Power System Dynamics, Control and Monitoring
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Lecture – 15
Power System stability (Contd.)

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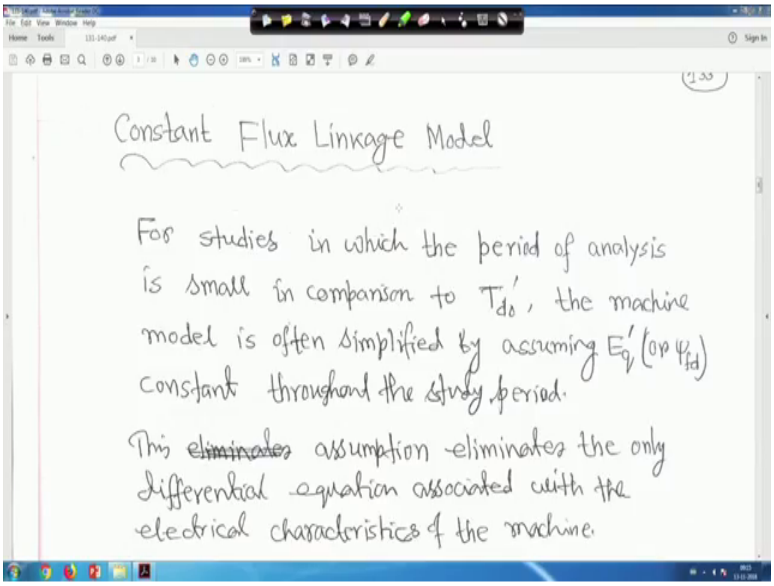

So, we have already started this constant flux linkage model right.

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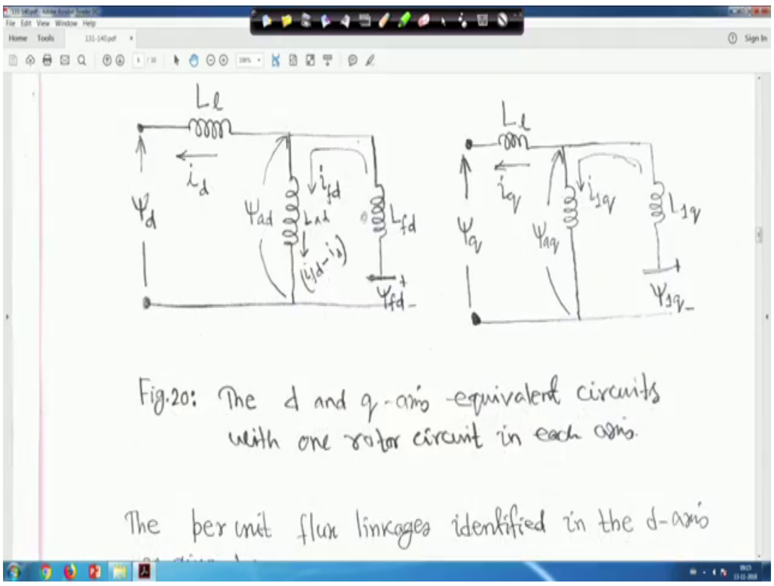

And we have come up to this, because every lecture I start this is already we have discussed right. So, just and we ended up somewhere here, right.

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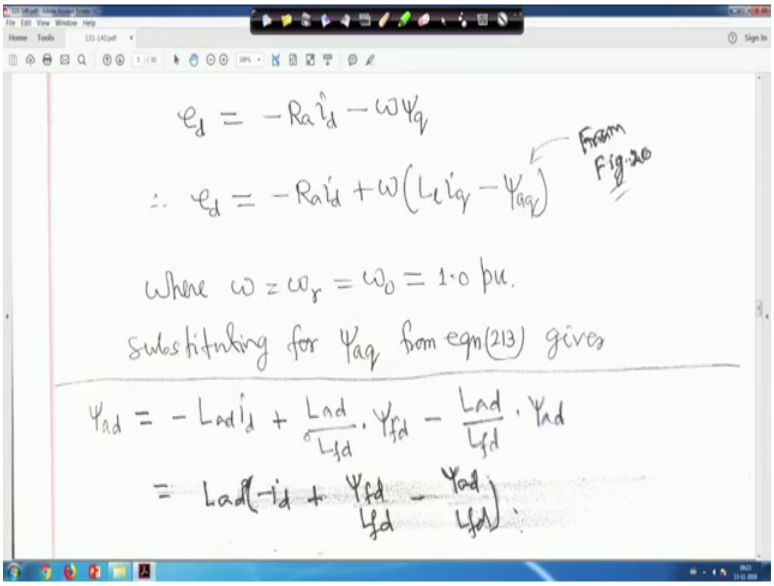

This is not required for you right, and then we are starting from here.

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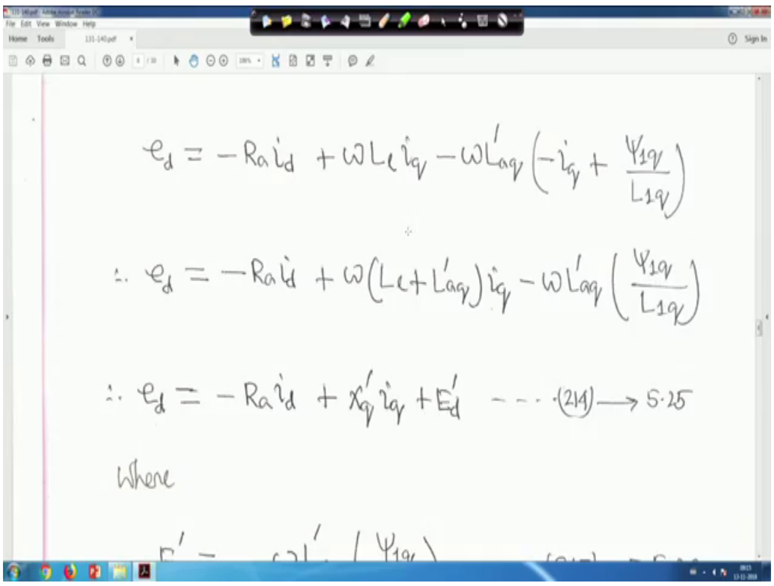

Although, we did it although we did it, but just we are starting from this last lecture whatever we ended from that page only. So, e d is actually minus R a i d plus omega L l i q minus omega L dash i q or rather L a q dash in bracket minus i q plus psi 1 q upon L 1 q. All this terminology have been defined before, but I suggest one thing whenever, because you are getting all the nodes. So, just nomenclature other thing you put in front of you, because again and again if I try to repeat all the nomenclature or symbols meaning, then it will be little bit monotonous right.

And therefore, e d is equal to minus R a i d plus omega in bracket L l plus L a q dash into i q minus omega L dash L a q dash in bracket psi 1 q upon L 1 q. And e d is equal to therefore, we can make it minus R a i d plus x q dash i q plus E d dash, this is equation 214 right. And this is actually for my reference, this is not required for you, this is for my reference right.

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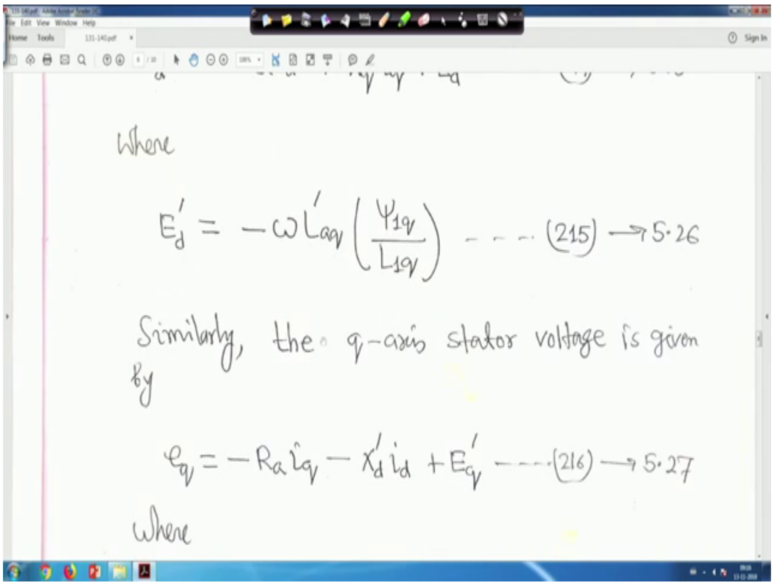

Where E d dash is equal to we are defining this term minus omega L dash a q psi 1 q upon L 1 q right. So, similarly, similarly the q-axis stator voltage is given by you go to the equations right, whatever have been derived before that e q will be minus R a i q minus x d dash i d plus E q dash this is equation 216. So, this all this your this thing no need to see this is for my reference right.

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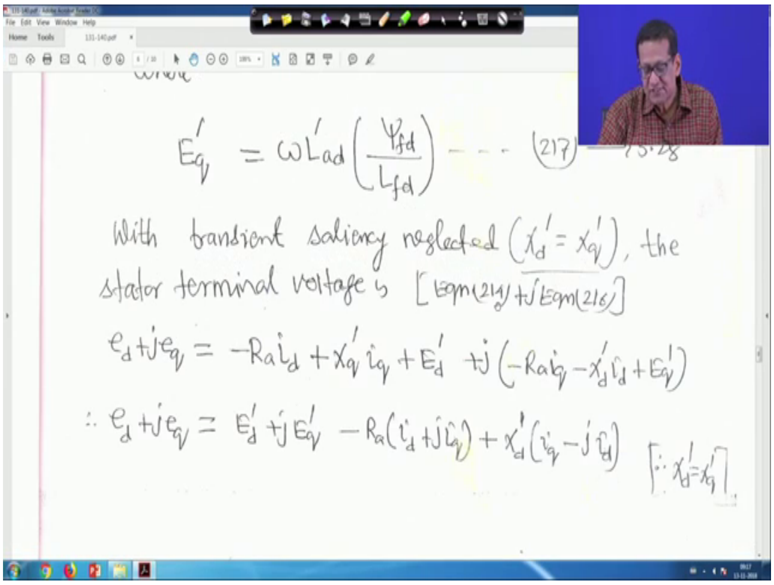

Where E q dash is equal to omega L a d dash into psi f d upon L f d this is equation 217, right. Therefore, with transient saliency neglected that means, when x d dash is equal to x q dash right, the stator terminal voltage that you add equation 200 plus equation 206 you multiply by j.

So, equation 214 plus j into equation 216, this mathematical manipulation we have to do right. If you I mean that means, we can make it e d plus j e q that is equation 214 plus j into equation 216. So, it will be minus R a i d plus x q dash i q plus E d dash plus j in bracket minus R a i q minus x d dash i d plus E q dash that means, this is my your e d. And this is my e q we are making is actually e d plus j e q right.

So, in that case this equation can be written as e d plus j e q is equal to say capital E d dash plus j capital E q dash right, this can be written as real here what you call minus R a i d plus j i q plus x d dash in bracket i q minus j i d. We have assumed that saliency is neglected, so x d dash is equal to x q dash right.

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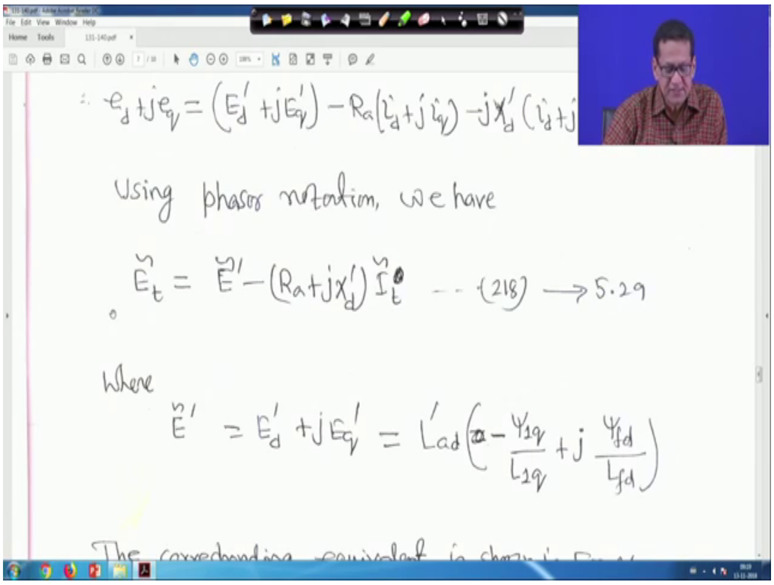

Therefore, e d plus j e q it can be written as capital E d dash plus j capital E q dash minus your R a this is actually E d dash plus j equal to minus R a R ok, this is. So, minus R a i d plus j i q minus j x d dash i d plus j i q, we are assuming x d dash is equal to x q dash right. Using phasor notation, using phasor notation we have your E t tilde is equal to E dash tilde minus R a plus j x d dash I t tilde, this is equation 218 right.

So, this equation we are representing e d da[sh] e d plus j e q is equal to E d dash plus j E q dash minus your R a i d plus j i q right and plus x d dash i q minus your i d dash right. And E d dash and E q dash, E d dash here defined like this and E q dash here defined like this right. So, and x d dash is equal to x q dash we have assumed.

So, with this using phasor notation that E t tilde will be E dash tilde minus R a plus j x dash into I t dash this is equation 200, this is for my reference no need to see this right, or E dash tilde is equal to we can write E d dash capital E d dash plus j capital E q dash is equal to L a d dash minus in brackets psi 1 q upon L one q plus j psi f d upon L f d, because E d dash and E q dash we have defined this is your capital E d dash, this is capital E d dash and this is capital E q dash right, just put those things in this equation, put those things in this equation right. So, it will be like this.

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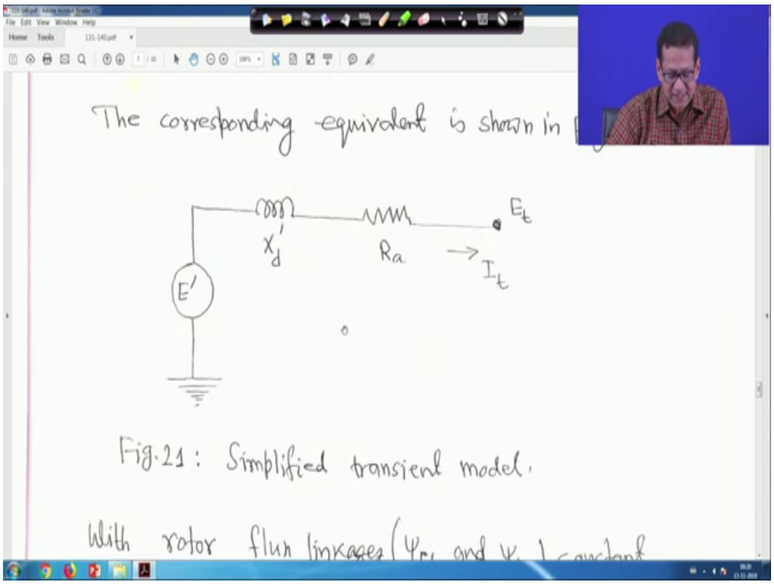

Now, the corresponding equivalent circuit is shown in this right that is this is your the E dash and this is my x d dash, this is R a and this is the current flowing to going to this load I t say, and this voltage is E t so that means, this is the simplified transient model, that means this equation that E t tilde is equal to E dash minus in bracket R a plus j x d dash I t tilde, and this is equation 218 right. And this is the corresponding your circuit diagram for that right. So, this is the simplified transient model.

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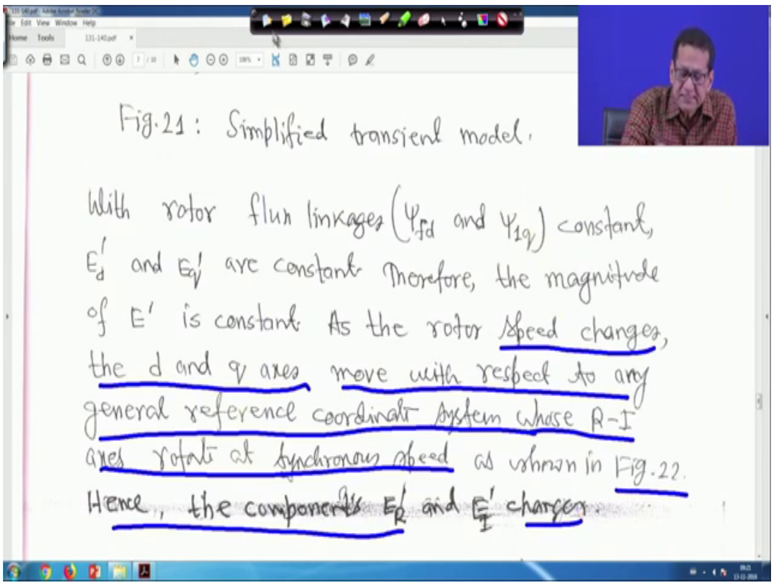

Now, with the rotor flux linkage that is psi f d and psi 1 q constant right, because it is a constant flux linkage thing, so that means, capital E d dash and capital E q dash are also constant. Therefore, the magnitude of E dash is constant right.

So, as the rotor speed changes right as the rotor speed changes right, the d and q axis move with respect to any general difference coordinate system whose R-I means R means Real, I means Imaginary that is real and imaginary axis rotate at synchronous speed as shown in figure 22. I will go to the figure 22. Hence, the component of your E R dash and E I dash, here changes right, so that means when we go to that next thing that.

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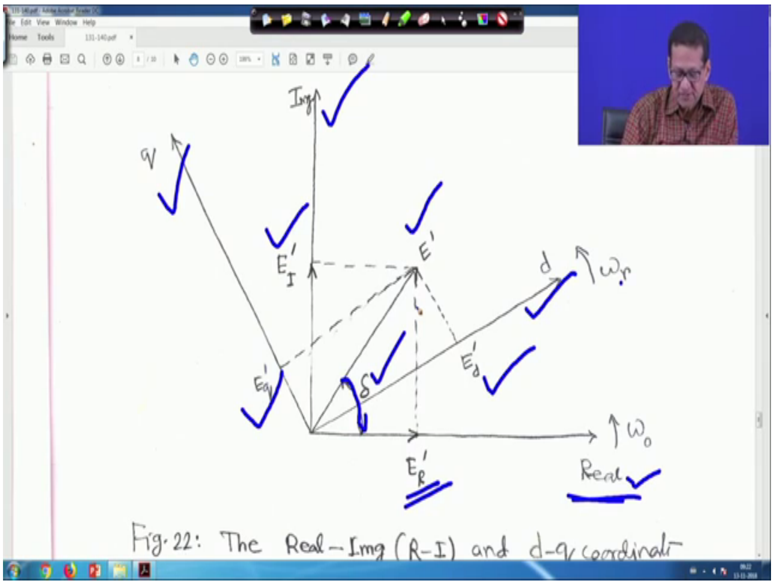

This is actually your real axis, this is your this is my real axis and this is my imaginary axis right. And this is our d axis and this is q x right and this is the omega r. Now, this is my E dash, this is my E dash its component of capital E dash, is component on d axis is capital E d dash, is component on q axis this one capital E q dash right.

And it components on the real axis that this is my real axis, it is E R dash right capital E R dash and its component on imaginary axis it is capital E I dash right. And this angle, that this angle this angle is actually delta right. So, this is this is your what you call, this is the real and imaginary and d-q coordinate system right. So, both are shown real imaginary as well as d and q right.

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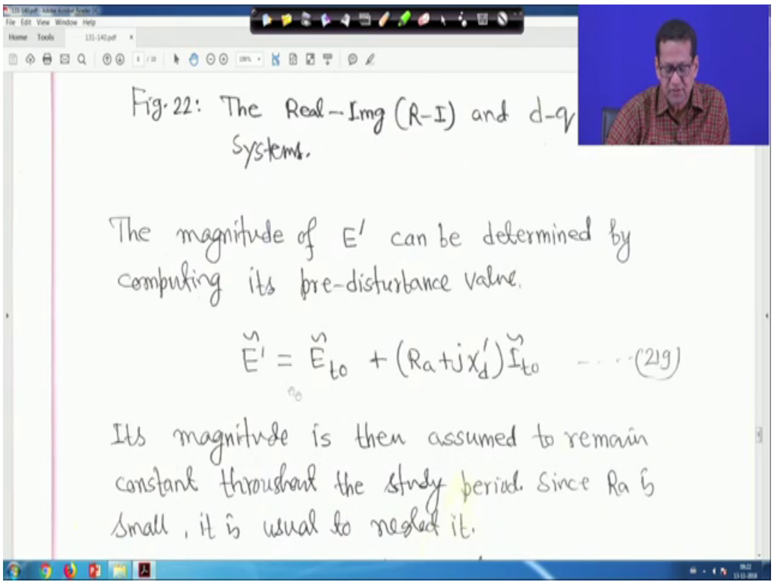

So, the magnitude of E dash can be determined by computing its pre-disturbance value right. I mean if you know the initial thin values therefore, E dash tilde is equal to will be E t 0 tilde plus in bracket R a plus j x d dash into I t 0 tilde; this is equation 219 right.

So, I mean if you I mean it can be calculated if you know the pre- disturbance value right, because this are all here what you call the your transient condition.

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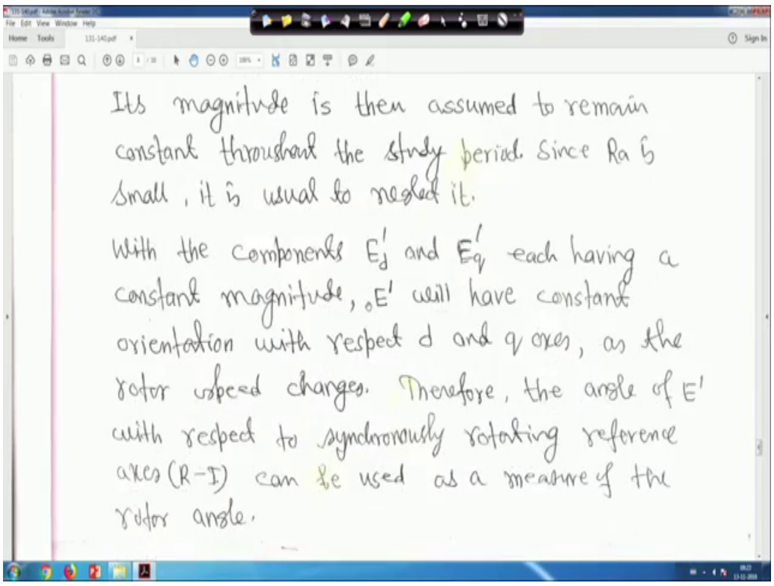

Now, its magnitude is then assumed to remain constant throughout the study period for the sake your simplicity. We will assume that it is constant throughout the study period.

Since, R a is very small that is it is neglected right it usual to neglect it right. Therefore, with the components E d dash and E q dash are each having a constant magnitude if this e d dash and this e q dash right, each having a constant magnitude.

And E d dash will have a constant orientation with respect to d and q axis as it is rotating you know, it is it is rotating its shown in that your anticlockwise direction right. So, with as the rotor speed changes right. Therefore, the angle of E dash with respect to synchronously rotating reference axis R-I can be used as a measure of the rotor angle that means this one, this one right, this delta.

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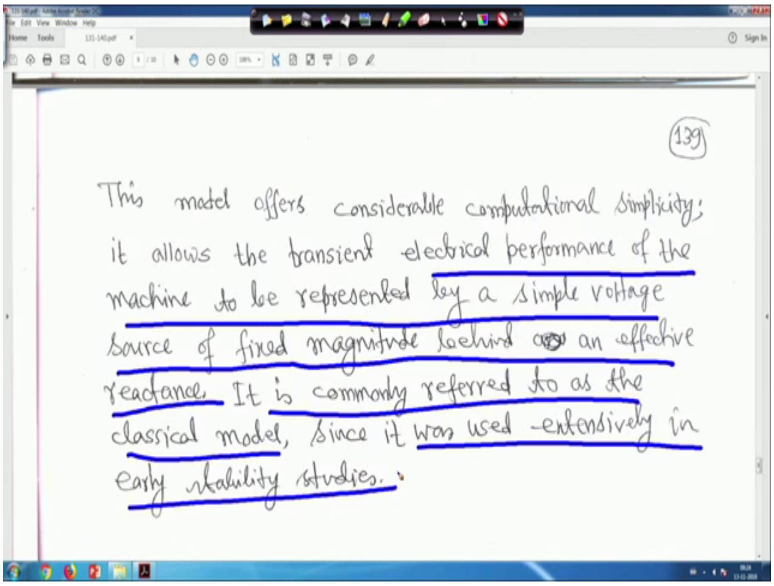

So, this model actually offers considerably computational simplicity; it allows that transient electrical performance right of the machine to be represented by a simple voltage source of fixed magnitude behind an effective reactants if we are assuming that R a is neglected. It is commonly referred to as the classical models, since it was used extensively in early your stability studies, because for in the for the classroom purpose also we will try to use this model right. And for the stability studies the simplified model.

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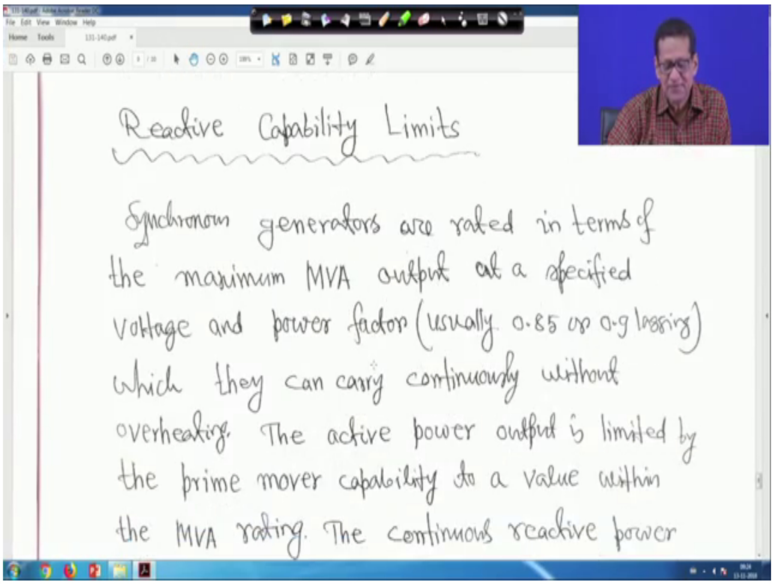

So, next is that reactive capability limits. Let me tell you one think, if time permits, then at the end we will try to explain certain things, but at present I do not want to discuss this then continuity will be lost. If time permits for this course, then at the need that means at the end we will see the state estimations.

And after that if time permits, then reactive to some extent we will try to talk about the exciter of the synchronous machine and the reactive capability limits of the machine that is at the end if I find couple of hours time at the end right, otherwise I have to skip this one.

So, synchronous generators are related in terms of the maximum MVA output at a specified voltage and power factor. Usually, 0.85 or 0.9 lagging right which they can carry continuously without over reading. The active power output is limited by the prime mover capability, of a just a minute. The active power here what you call output is limited by the prime mover capability to a value within the MVA rating, right.

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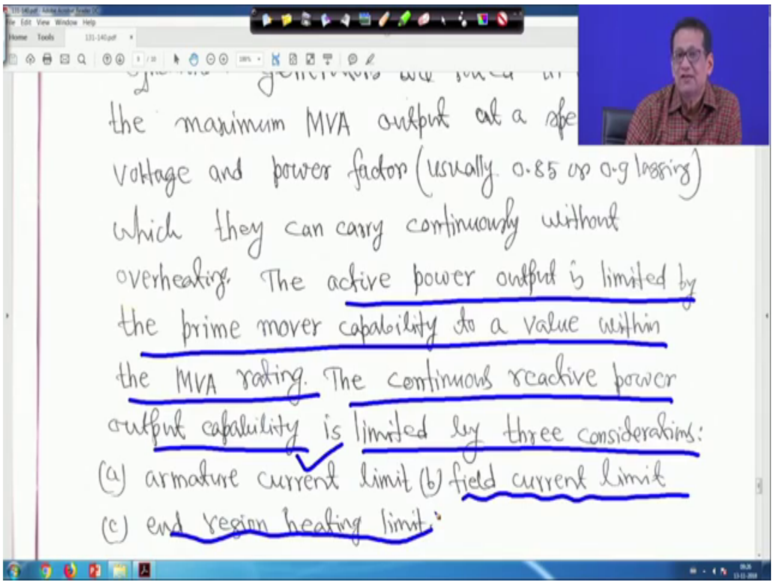

The continuous reactive power output capability is limited by three considerations, one is armature current limit right, another is that field current limit, another is end region heating limit right.

So, these three thing that armature current limit, field current limit and end region heating limit if time permits, then at the end we will discuss that one right, because it will consume sometime, but here we will not discuss that that continuity of this here, what you call dynamics part will be lost. So, if time permits, I do it at the end right.

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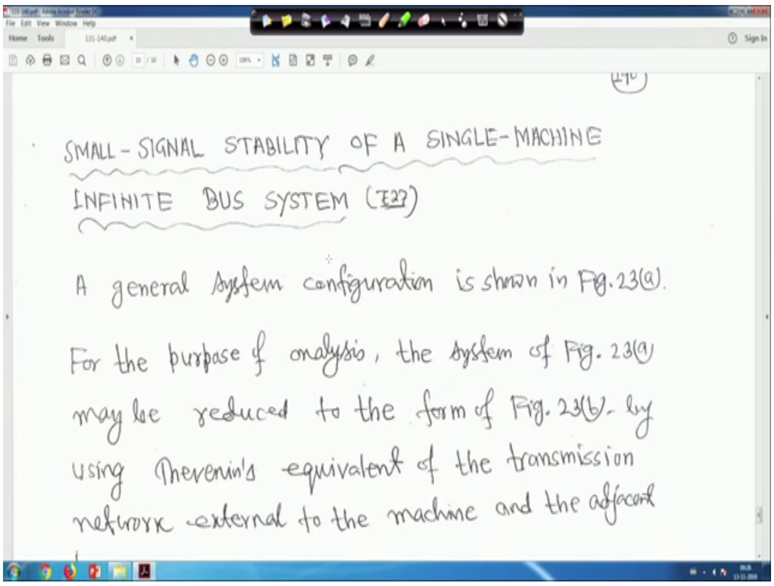

So, next we will now we will come slowly and slowly we will enter to that dynamics stability that is small signal stability of a single machine infinite bus system. So, for this course we will only study small signal stability of a single machine infinite bus system.

Multi-machine system it is really on as per as here what you call, in the class room is concerned that multi-machine stability studies is really too difficult to learn because of dynamic equations, all state variable equations it will be very complicated one right, but as per as class room studies, we will only follow small signal stability of a single machine infinite bus system multi-machine system.

A multi-machine study if somebody if somebody is doing research or masters project other thing for that they can consider, but for the class room study I will skip that one right. So, small signal stability of a single machine infinite bus system right.

So, in general configuration it is shown in figure 23 a, for the purpose of analysis right. So, I will come to the figure the may be reduced to the form of figure 23 b by using Thevenin's equivalent of that transmission network external to the machine at the adjacent transmission line.

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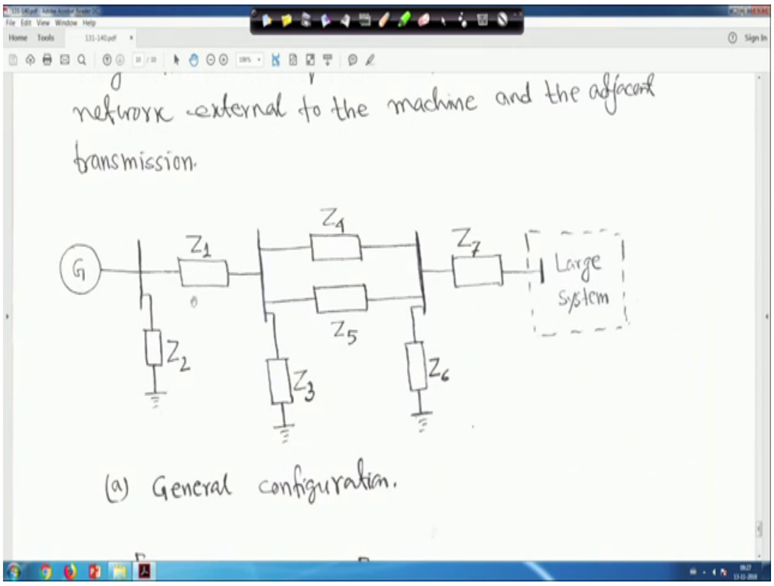

And this is simple general configuration is taken, say it is a single generator. This is the transmission line having different branches that your son branches are also there right, that your all the it is represented in terms of impedances only in general right. And here it a large system is connected, a very large power system is connected so the right.

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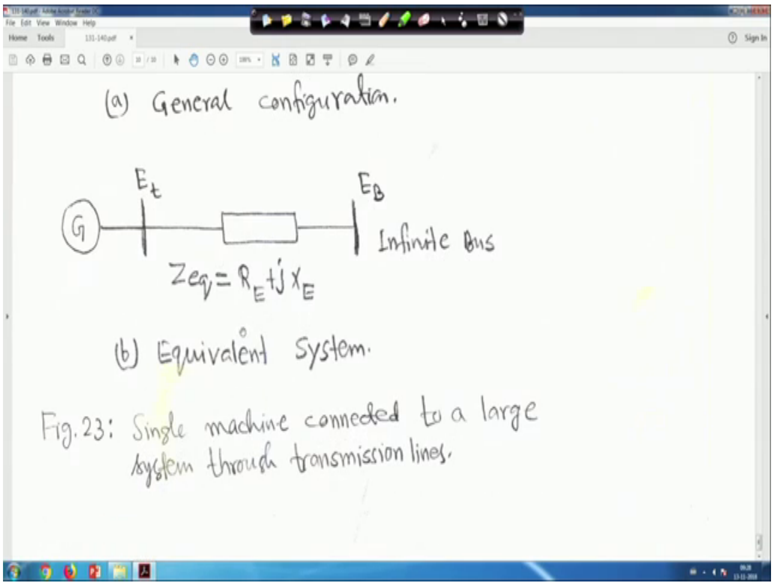

Now, if you try to make it a Thevenin equivalent one. So, this generator is there, this generator will be there and this is its terminal voltage E t, this is E t this is E t and this equivalent impedance say it is Z e q is equal to R E plus j x E right. And this bus, we call infinite bus E B that is the infinite bus, we call right we will come to that what is infinite bus.

So, this is actually equivalent system, this is figure 23, this is 23 a and this is 23 b. This is single machine connected to a large system through transmission line. So, this portion is actually, this portion actually your what you call it is a transmission system and all are impedances shown and their equivalent one is R E plus j x E, and this is a very large power system right.

And this is your terminal voltage generator, whose voltage is shown here E t and this bus voltage infinite bus voltage is shown as your E B right. So, we will go to the next slide, just hold on.

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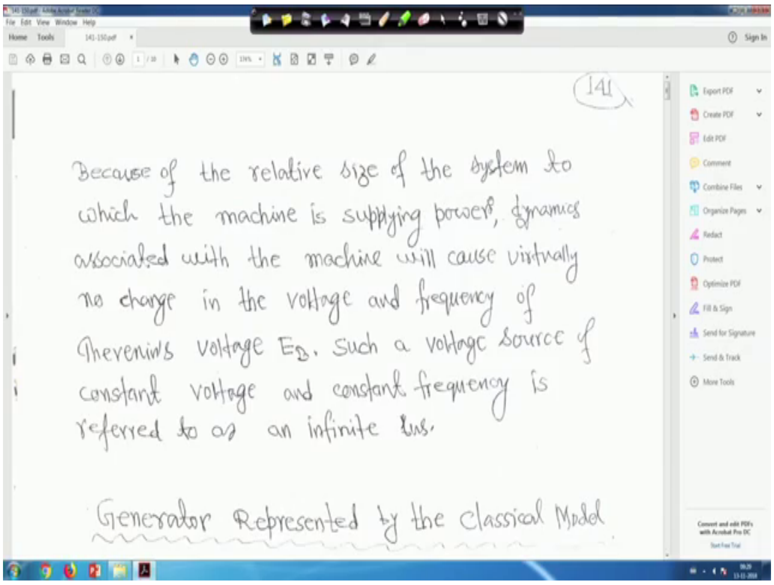

Because of the relative size of the system right, to is the machine is supplying power, because that is large system we are talking that is here what you call, so that is why because of a relative size of the system to is the machine is supplying power, dynamics associated with the machine will cause actually virtually your no change in the voltage and frequency right of Thevenin's voltage E B right, so that voltage that infinite voltage the Thevenin voltage the last system is a huge system right.

And, and the generator which is connected the dynamics associated with the machine that is your sending end that is the generator right, will cause virtually no change in the voltage and frequency of the Thevenin's voltage E B. Such a voltage source of constant voltage and constant frequency is referred to as an infinite bus right, this is the definition of infinite bus right. I hope it is understandable.

You have a generator and you have a that through the transmission line that generator is say, it is connected with a very large power system right having right. And in that case that if the dynamics associated with the machine that your sending in that is generator right, actually it does not cause any change through the voltage and frequency of the last system that is why, the Thevenin voltage E B actually that is called infinite bus voltage. And the frequency actually it will remain constant, both will remain constant and that bus is actually referred to as infinite bus right. So, now generator your represented by the classical models.

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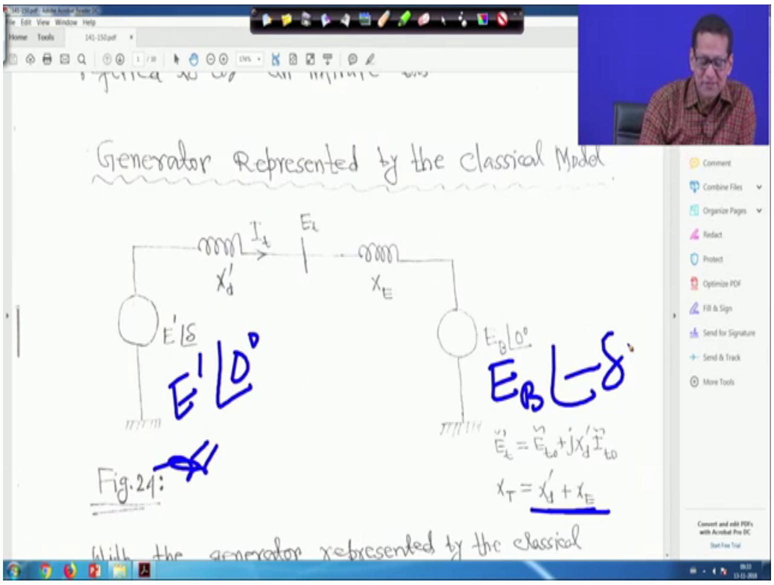

Therefore we can write the same system that E dash tilde, this is x d dash I t, this is E t, this is x E and this is E B angle 0 that means, that your that is your that figure 23 b right, figure 23 b you have the generator.

You have that here, what you call just hold on, I will I will I will go I will go back to this figure once again right just hold on, this figure right this is my E t and this is my E b right, and this is Z e q R E plus which is infinite bus. And, and x d dash also you have to consider right for the generator right. And this is my R E plus j x E and if R E is neglected suppose I mean sorry, R a is neglected only we will consider x d dash right.

So, this that means this is my E d dash tilde, this is E t that is voltage bind transient reactants right x d dash. And this is x E and E B angle 0, R E we have not considered here right. We have to thus this is x E, and this is your E t, and this is E B angle that means this voltage actually leading this voltage by an angle delta right.

And E t tilde that is your E t tilde is equal to your E t 0 plus j x d dash in to I t 0 tilde, this we have seen before right that pre-disturbance value right. So, from which you can that will remain constant throughout the study.

So, E t tilde is equal to E t 0 tilde plus j x d dash I t 0 tilde, this I have told in the previous phasor diagram right. And x t is equal to total x T is equal to x d dash plus your x E right. Therefore, you are what you call that with the generator represented classical model right.

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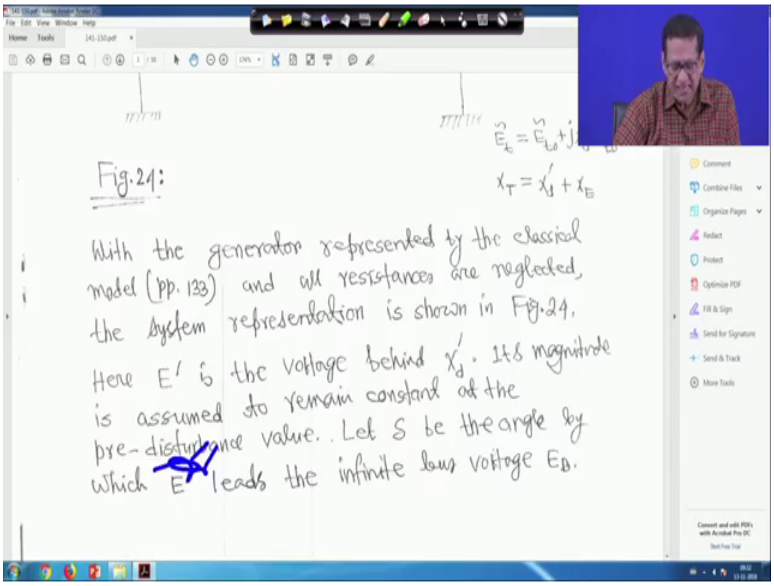

This is this is for my reference, this is not required for you. So, classical model and all resistances are neglected the system representation just hold on, system representation as shown in figure 24, where your E dash is the voltage behind x d dash. Its magnitude is assumed to remain constant at the pre-disturbance value.

Let delta be the angle by which E leads the infinite bus voltage E B right, that means this, this one E dash tilde is leading this infinite bus voltage that is by an angle delta right. So, where E dash is equal to as the reference phasor that means, here your x t will be your total x T will be your, x d dash your x d will be is equal to x d dash plus x E right.

We have not considered R, anyhow I assuming they are very small right for our for the for our your simplicity of the analysis right. If this is E dash delta, this is E B 0. So, E dash actually leading E B by an angle delta otherwise also we can put, suppose we can write this E dash it if you make this is angle 0 degree, then this one you can make E B angle minus delta both are same right.

Here also your both are same, because if we make this as 0, this will be angle minus delta, because E B actually E E E dash leading E B or E B is lax E dash by angle delta.

So, E B lax E dash by angle delta. Same way you can write, when you will use the mathematical rotation, we will use this one meaning is same meaning is same right, meaning is same.

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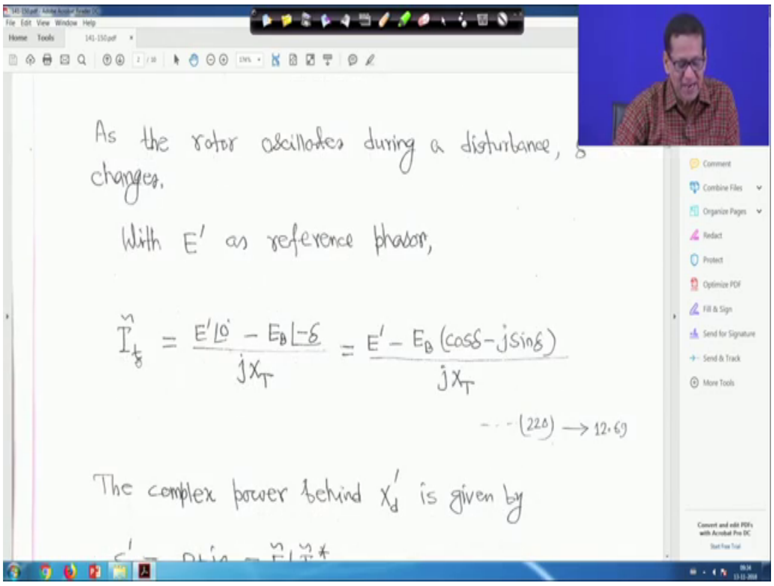

So, so therefore with E dash as the reference pressure that is I told you, that I t tilde can be written as E dash 0 minus E B angle minus delta upon j x T, I mean here instead of this one instead of this one.

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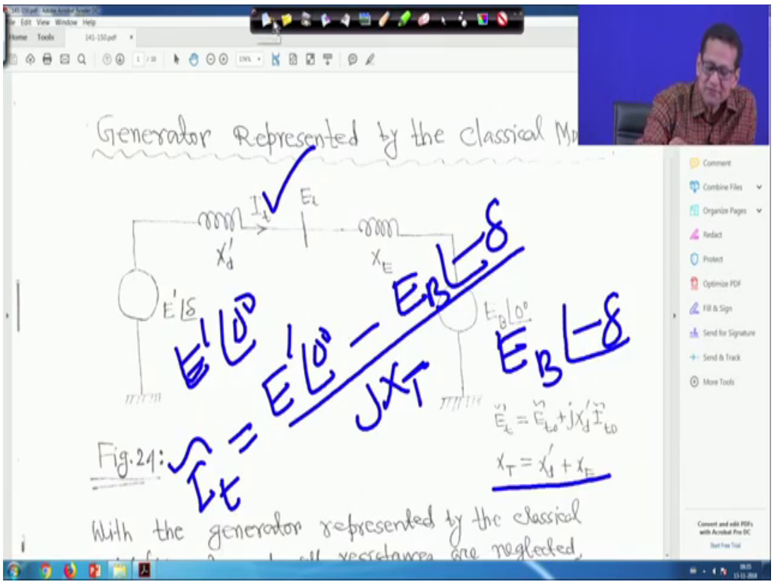

Here E I can write this is this thing, and this one I can take this is minus delta right. So, if it so, then this is my I t. So, I t will be right, I t will be E dash angle 0 degree minus E B angle minus delta right divided by your x d dash, then x T is equal to x d dash plus x e. So, we can write j it is reactance. So, j divided by j x T right.

So, this way you can make that this is my I t or tilde the phasor representation, instead of writing other thing is also true that E angle delta minus E B 0 for our easy analysis, we have made the same thing, it is same actually, this the same thing meaning is same right, so that is why this equation, this equation is written like this that E d E dash angle 0 minus E B angle delta, this is actually minus E B, here what you call cos delta minus j sin delta upon j x T right.

So, now next I from that that complex power by x d dash is given by S dash is equal to you know, this is your P plus j Q is equal to E dash tilde, then I t conjugate right. So, let so this one, this one if you just try to do it, I am just making it for you right. So, this is nothing this is for my reference, this is your E dash minus E B cos delta minus j your sin delta right.

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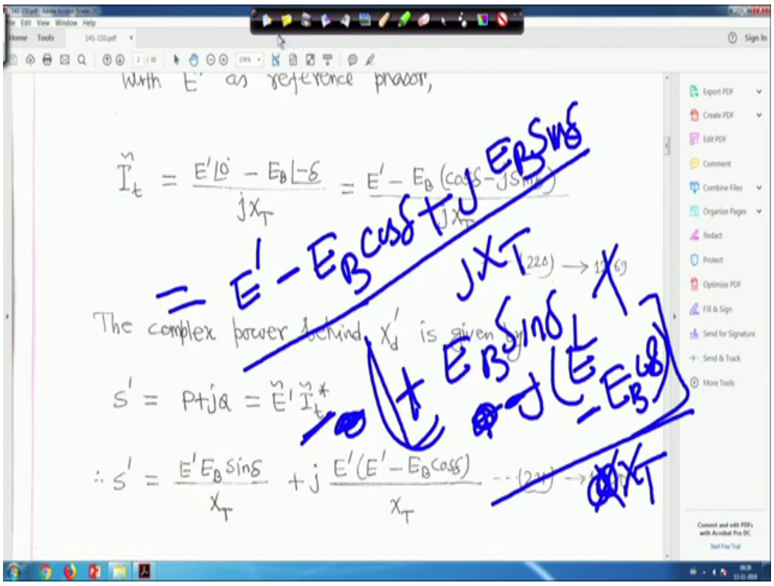

So, numerator and denominator first you multiply by your what you call, this one, this one I can write like this E dash minus your I am now writing over it E B cos delta right. And then, plus your minus plus then j then E B, then your sin delta divided by j x T right, this is your full thing right, divided by j x T.

Now, in this case so this is my I, this is my here what you call that your I t tilde is equal to right. Now, question is that numerator and denominator you multiply by j, numerator and denominator and simplify. If you multiply numerator and denominator by j, so it will be something like this say minus, because j new denominator new denominator j square will be minus one. So, it is minus and multiply this one by j.

So, and if this one if you multiply by j right, so it will be j square, so it will be minus E B it is sin rights, E B sin delta and then your plus j, your E dash just hold on, E dash minus your E B cos delta right. So, this is your, you just multiply numerator and denominator by j right. So, this will be j square, so that side it will be minus and here it will be j square. So, minus E B sin delta, and here it is j means j into E dash minus E B cos delta, this one right.

Now, if you just multiply this one by minus, then this should not be there, this should be plus E B dash sin delta right. And divided by of course, your x T right divided by your divided by your x T right. And this will be your instead of j, it will be minus right.

And if you take its conjugate one, because P plus j Q is equal to E dash tilde I t conjugate if you take its conjugate one, then it will be basically E B sin delta minus j, your into your E dash minus E B cos delta upon x T right. So, if you do so if you do so, then just hold on right if you do so, then what will happen that your.

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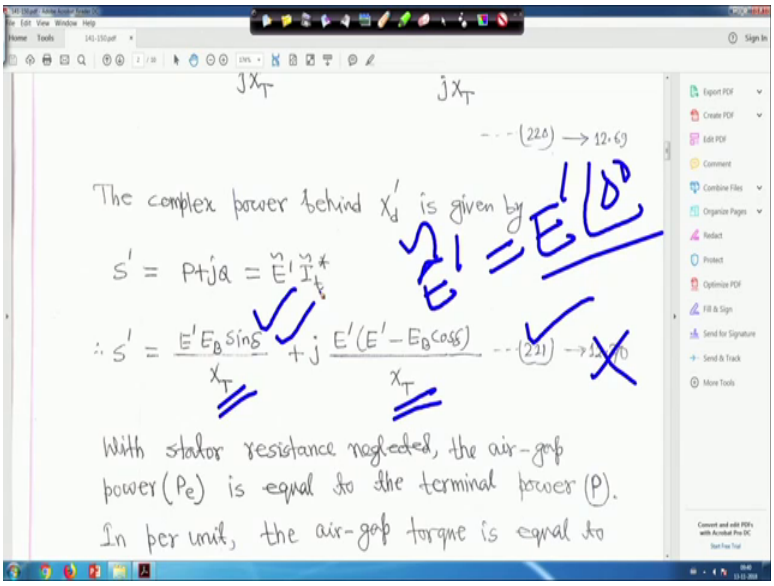

Complex power that P plus j Q is equal to E dash tilde I t conjugate. Now, I t conjugate will be an here what you call, it will be basically E dash E B sin delta, because it will be multiplied by this one E dash E B sin delta, because we have taken this one that your E dash tilde is equal to your E dash angle 0 degree right. So, because we have taken that E B angle minus delta, so with that that here you put an I t conjugate you put and you simplify whatever I showed.

You will find that E dash E B sin delta upon x T plus j E dash into E dash minus E B cos delta upon x T, this is equation 221 right, so that means my P is equal to E dash E B sin delta upon x T, and Q will be is equal to your E dash into E dash minus E B cos delta upon x T, but our interest is now only with that real power. E dash if the way you have studied for power transfer know b 1, b 2 upon x sin delta. So, it is a same thing same thing right.

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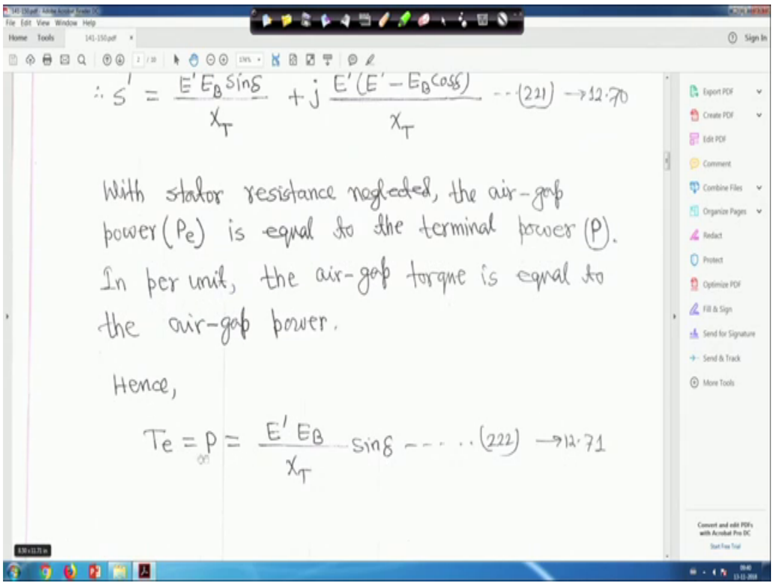

So, with this stator resistance neglected the air-gap power P is equal to the terminal power, this we have seen earlier, this we have seen earlier that P is equal to here, here what you call that air-gap power equal to the terminal power.

So, in per unit the air-gap torque is also equal to the air-gap power that also you have seen before right. Therefore, that T e is equal to P, because it is per unit right that will be E dash E B upon x T sin delta, this is actually equation, 222 this is not required for my reference right. So, this is this is the same thing whatever you have studied in your third year, under graduate power system course that is your b b 1 if sending and receiving b 1, b 2 and resistance is neglected and the reactance is x. So, it is b 1, b 2 upon x psi data.

Same thing here also, see expression is same and in per unit torque is equal to power. So, T e is equal to P E dash E B upon x T sin delta right.

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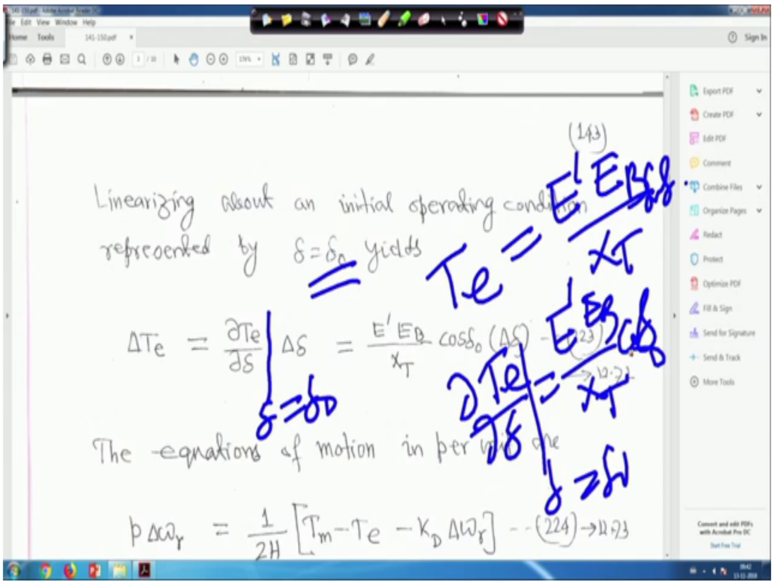

So, if you linearizing about an initial operating condition represented by delta is equal to delta 0, that means this here what you call this equation, suppose this is your this is my T e equation, because in per unit E dash E B upon x T sin delta.

Now, if you take delta T e you can write, the delta T e upon delta delta into your delta delta right that means, that this delta delta I can put here just hold on, I can put here it is at the if suppose an initial operating point is given delta is equal to delta delta, this one actually delta is equal to delta 0 right.

Therefore, if you if you take the here what you call that T e is equal to E dash E B upon x T your sin delta. So, if you take delta T e upon delta delta that means, your T e is equal to your E dash E B upon x T then just hold on, x T into your sin delta right sin delta.

Now, if you take your delta T e upon delta delta that is E dash your E B upon x T your cos delta and at delta is equal to delta 0, this will be delta 0 right, so that is why this is your delta T e is equal to delta T e delta delta into delta delta. So, E dash E B upon x T cos delta 0 into delta delta, this is equation 223 right.

The equation of motion, we have seen earlier in per unit that is your this is not required for you. So, this we have seen earlier p delta omega r is equal to 1 upon 2 H in bracket T m minus T e minus K D into delta omega r this is equation 224, this one also we have seen.

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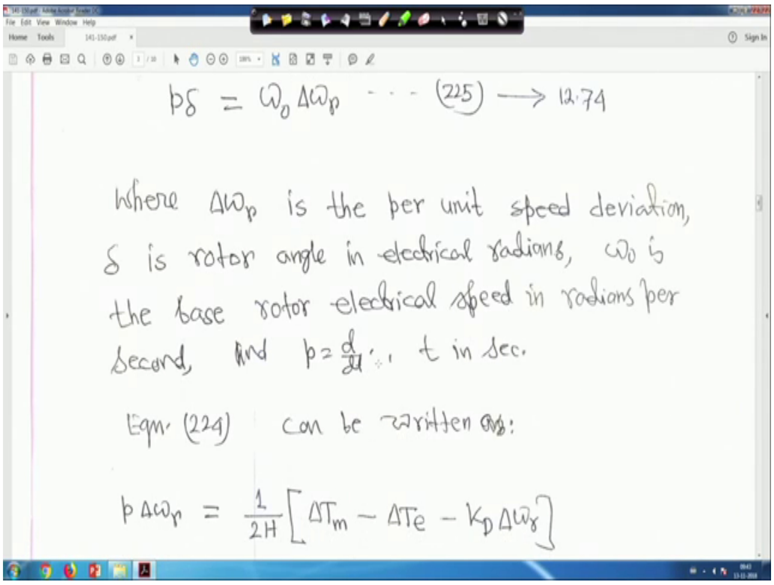

p delta is equal to omega 0 into delta omega r this is equation 225, this is for my reference right, so let me clear it. And where delta omega is the per unit speed deviation and delta is the rotor angle in electrical radiance right, this we have seen earlier.

So, omega 0 is the base rotor electrical speed in radiance per second right, and we know p is equal to that is your what you call, d d t we have represent by this side. So, differential operator, but later we will represent by Laplace domain. So, we will put in you replace p by a s right and t in second.

So, equation 224 can be written as that p delta omega r is equal to 1 upon 2 H is equal to your into delta T m minus delta T e minus K D into delta omega r, I mean this equation p delta omega r again we can write 1 by 2 2 H T m minus T e minus K D delta omega r is there right. But if you again this can be written as p delta omega r is equal to 1 by 2 H delta T m minus delta T e minus K D delta omega r.

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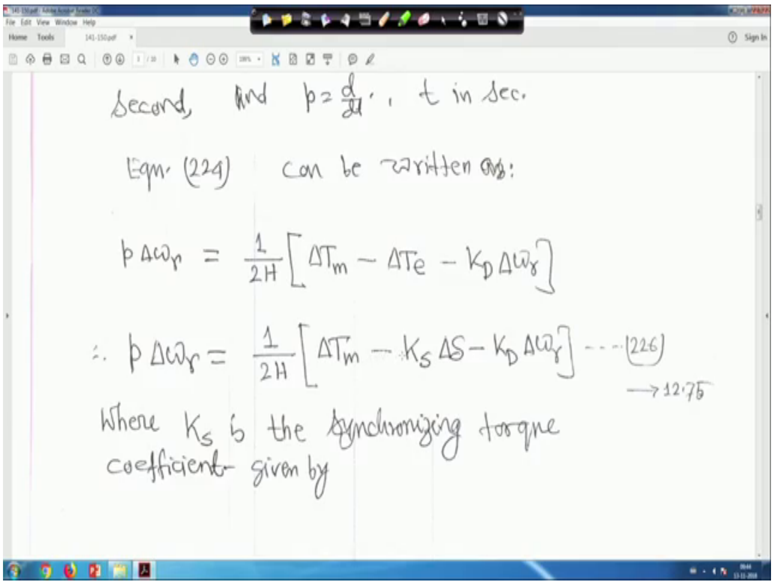

The how things are how this from everything is same, but to just we are making delta T m minus delta T e, this small perturbation how things are coming, how these two things are coming, we will come back in the next hour, next lecture.

Thank you.