that pound feet per radian, but we will convert it to your what you call that kg meter per radian and here also we will make your kg meter square, right.

(Refer Slide Time: 06:36)



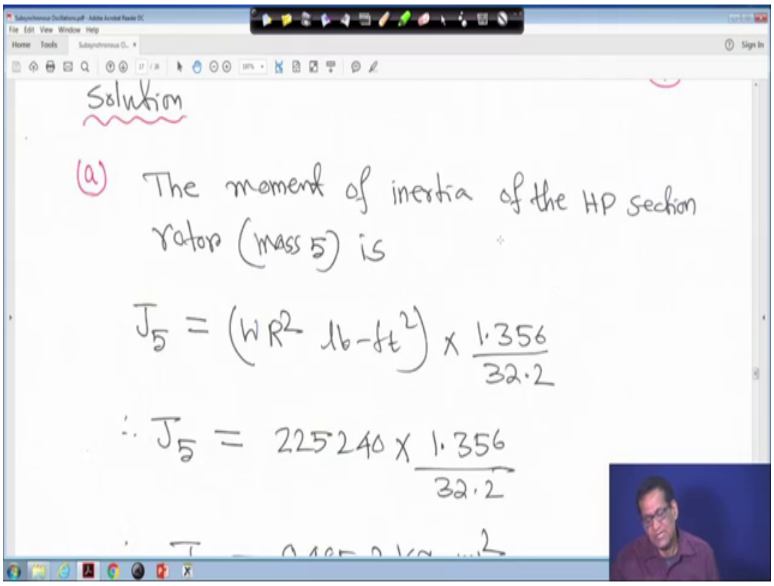
So, you have to find out that determine the inertia constant H in megawatts second upon MVA that is in second, right. For each of the 5 masses and the stiffness K in per unit torque per electrical radian for each of the 4 shaft section that we have to determine.

(Refer Slide Time: 06:52)



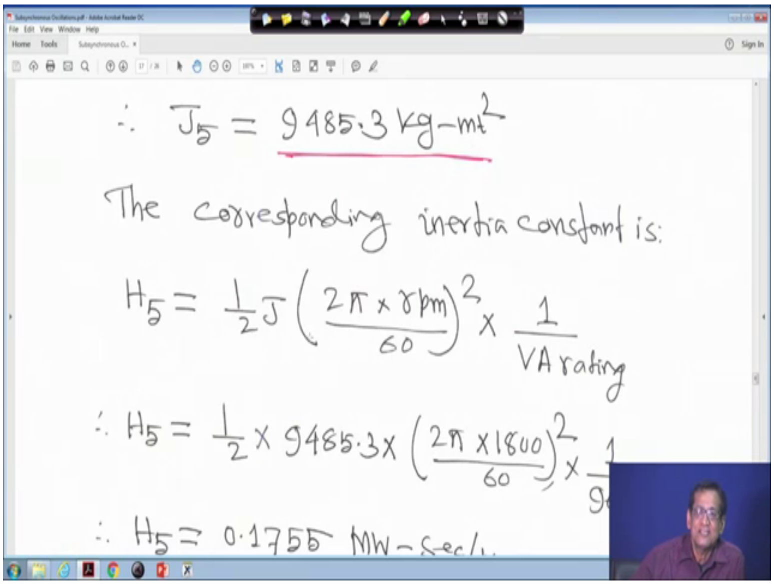
And b, compute the steady state value of torque transmitted by each subsection and the angular displacement between the generator and the high-pressure turbine section when the generator is operating at rated output, right; so these two things.

(Refer Slide Time: 07:12)



Now, solution the moment of inertia of the HP section rotor mass that is mass 5, right that is your what you call that high pressure section. We know these transformation for your what you call while doing your synchronous machine chapter, right that it will it is given inertia is given lb feet square into 1.356 upon 32.2 this already we have done it. So, here this inertia is given for section 5, this much, it is pound feet square that is 225240 pound feet square into 1.356 upon 32.2. So, that is actually 9485.3 kg meter square, right.

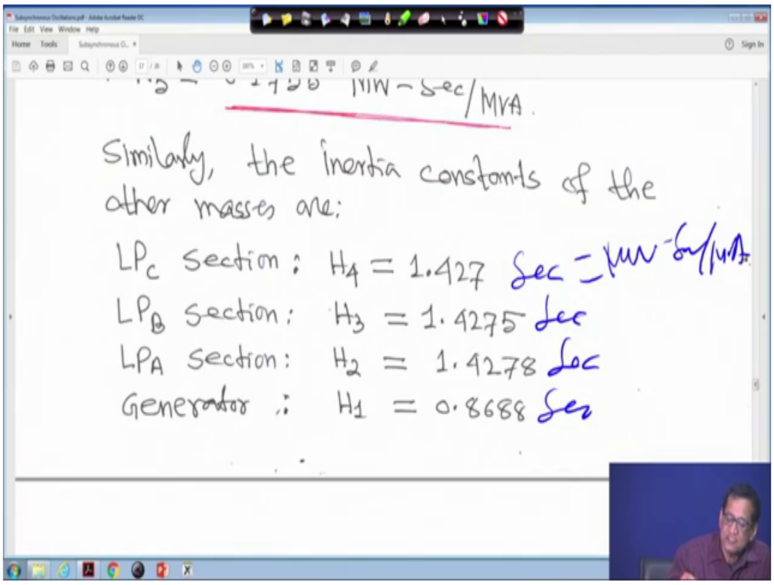
(Refer Slide Time: 07:49)



Similarly, the corresponding inertia constant is this also we have done it this also we have done it for your synchronous machine topic, right. So, somewhere we have done it. So, this is for each section we are writing, but general formula is half J 2 pi into revolution per minute rpm upon 60 square into 1 upon volt ampere rating. This also we have done it.

So, if you substitute all these values half into J, so J value just now we have got this one this is the J value, right into 2 pi, rpm was given in the data that is 1800 divided by 60 square into MVA was given 960 MVA we have to convert it to volt ampere, so 1 upon 960 into 10 to the power 6, right.

(Refer Slide Time: 08:41)

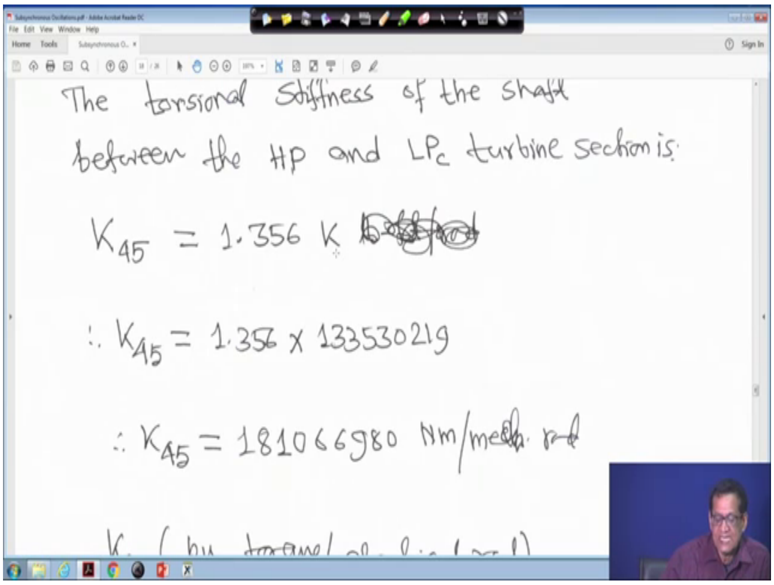


Therefore, H 5 will become 0.1755 megawatt second per MVA that is nothing but 0.1755second, right. So, this is inertia for the section 5, that is your high-pressure turbine section, right.

Similarly, similar way you calculate that inertia for other 4 masses, the LP C, LP B and LP A as given in figure 1 and the generator, right. If you follow the same procedure you will get these are actually you will get units are not written it is all are second actually, all are second, all are second, all are second, sometimes we write that your megawatt second per MVA, right. So, all are second.

So, if you follow this and calculate you will get your what you call this values H 4, H 3, H 2, and H 1, similar way that is why your, that is why other these calculations only one calculation shown. So, other you can easily compute. So, calculations are not shown that is why, right.

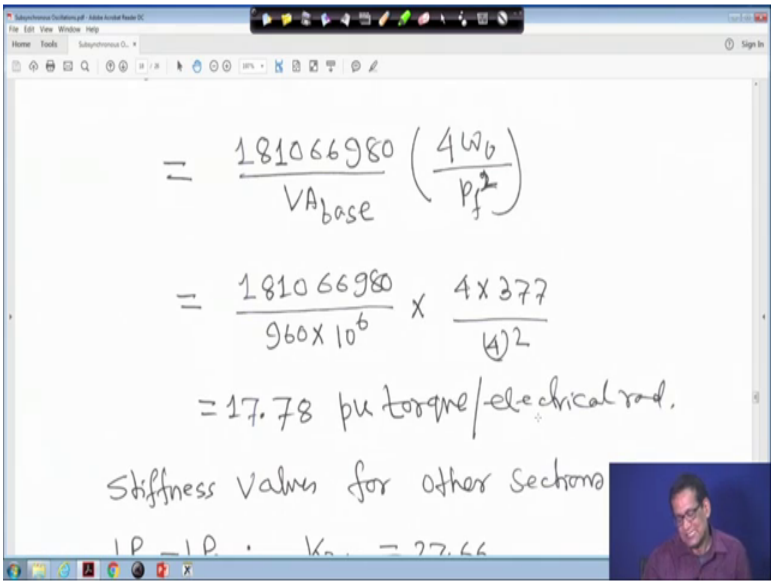
(Refer Slide Time: 09:42)



So, now the torsional stiffness of the shaft between the HP and LP turbine section is that K 45 is actually is equal to 1.356 K, right therefore, it is 1.356 and K is given because huge data is given for section 4 5, right. So, it will be 133530519, right. So, it becomes actually huge figure Newton meter per mechanical your; what you call radian. So, all these things you are what you call that the way we have converted your what you call that is your inertia that is 1.356 this we have derived earlier, similarly, for stiffness also you try to try to do little bit yourself, right.

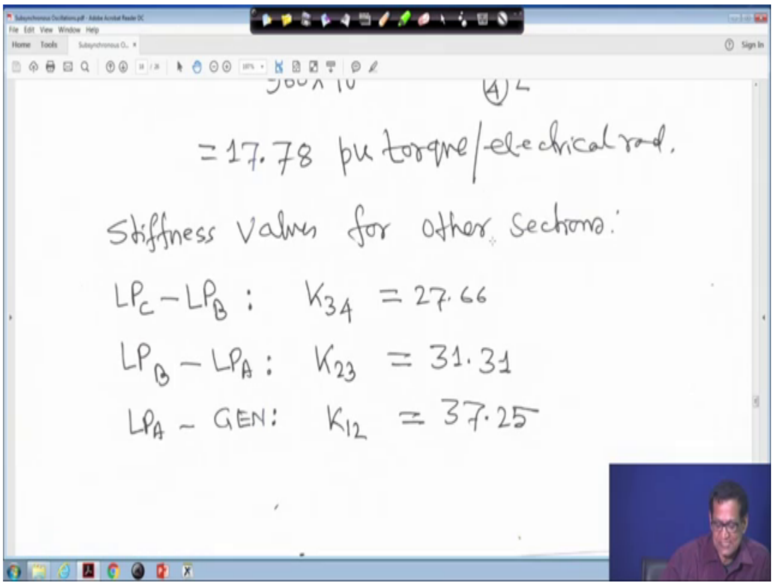
Same thing we have made it in synchronous base in chapter, but stiffness was not there; stiffness was not there, but same philosophy you follow to change the unit because it was given in British unit you convert to that m case, right. So, it is it is becoming K 45, will become this much of Newton meter per mechanical radian therefore, if you make it per unit it will be K 45 per unit torque per electrical radian will be whatever you have got it divided by V A base into 4 omega 0 upon p f square. This we have derived in the beginning, right. In the previous lecture this one was made it, right. So, K 45 per unit torque per electrical radian and this one just derived in the previous lecture.

(Refer Slide Time: 11:05)



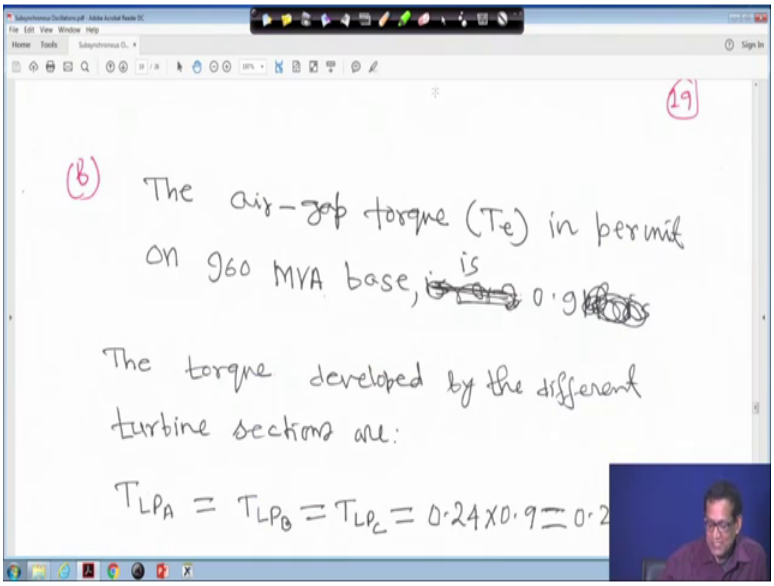
If you put it will become actually 17.78 per unit torque, but electrical radian p f is equal to 4 and 60 hertz omega 0 is 377, right. Therefore, stiffness value for other similar way you find out the stiffness values for other sections, right. So, LP C to LP B, LP B to LP A that is 3 to 4, 2 to 3 and 1 to 2.

(Refer Slide Time: 11:17)



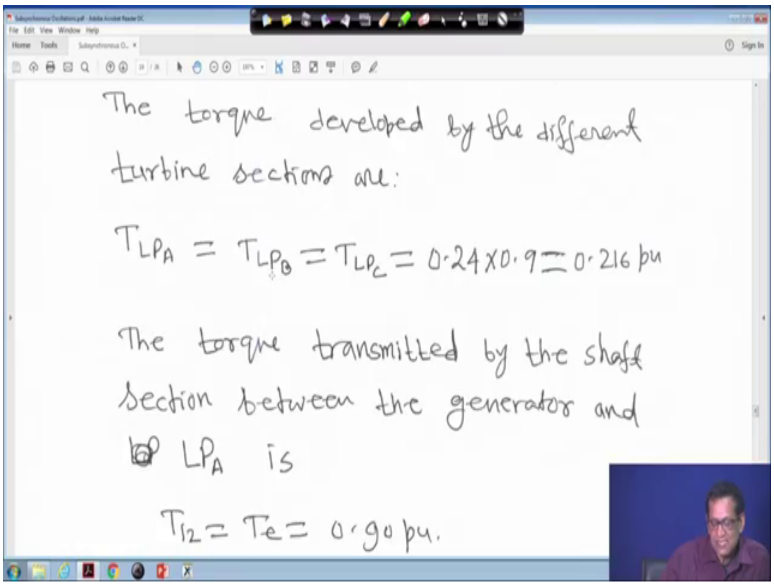
So, you will find K 3 4 will be 27.66 all are in per unit, right that is per unit torque, per electrical radian. K 23 will get 31.31 and K 12 we will get 37.25, right. Just I did not solve this calculation, but only one calculation is shown. Similarly, others you can easily calculate, right.

(Refer Slide Time: 11:50)



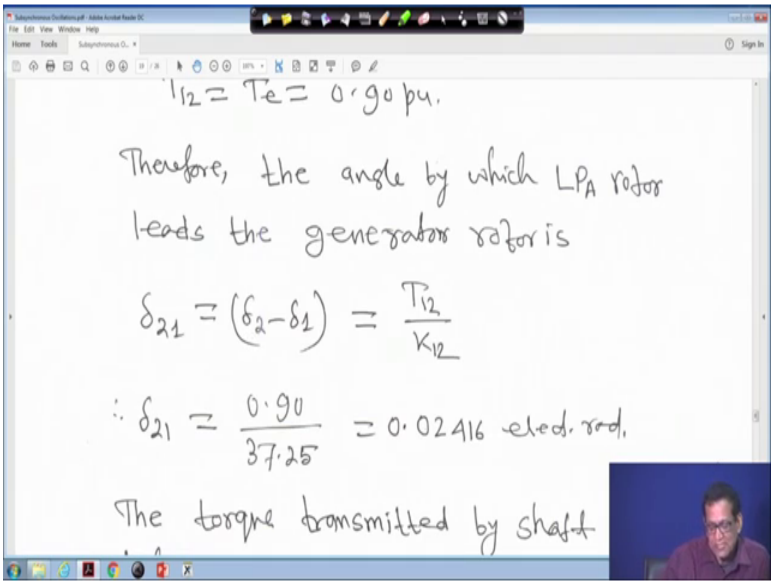
Now, part b, the air gap torque T in per unit your what you call 960 MVA base is 0.9. This one, this is this is your this is you just see it, right, from where it has come, right.

(Refer Slide Time: 12:11)



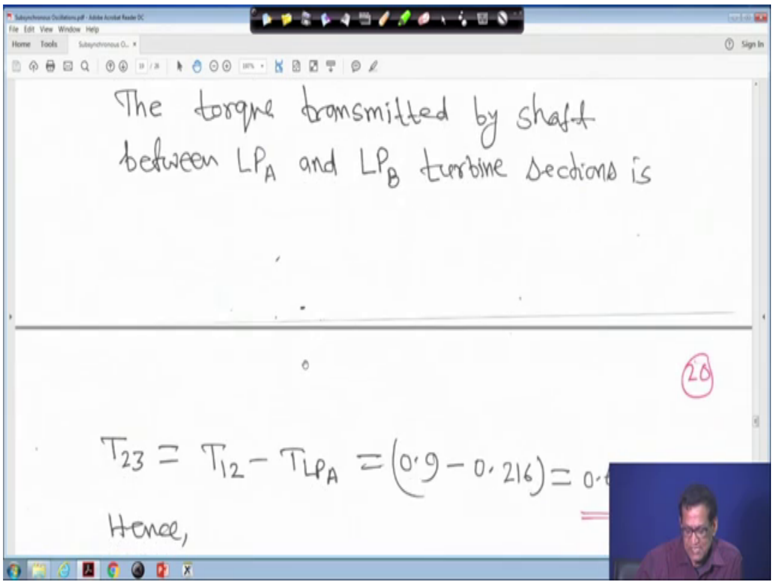
So, the torque developed by the different turbine sections are that is your this one T LP A is equal to T LP B is equal to T LP C, because all are 0.24. There it was given your what you call that in the data I am going to the data that it was given that all 0.24, 0.24, these 3 are equal, these 3 are equal multiplied by 0.9. So, these 3 are equal, right. So, here it is, right. So, it is 0.24 into 0.9, so 0.216 per unit for 3, right. And for your what you call the torque transmitted your by the shaft section between the generator and LP A is at T 12 is equal to Te is equal to 0.9, right this is 0.9.

(Refer Slide Time: 13:02)



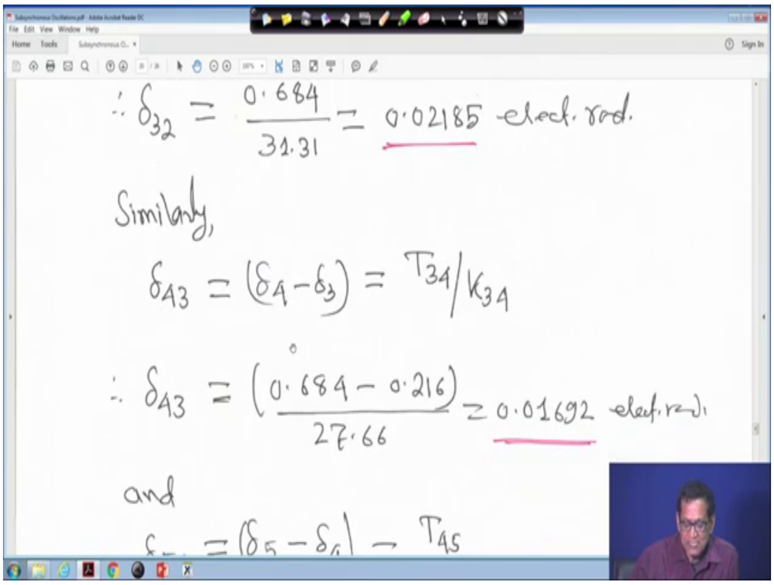
So, therefore, the angle by which LP A rotor leads the general rotor is the delta 21 is equal to delta 2 minus delta 1 is equal to T 12 upon K 12 because we K now T 12 is equal to K 12 into delta 2 minus delta 1, right. Therefore, this is your what you call the delta 21 will be then 0.9 divided by 37.25. So, it will become 0.02416 your what you call electrical radian, right.

(Refer Slide Time: 13:32)



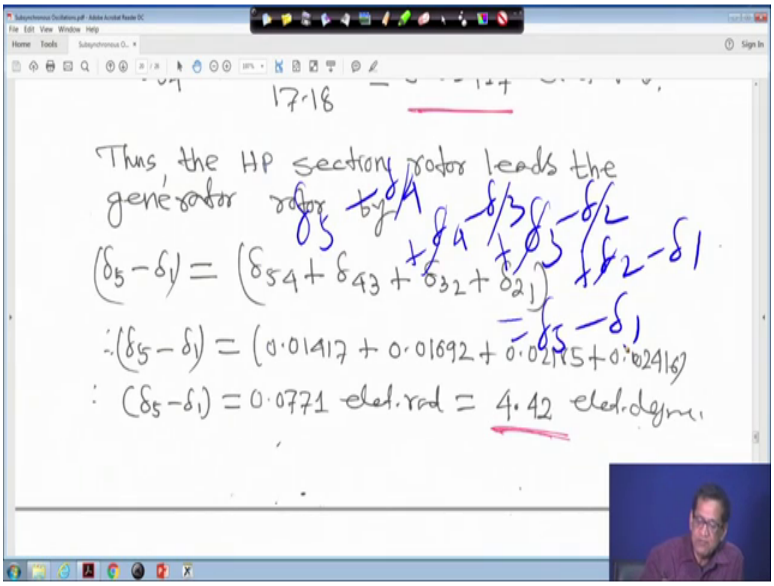
The torque transmitted by the shaft between LP A and LP B turbine section will be similarly that your T 23 will be T 12 minus T LP A, right is equal to this much minus 0.216 it will be 0.684 per unit, right. The hence your delta 32 will be delta 3 minus delta 2 is equal to T 23 upon K 23. So, T 23 is known, K 23 also you have computed before, so it will become 0.02185 electrical radian. Although this variation if you look it is very small, but it has some meaning, right.

(Refer Slide Time: 14:05)



Similarly, delta 4 3 will be delta 4 minus delta 3 is equal to T 3 4 upon K 34 that is your 0.684 minus 0.216 upon 27.66. So, that is actually 0.01692 electrical radian, right and delta 54 will become, delta 5 minus delta 4 is equal to T 45 upon K 45. So, delta 54 will become 0.252 upon 17.18 because all stiffness have been computed before, so it is 0.01417 electrical radian, right.

(Refer Slide Time: 14:41)

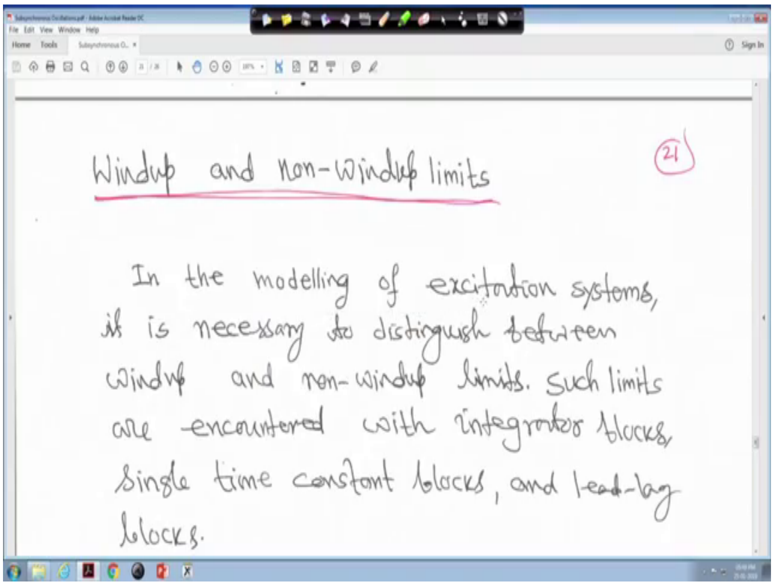


Thus, the HP section rotor leads the generator or rotor by delta 5 minus delta 1 because this delta 5 by delta 54 means it is delta 5 minus delta 4, right. Then plus delta 43 means delta 4 minus delta 3 plus delta 3 means delta 3 minus delta 2 plus delta 2 minus delta 1. So, delta 2 delta 2 will be cancelled, right delta 3 delta 3 will be cancelled, delta 4 delta 4 will be cancelled.

So, finally, it will be delta 5 minus delta 1, right. That is why we are just what we are doing is that you delta 5 minus delta 1 is that you add all, right. So, that is nothing but delta 5 minus delta 1. If you add all you will get 0.0771 electrical radiant that is 4.42 your what you call electrical degrees, this is electrical degrees, it has converted to degrees, right. So, that is the problem what is you asked, right.

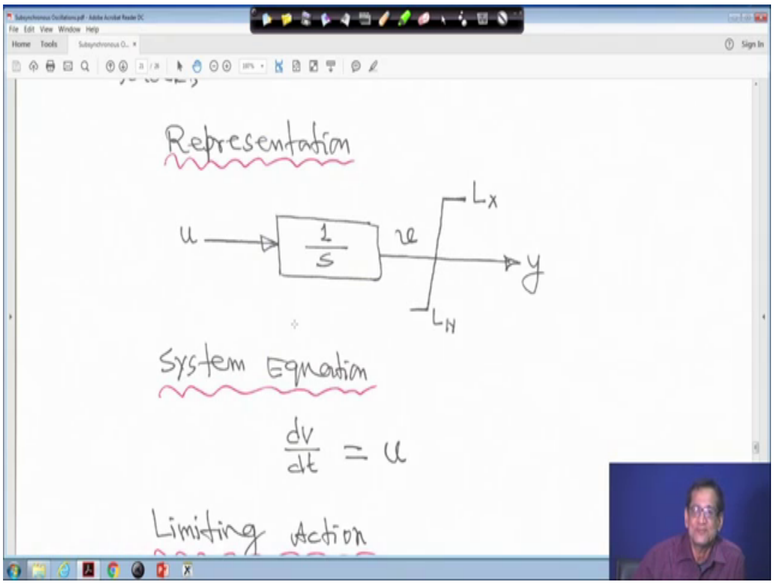
After this, with all these things your subsynchronous, your oscillations all these things that little bit we have touched, right it is basically a vast chapter. So, after this that whenever we go for your stability studies or any other control thing there are limiters is there, right. So, little bit will touch limiter that how actually mathematically it works, right; so for example, windup and non-wind up limits; so these two things.

(Refer Slide Time: 16:11)



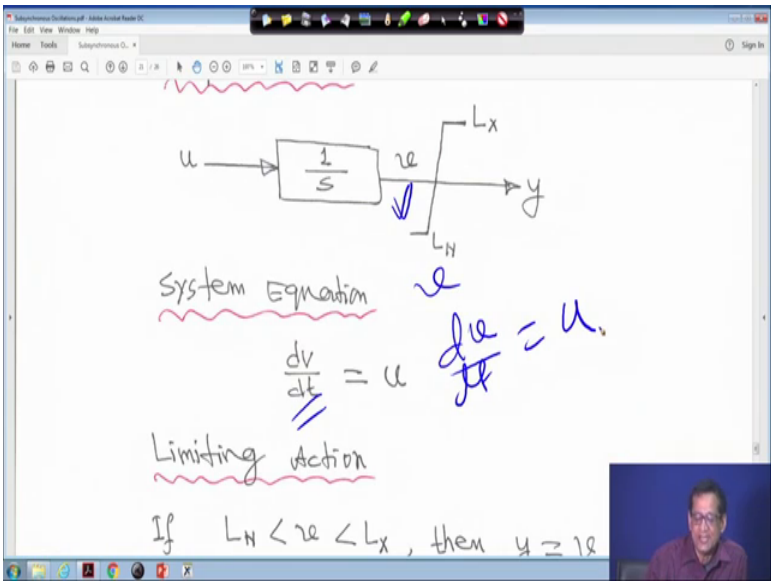
So, now in the modelling of your what you call excitation system it is necessary to distinguish between windup and non-wind up limits. Although modelling excitation part we have no time to do that. So, we could not do we could not touch it only little bit we have talked, but we could not catch it, right. But not only that in other control part also sometimes we use the limiter, right. So, windup and non-wind up your what you call limits. Such limits are encountered with integrator blocks, single time constant blocks and lead lag blocks. So, this thing we will see that how actually mathematically it works representation.

(Refer Slide Time: 16:52)



So, first you see that your what you call it is your what you call windup limit. So, representation this is input is u, this an integrator, output is v, right, but is restricted to L X to L N and this output is y. Now, how it behaves? So, when you put this symbol actually how it behaves.

(Refer Slide Time: 17:05)

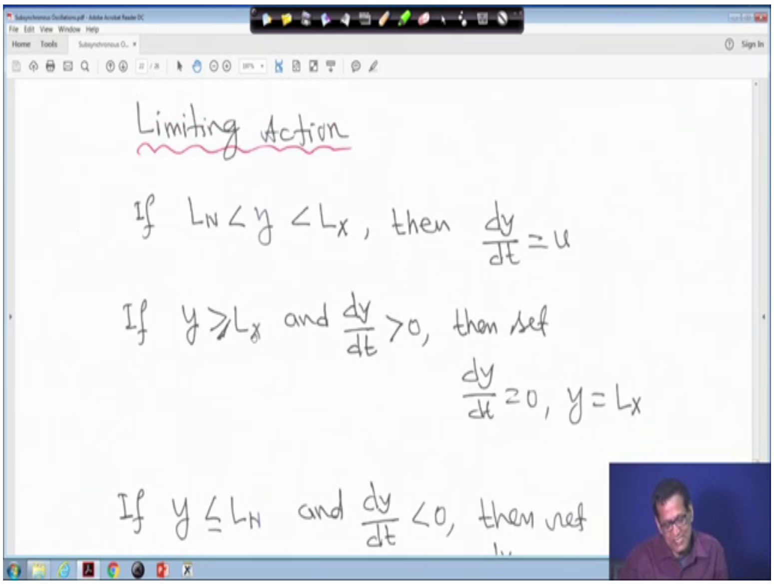


So, first system equation will be dv this is v, actually here I have written dv dv by dt. So, this is actually v, right. I have written like this, but this is actually dv by dt. So, dv by dt is equal to u, right. So, now, system equation actually it is dv by dt first you make it u the dv by dt is equal to u.

Now, how limiting action will be there. This is for integrator and you are putting a limit, right. L X and your what you call L N that upper and lower bound. So, limiting action when v this output lying in between L N and L X that is your constant is not violated, this not violated then y is equal to v that is pass, right. So, v will pass if v is lying between L N and L X, right and dv by dt is equal to the constant is dv by dt is equal to u, right.

Now, if v greater than L X, I mean if v greater than L X you set y is equal to lx. So, you set y is equal to L X, right and if v less than equal to L N you set y is equal to L N, right.

(Refer Slide Time: 18:15)



So, this is actually limiting action and this is figure a, that is integrator with windup limits this is we call windup limits, right.

Next is your representation, non-wind up limits, right. In this case we mathematically your block diagram representation is like this, this is input is u and output is y and we put that limiter like this L X and L N and how what actually made. So, equation will be dy by dt is equal to u, same as before earlier also dv by dt u, but here no question of v it is dy by dt is equal to u and it is L X it is L N.

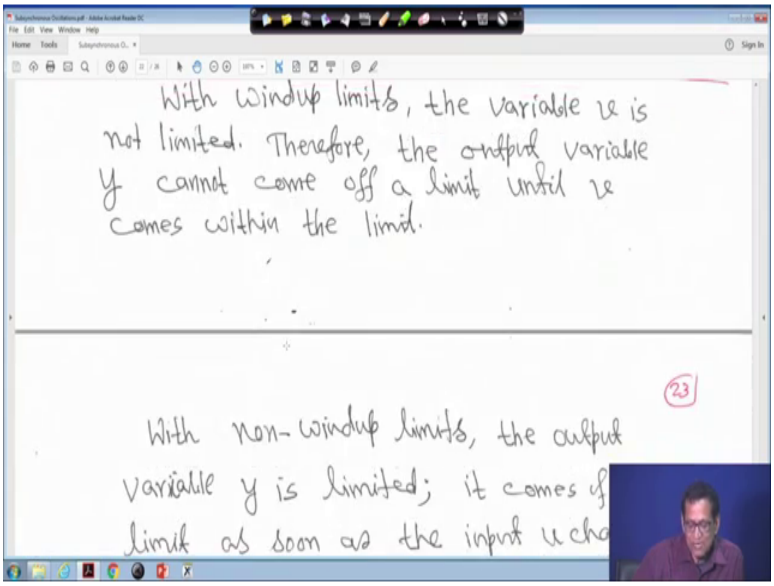
Now, limiting action, that y if y is lying between your L N and L a your L N and L X then dy dt is equal to u I mean if y is lying between your L N and lx, right then dy by dt is equal to u this is the constant, right then it is that derivative is dy dt is equal to u.

Now, if y your what you call greater than equal to L X; that means, if y greater than equal to L X, right then your what you call that then and dy dt 0 [FL] both things are there if y greater y is greater than L X and if dy dt the dy dt is greater than 0 and if positive if y greater than L X and dy dt greater than 0 then you set dy dt is equal to 0 and y is equal to L X. So, this another constant, right.

Similarly, if y less than equal to L N and dy dt less than 0 then set again dy dt 0 and y is equal to L N. So, this is your non-wind up limits, right. So, this is a symbol; that means, when you are using controller and some other things that what you call we use your what you call limiter, right. So, different that windup limits and non-wind up limits. So, this is for when integrator is there and this is the condition suppose your system deserve this kind of your what you call applications then accordingly you have to design, right, accordingly you have to design.

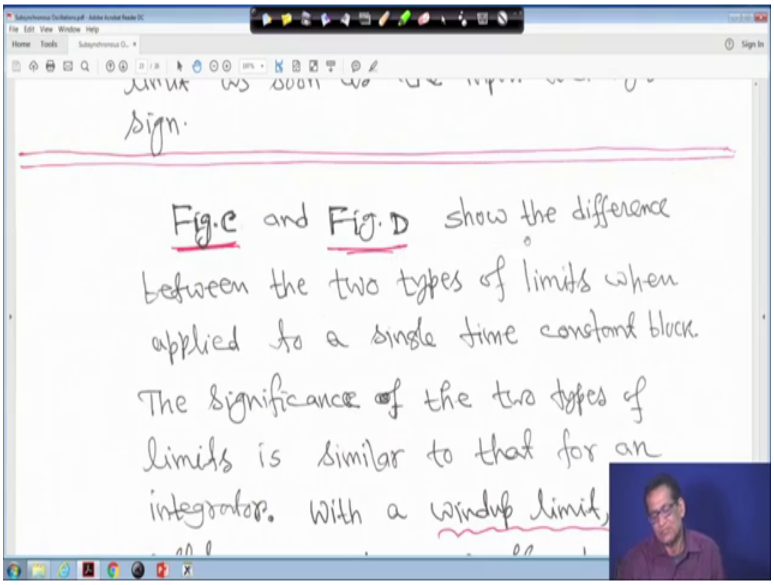
And you can write code of course, nowadays we are putting everything in MATLAB, but at least see that how things are happening if you write code of your own, right. So, this is integrator with non-wind up limits.

(Refer Slide Time: 20:30)



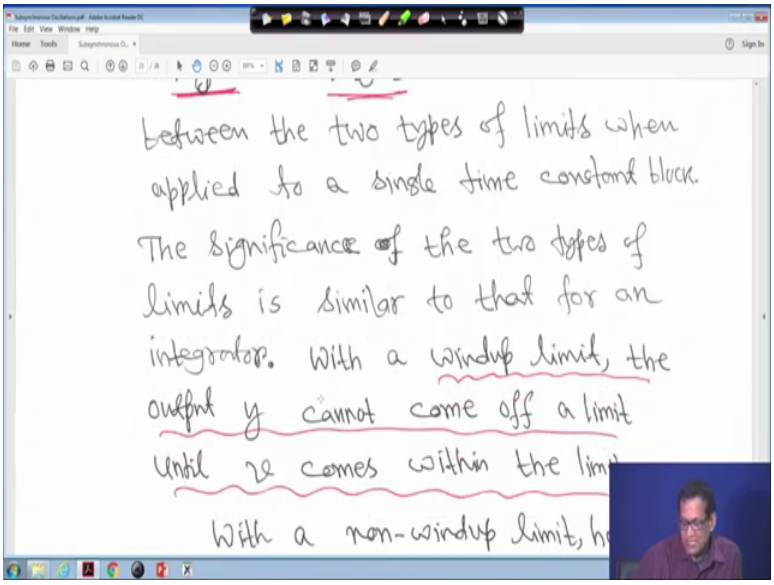
Now, next is your what you call with windup limits the variable v is not limited, right therefore, the output variable y cannot come up a limit until v comes within the limit, right. Similarly, with non-wind up limits the output variable y is limited it comes up the limit as soon as the input u changes sign because positive or negative, right.

(Refer Slide Time: 20:58)



So, now next is the figure C and figure D we will come to that. So, the difference between two types of limits; so in applied to a single time constant block. The significance of the two types of limit is similar to that for an integrator, right. So, with a windup limit the output y cannot come up a limit until v comes within the limit, right. Similarly, with a non-wind up limit; however, the output y comes off the limit as soon as the input u re-enters the range within the limits that is why all I have underlined.

(Refer Slide Time: 21:18)



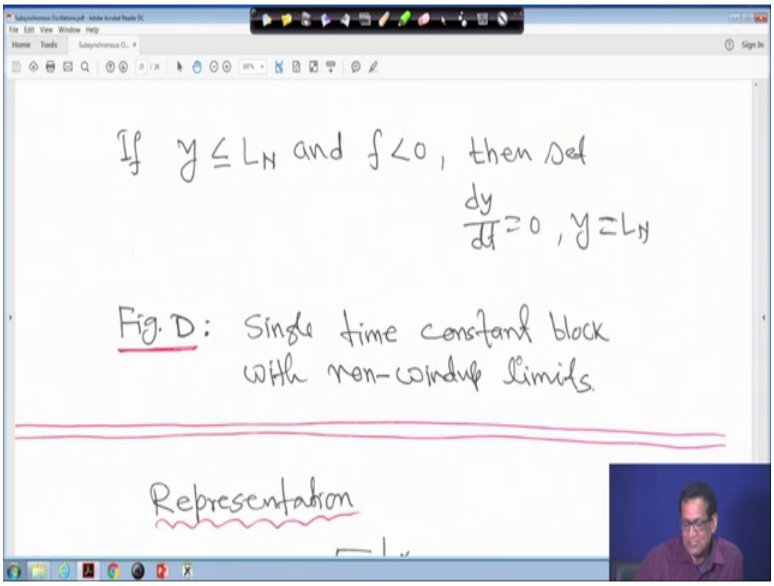
So, representation, so now, it is a first order transfer function, it is a first order transfer function. Earlier it was integrator now it is a first order transfer function, and input is u and output is v, but restricted that your L X and L N this limit is there and this is y. Now, for this one system equation will be you can try to write it that this is dv by dt will be u minus b upon T. This T 1 plus s T the capital T, right. So, it will be dv by dt will be u minus v by T for this one it is a first order block diagram, right.

Now, limiting action. Now, if v actually lying in between L n and L x then y is equal to v same as before, right. Now, if v greater than L x then y is equal to L X, right and this is the equation dv by dt is equal to u u minus v by T, and if v less than equal to L N then y is equal to L N, right. So, this way this way that your what you call limiting action will takes place. So, this is actually single time constant block with windup limit. This is actually windup limits, right.

Similarly, for non-this is for non-wind up limits. This L X and L N limiter this is 1 upon 1 plus ST, this is u and this is y. So, let us define that f is equal to u minus y by T, u minus y divided by T, right. So, let us define system equation f is equal to u minus y by T, right. Therefore, therefore, if you put the limiting action if y is lying between your L N and L X, right then dy by dt is equal to f, then your dy by dt will become f, right if it is lying in between this, right. So, but we are defining f is equal to u minus y by T, right, so dy dt will be f. That means, dy by dt will be this equation u minus y by t, right.

Now, if y greater than L X and f is positive that is greater than 0 then you set dy dt is equal to 0 and y is equal to L X, right. So, that is if y greater than equal to L X and f is positive, right, that is f is equal to this 1 u minus y by T.

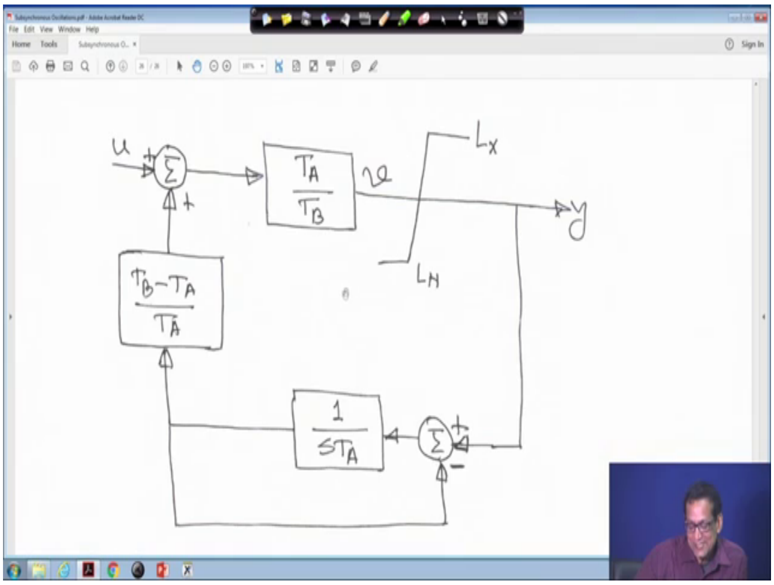
(Refer Slide Time: 23:38)



And similarly, if y less than equal to L N and f is negative then again you said dy dt is 0 and y will be is equal to L N; that means, you are restricting this, right. So, I mean when you will design your what you call this kind of limiter for your system, I mean what kind of limiter you want, right depending on your system. So, this is single time constant block with non-wind up limits.

Now, so next is your what you call lead lag you have studied know lead lag power system stabilizer, but there we have not consider your what you call that your this limits, right because we wanted to avoid those things for the classroom purpose. So, just representation will show you. So, this is 1 plus ST A divided by 1 plus ST B, input is u, output is y and T A less than T B, this time constant T A less than T B and this is the representation, right. So, this representation will represent this thing like this, physical representation. I mean electronically when you realize it will be like this, I mean this one this whole thing when you realize electronically it will be like this.

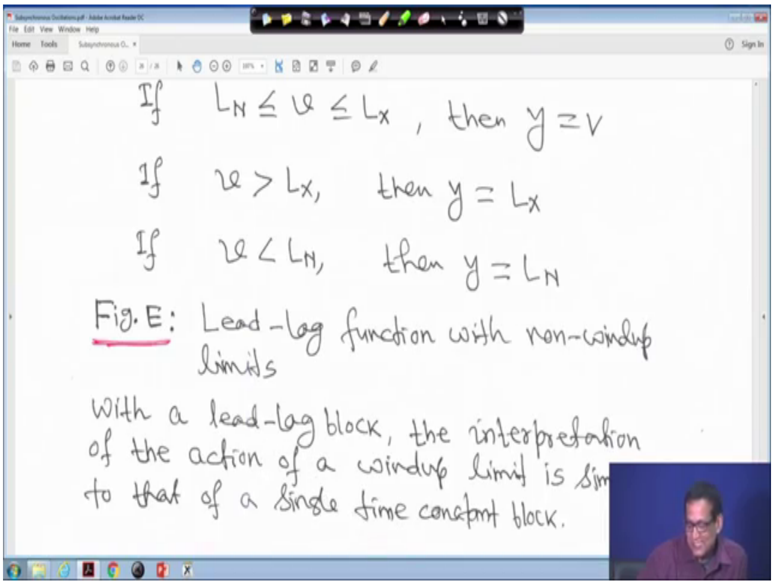
(Refer Slide Time: 24:49)



So, this is a small exercise for you to do this, right it is not a difficult one. So, in this case if you look into this the representation like this and if this is u, this is T B minus T A upon T A, this is 1 upon ST A and this is y feedback is coming here, a negative feedback is here and this is L X, L N and this is your just your wind-up limits like this, right. So, only this part you have to take care off, right and this is your here it is u and whatever feedback is going here, right. So, it is like windup limits, this is L X and L N, right this is you try yourself, right. From there you can make electronically if you want to realize the if you want to realize this one electronically you have to design this way, you have to design this way, right.

So, limiting action will be now if v is lying in between L N and L X then y is equal to v, right. So, this is v and this is y, right same as before.

(Refer Slide Time: 25:42)



And if v greater than L X then y is equal to L X and if v less than L N then y is equal to L N. So, lead lag function with non-wind up limits, but this expression looks like windup limits because we have made the things simpler, right. So, with a lead lag block the interpretation of the action of a windup limit is similar to that of a single time constant block that we have seen before, right

So, with this with this just what we will do that this step this topic that power system dynamics control and monitoring is actually close. Now, question is that, right from the beginning just 2 3 minutes, I would like to tell we have studied the synchronous machine model. It took I think if I recall correctly if 14 hours or even little more than 14 hours, right. So, that is actually I have to I have to cut short many things, but tried my best to see that things are meaningful for you, right.

Then we have studied and there in the synchronous machine we have studied your participation factor also, then totally single machine infinite bus model, but multi-machine system not possible in the video course it is very very complicated mathematics and lot of derivations are there which is not possible, right. And that that is why single we have restricted our self to single machine infinite bus. We have studied participation factor, eigenvalue analysis, right all sort of things we have studied.

Then we have studied your tons in stability analysis for multi-machine system only, right I think 4 or 5 examples, good examples we have taken. Just when you will go through this course if you find any error I have made or any calculation errors just send me a mail; so I will appreciate that.

And then we have studied your automatic generation control in deregulated environment, because initially we started with your what you call in conventional scenario then deregulated environment. So, certain things we have made it; calculations and other thing just read listen carefully all these things. Perhaps something may not be available one or two thing may not be available in the book, but when you listen to the lecture at the time everything will be what you call explained in the forum, right; so these things we have studied.

After the state estimation also whatever is possible as far as the classroom exercise is concerned that way I have tried, right otherwise many cases you need that your aides of computer, right without the help of computer you cannot do this, right. And at the last we have taken little bit of your hydro turbines. Although governor model of hydro turbine we did not do, but thermal power plant also modelling we have done it, but for hydro turbine governor model we did not do, but a simplest hydro turbine model we have considered and a simple problem we have considered. And the last the subsynchronous oscillations I thought little bit I should cover with u windup and non-wind up limits, right.

With this hopefully I do believe that it will be useful for you particularly for postgraduate students, right as well as those who are teachers in various colleges, right. But question is that this course is highly mathematical, from the beginning you will be knowing that this course is purely mathematical, right. But hope that whatever we have tried, so just have a look. And if you have any any comment or anything you please send me mail, right, directly you send me email and I will appreciate that. So, thank you very much and ok. So, this is the end of this course.

So, thank you very much.