Power System Dynamics and Control
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Module No. # 01
Lecture No. # 18
Synchronous Generator Models Using Standard Parameters
Per Unit Representation

Our effort so far, has been to obtain state space models of a synchronous machine, which use what are known as the standard parameters, which are essentially obtained from measurement. So, the standard parameters effectively are the coefficients of the transfer functions, which are obtained by fitting the experimental responses.

Now, the important issue which we try to tackle in the previous lecture was, with a limited number of standard parameters, how to get a meaningful synchronous model synchronous machine model. Now, there are two issues there, one of them is if I get a state space model using the standard parameters, there is no unique way I can get in fact a state space model; so you have got a transfer function of a synchronous machine but, there is no unique state space model of a synchronous machine, which yields this transfer function.

However, if you recall when we were doing the basic theory of a synchronous machine, we had in fact model of the synchronous machine using some certain states, which are very meaningful like the rotor fluxes, the rotor F field winding flux, the damper winding fluxes as well as the d and q fluxes.

Now, the point is that if you have got a transfer function and you get, you want to get a state space model out of it, you can you know you can get any you can there is no unique state space representation. So, you can in fact get a model which uses only the parameters which are obtained by measurement, what the real issue, which really which we confronted was with a limited number of measured parameters, how to get the original model, which use the original states that the stator and rotor fluxes.

In fact you cannot do that therefore, we have to make certain assumption approximations or use a model in which the states are not easily relatable to the original states.

So, today of course, we continue in the same way but, by the end of the lecture, we should come up with a model which we are going to use and another point of course, is that will per unitize model, that is will normalize the model and get everything in per unit, so we can actually do fairly realistic studies.

So, today's lecture is continuing with synchronous generator models but, will be using standard parameters with per unit representation but, before we of course, we come to this let us just quickly recap what we did in the previous class, if you look at the synchronous machine models there is a state space model.

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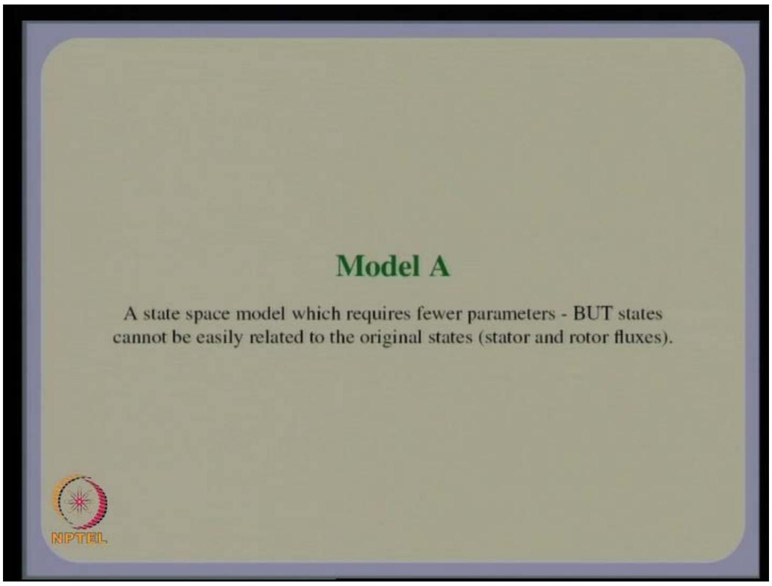

We discussed model A, which requires few parameters, in fact we use directly the standard parameters but, the states cannot be easily related to the original states, which are the stator and rotor fluxes. So, in fact we do retain the stator d and q axis flux state variables but, the rotor flux variables are not retained in this model.

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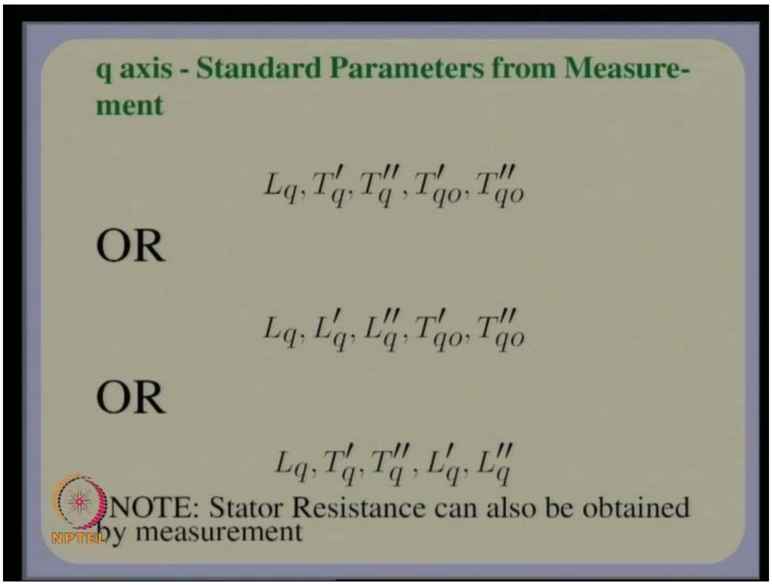

So you have got this q axis, in on the q axis of course, you have got a standard parameters from measurements, they may be specified in terms of 4 time constants and an inductance or 3 inductances and 2 time constants.

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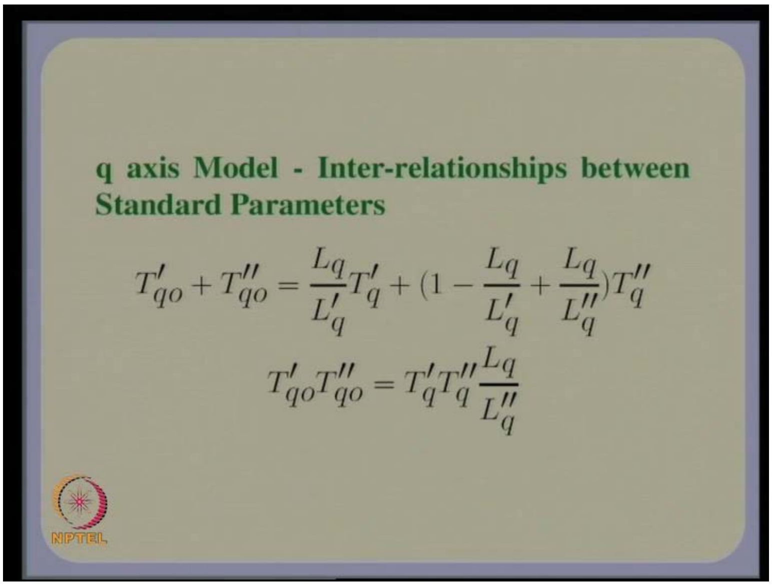

So in any form you may get this data, any of these forms but, the time constants and the reactance or the inductances are in fact, related by this relationship, so they there can be interchangeably used.

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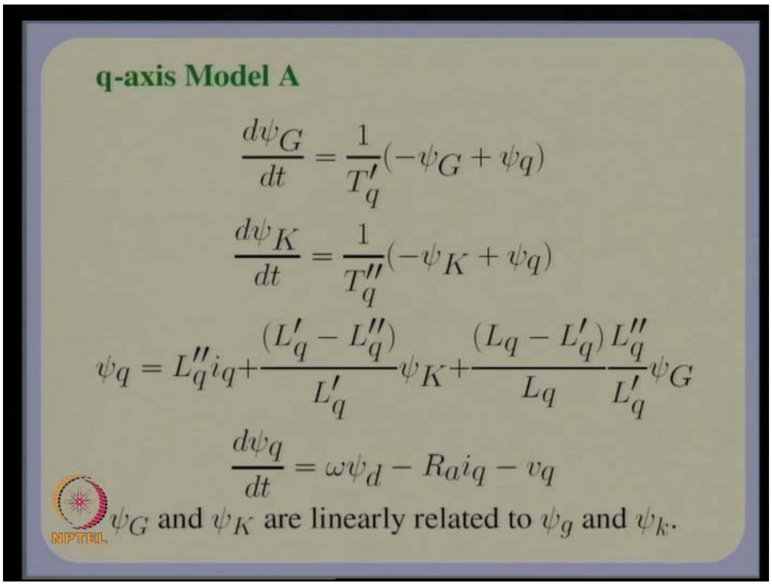

The q axis model A uses the states psi G, psi K but, importantly the variables are psi upper case G and upper case K to actually distinguish them, from the original state psi G and psi K.

Now, psi upper case G and K are relatable by a linear transformation from psi g and psi k lower case the original state variables of course, we do not know, what that transformation is however, remember that this particular state space model will yield, the same transfer function as before between psi q and I q. So, we will get the correct transfer function we will get it in proper form so that is this is a valid state space model.

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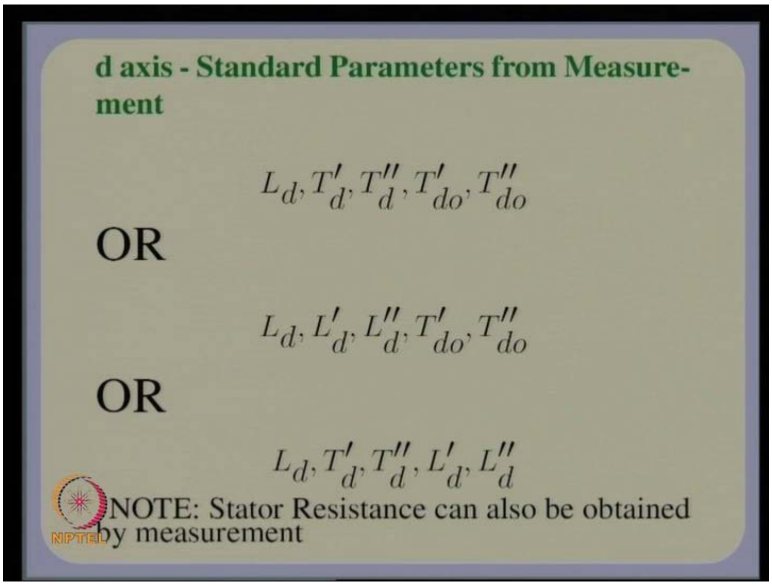

In the d axis, we have got again the standard parameters on the d axis.

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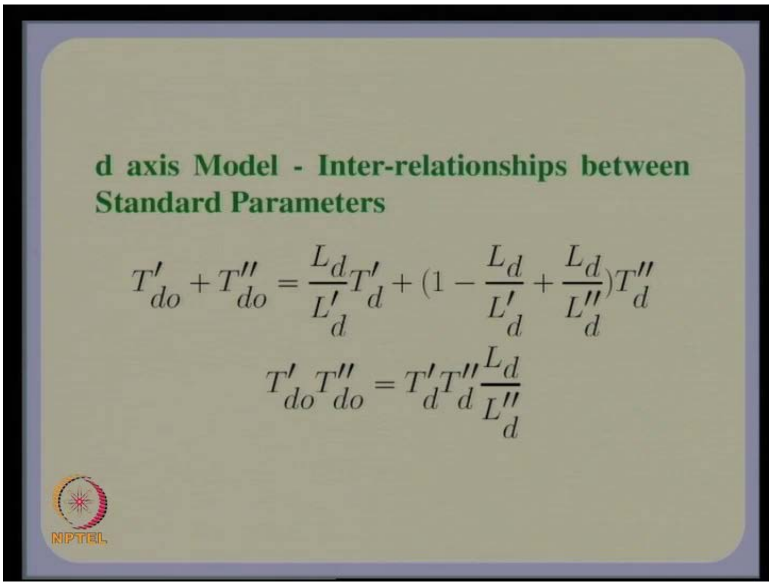

Again we have this relationship between, inductances and the time constants.

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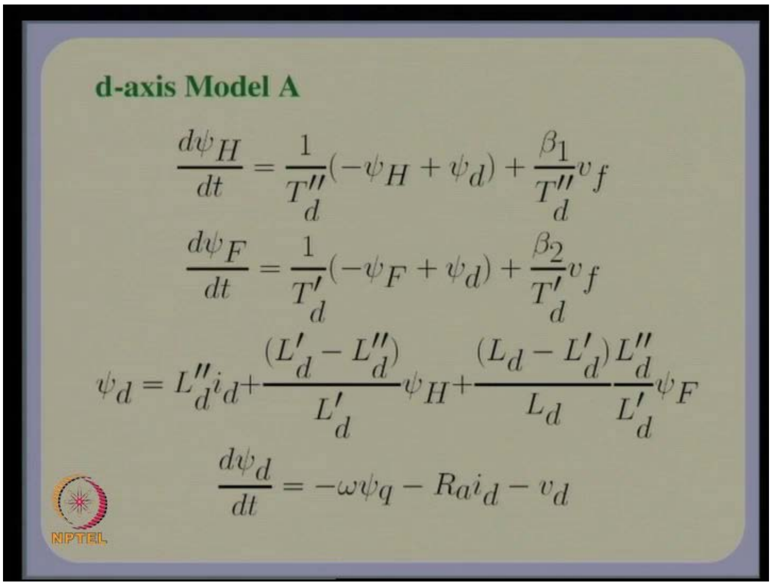

And this is the d axis model A this is a model which uses the state psi upper case F and psi upper case F and psi d, psi d of course, is the old or the original flux in the d axis winding but, psi upper case H and F are in fact not the same as the original states.

So, this is the valid state space representation but, it uses states the rotor flux states are not exactly the same as what we have used in the original derivation of the synchronous machine. And of course, V F is the field voltage, the voltages applied to the field winding remember that model A is completely in terms of the standard parameters, there is no back calculation involved, etcetera.

You can directly use this model in, so far as the effects on the stator or as seen from the stator are concerned, you can use this model A, in spite of the fact, that the fluxes the rotor fluxes here, are not the same as the original. The rather the fluxes psi upper case H and upper case F, upper case G and upper case K, are not the same as the original flux variables but, this is still a valid state space model, in the sense that you will get the same relationship between psi d and I d the transfer function relationship if you use this model.

And of course, the transfer function relationship between psi q and I q also is the same if you use the q axis model, the relationship between psi d and V F also is maintained by this model. So, in so far as all effects on the stator are concerned the transfer function relationships or you can say the behavior of all the stator variable; that is psi d and I d are concerned this will be a valid state space model but, if somebody asks you the question what after you use this model. What is the ampere value of the current on the field winding in the field winding or the flux passing through the field winding coils. This question cannot be answered, because the exact relationship between these upper case subscripted size and the original rotor fluxes is not given. In fact it is not with the given data it is not possible to get that, so that is the important point which I want to emphasize.

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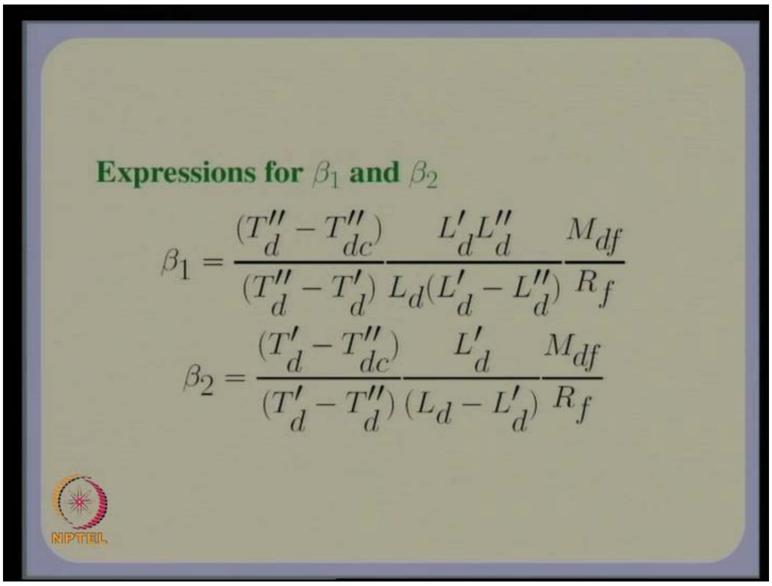

Beta 1 and beta 2, which are used in the state space model are again in terms of the standard parameters, of course, here you need to have T d c double dash, which is also a part of the transfer function which we have discussed before.

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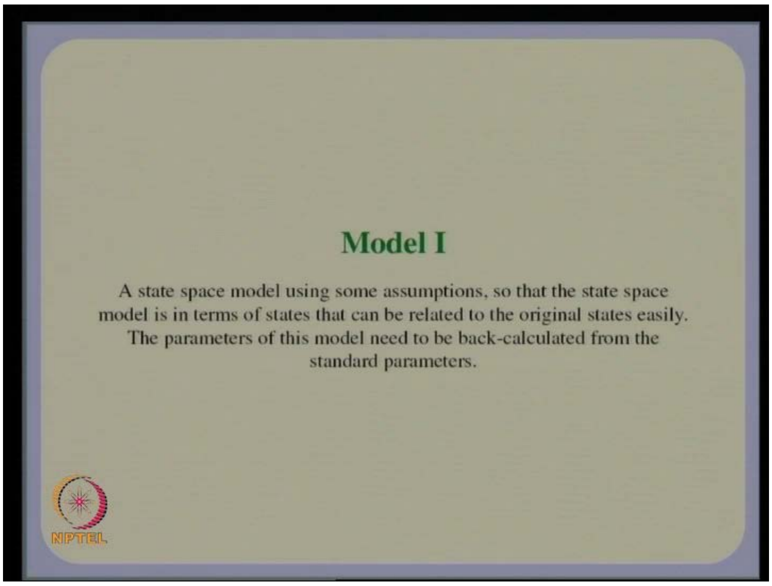

In the in the previous lecture in the later half I also introduced model I, in model I we attempted not only to get a state space model but, we tried to relate the states to the original states in an easy way.

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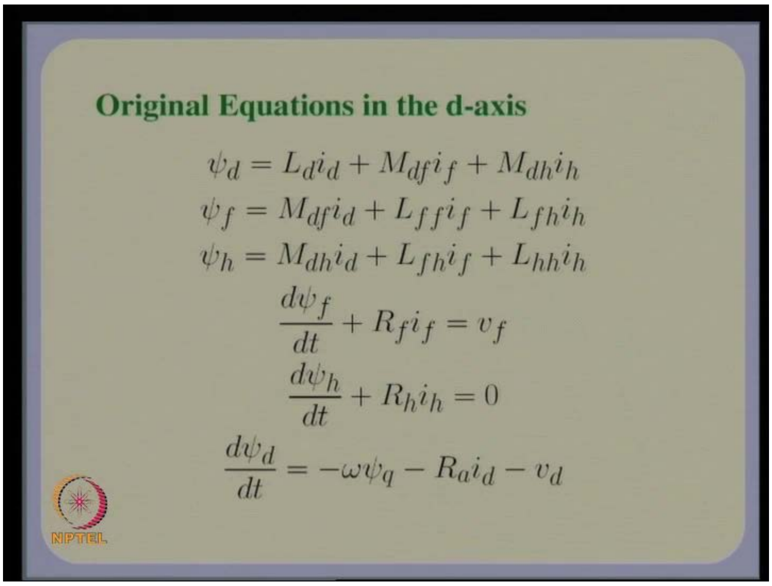

So model I, is in fact if you look at what exactly model I is, it is the same as model, the original model in basic parameters except that, we refer the states onto the stator onto the stator d axis.

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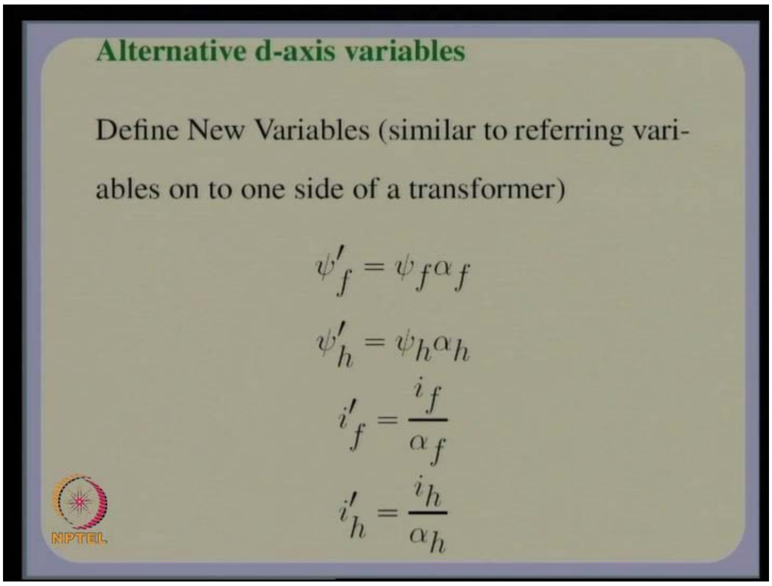

So, alpha F is in fact in some way it is a turn's ratio, alpha h is also turns ratio but, we will in fact choose it such that M d h dash is equal to M d f dash.

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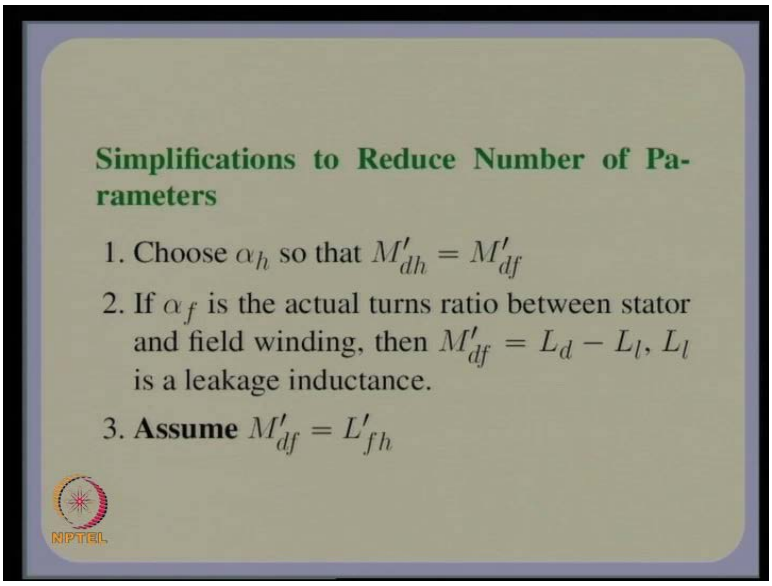

So, alpha h cannot actually be the turns ratio it is actually chosen, in a such a way that M d h dash is equal to M d f dash M d f dash is equal to L d minus L l, L l is a leakage reactance. And of course, there is a assumption made also that is M d f dash is equal to L f h dash; so we have discussed this model in the previous lecture, so I will not spend too much time on it but, the important point is that, this model uses the states psi f dash, psi h dash, which are easily relatable to the original flux; so the there is a direct proportionality relationship between psi f dash and psi f.

Importantly although the equations in the new variables will look in this form, again we have the issue of trying to obtain the new parameters, M d f dash, M d h dash, L d, L f f, dash L h h dash and L f h dash.

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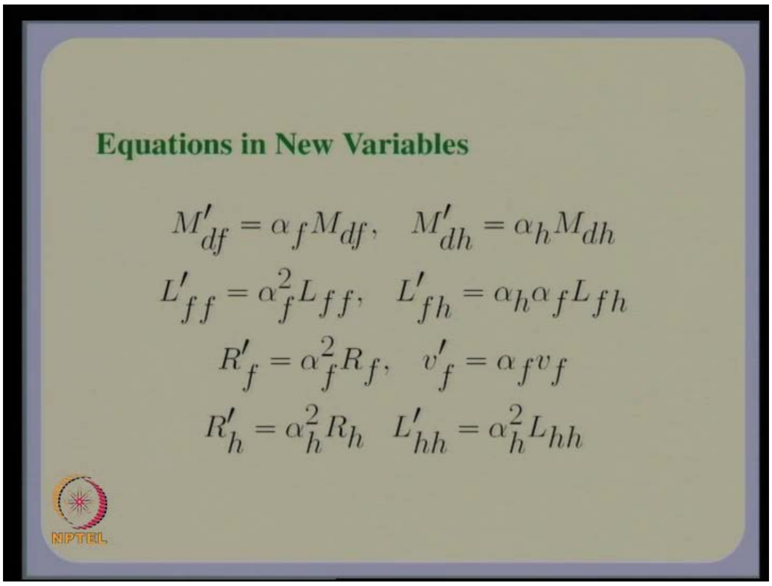

Remember that, because of these assumptions which we are making, which I will show you shortly, the number of parameters actually reduced in the model.

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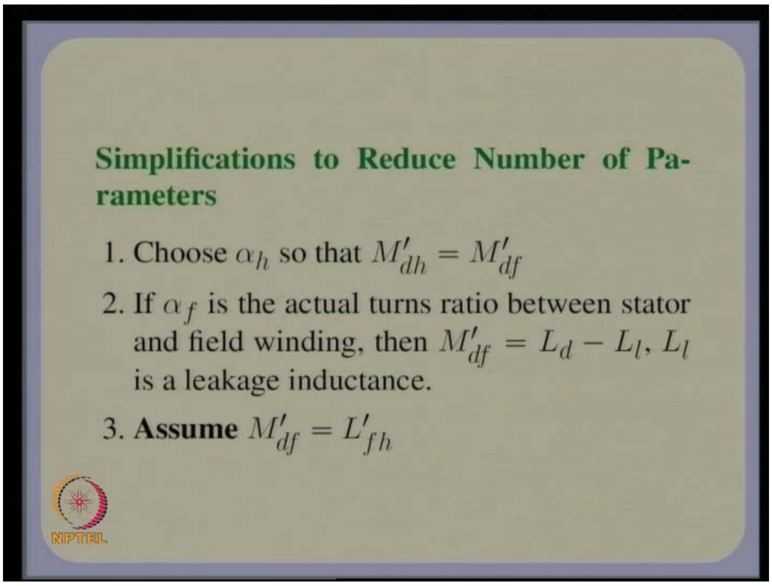

So, what we are going to do is, let us say we have chosen alpha h, so that M d h dash is equal to M d f dash, so we have actually reduced one, need for one parameter, because if we have equated it with another parameter. So, another thing of course, we will of course, if we know the leakage inductance, then M d f dash is also known and then L f h dash is also equated to M d f dash by an assumption, this is an approximation which we make.

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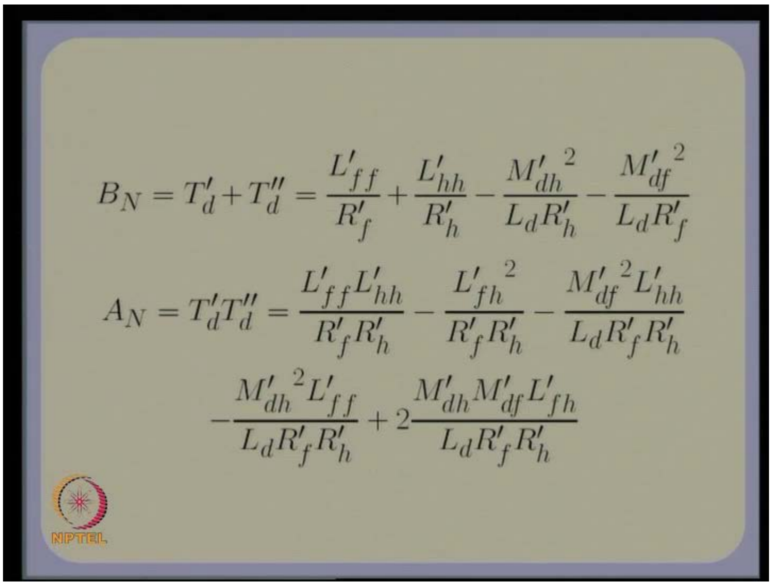

So, actually from the standard parameters the standard time constants, which we have, we back calculate the values, of L f f dash L h h dash R f dash and R h dash.

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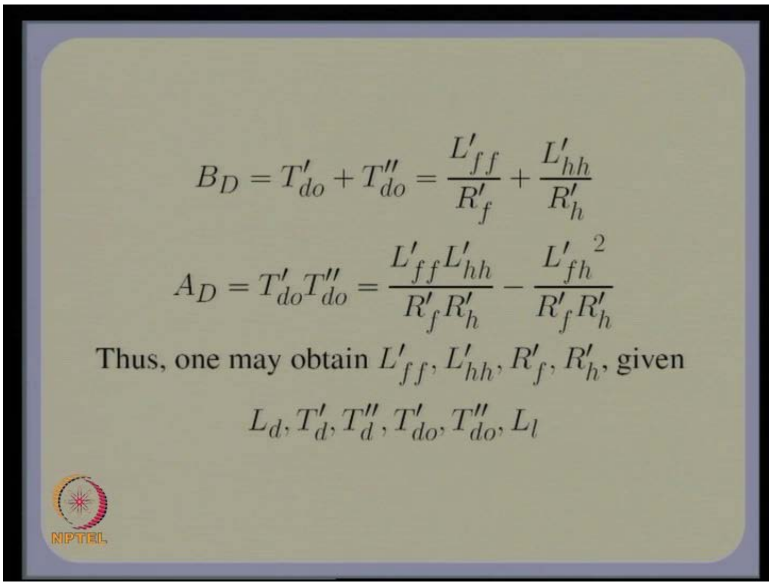

So, in this in fact in this model, we require we require of course, to obtain this model L d, L f f dash L h h dash R f dash and R h dash and L l.

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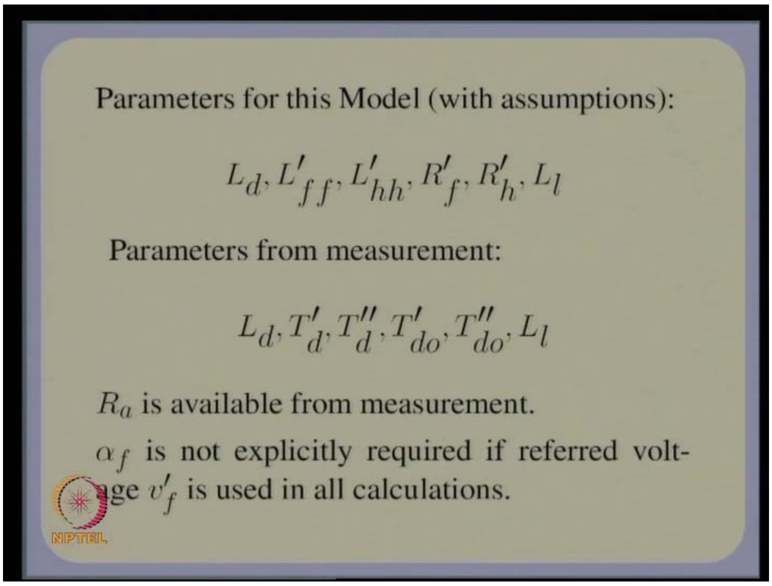

And the parameters which we get from measurement are these, alpha f is not explicitly required, if in all our calculation we use v f dash which is the referred voltage.

Now, M d f dash, M d h dash and L f h dash do not appear in this first list, that is because because due to the assumptions made L f h dash is not required, L f h dash is equal to M d f dash M d f dash, itself is equal to L d minus L l and alpha h is chosen, so that M d h dash is equal to M d f dash.

So you know the number of parameters, we can if you have given, if I have given a limited number of parameters, these parameters the second, set of parameters which are given, which are obtained from measurement I can back calculate the rest of the parameters.

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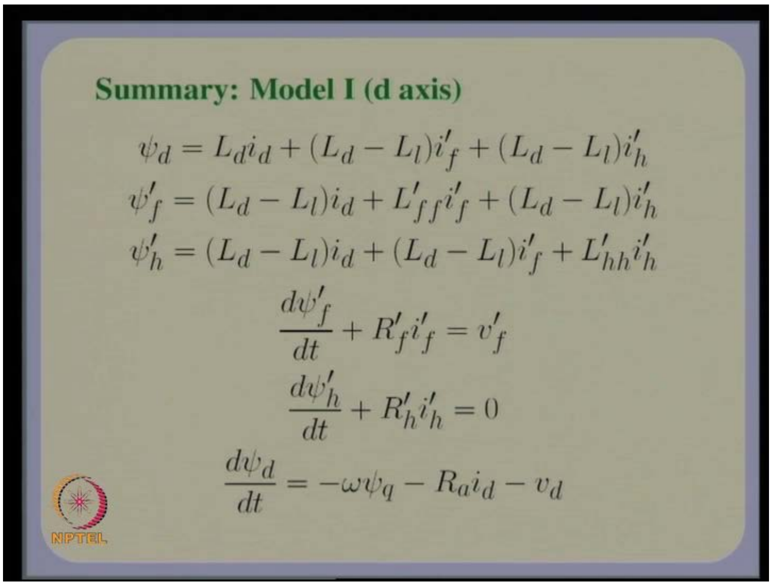

So, that is the important thing once you are back calculated the rest of the parameters you simply, you can rewrite the original model in this form; so it is a fairly straight forward kind of a a process only of course, there is one step which you have to do is, back calculate L f f the values of L f f dash, L h h dash, R f dash and R h dash, from the standard parameters using these relationships.

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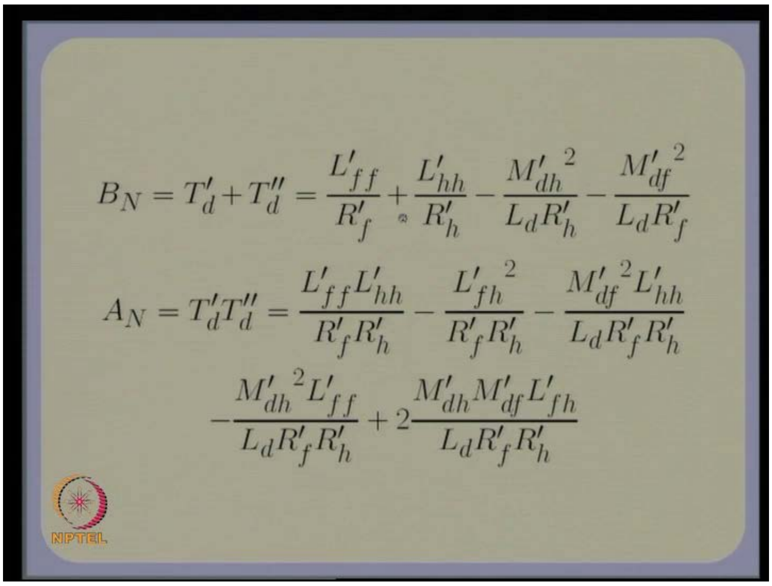

Of course, in these relationships I have not actually substituted, for the values of M d f dash, M d h dash, remember that M d f dash in these equations has to be substituted by L d minus L l and M d h dash also has to be substituted by L d minus L l, f h dash also has to be substituted by L d minus L l.

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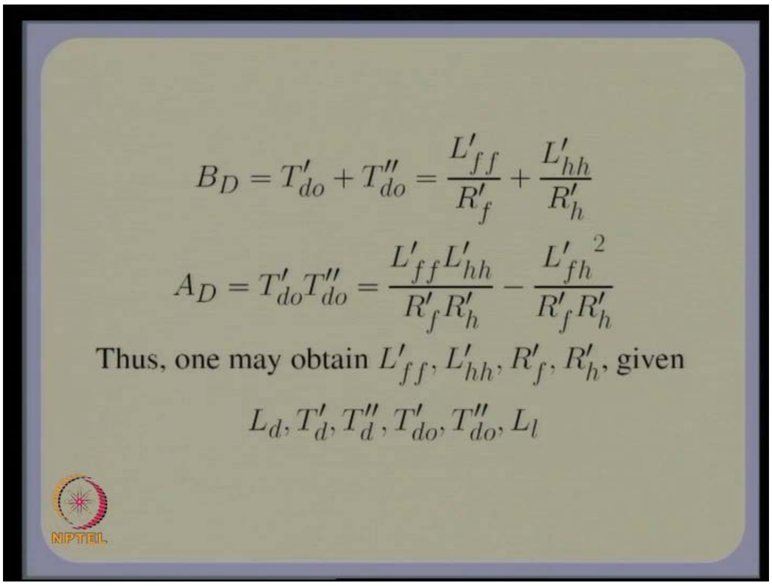

So, the number of actually the number of equation is adequate to get the required parameters for the model, so this is the important point which you should know, so this is our final model I d axis, this is a very popular model.

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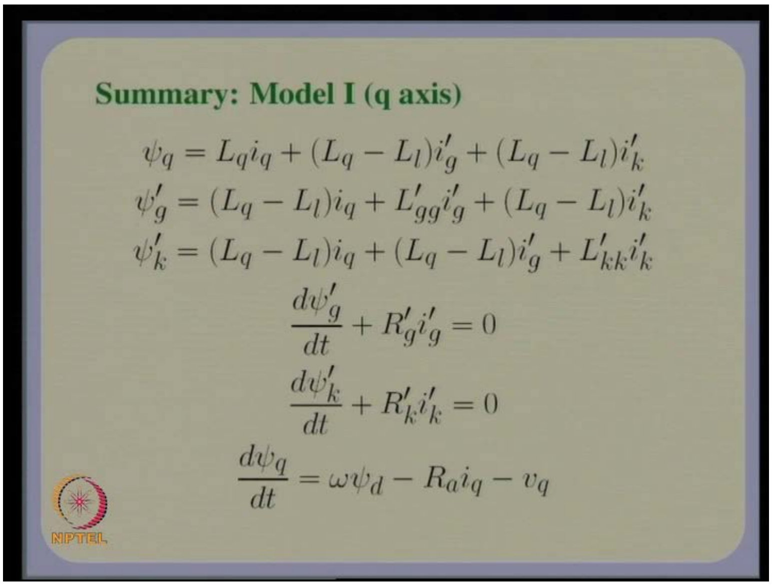

On the q axis similarly, I will not go through the derivation of it, then the q axis similarly, you have got a model of this nature, you can directly use it and do your analysis of a synchronous machine.

Remember an important property of model I is that psi g dash is proportional to the original state psi g, so it is a direct proportionality, unfortunately alpha h is not known, it cannot be known from the data which is given, just from the standard parameters which are given, I cannot tell you what alpha h is but, I can tell you that it is proportional to psi g.

So, if somebody asks you use this model, with the data which is given and tell me what is the ampere value of the current flowing through the through the damper G winding or the damper K winding, I will not be able to tell you. Usually we do not require explicitly these currents or fluxes through the damper winding but, only want to know, how they affect the quantities on the stator; so that is it, does not we really do not want to know the actual ampere value or the test lab value of the fluxes through the damper windings.

Of course, the same may not be throughout the field winding, there may be reasons very good reasons, why especially when we come to excitation systems we will realize this, that we actually may need the field winding current. We may require the field winding current and the field winding voltage, so there has to be some more data or the turns ratio in some sense has to be given to us to for us to know, what alpha F is and actually the field voltage in volts.

And all can be calculated from it but, in so far this model is concerned, if we are working with working with the assumption, that we are going to use only V F dash that is the referred value of the field voltage that is alpha F into V F; in that case this model is self contained and self complete and it is in fact give you the correct effects on the stator.

Of course, there is an approximation involved in this model approximation is that L f f, L f h dash, has been equated to M d f dash, which is equal to L d minus L l, so that is one approximation which is made but, the advantage of using this model is that, there is a direct one to one relationship, there is a proportionality relationship, between the psi f dash and psi f and psi h dash and psi h and psi g dash in psi g and psi k dash in psi k.

So, that is the advantage of this model, in fact if you look at this model, you can actually draw a kind of an equivalent circuit of this model I.

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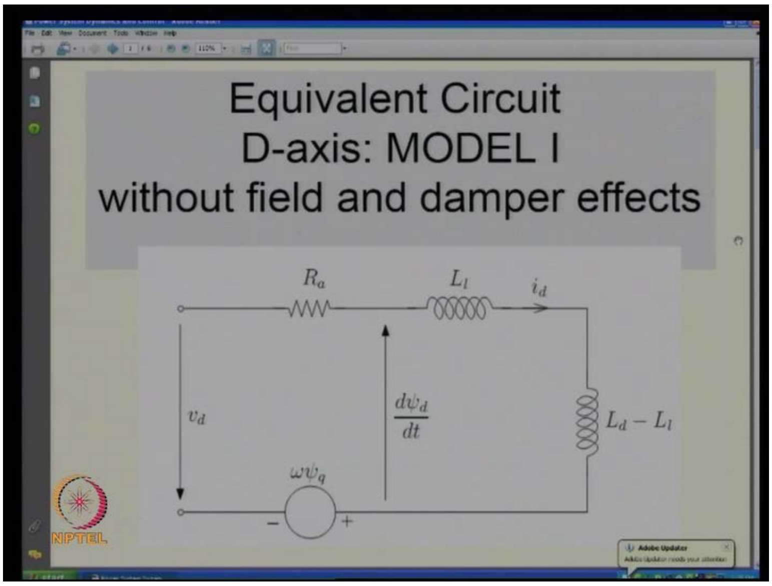

So, when we are developing this circuit effectively, what we are doing is just writing down a circuit, which the equations of which satisfy the equations, which we have just discussed equivalent circuit of course, is easy to remember. So that is the reason, why that is the motivation, why we are considering an equivalent circuit you can just as well remember the equations instead of the equivalent circuit.

So, for example, if you neglect the effect of I f dash and I h dash, you can see that the differential equation corresponding to d psi d by d t is given by the equations of this this particular circuit. So for example, you have got V d is equal to minus omega psi q minus V psi d by d t minus R a into i d and also psi d is equal to L d into i d.

So, this is basically a restatement of what the equations, which you have written, so the equivalent circuit is essentially only a kind of a restatement, if you go to the, if you try to include the field winding effects or the field current effects.

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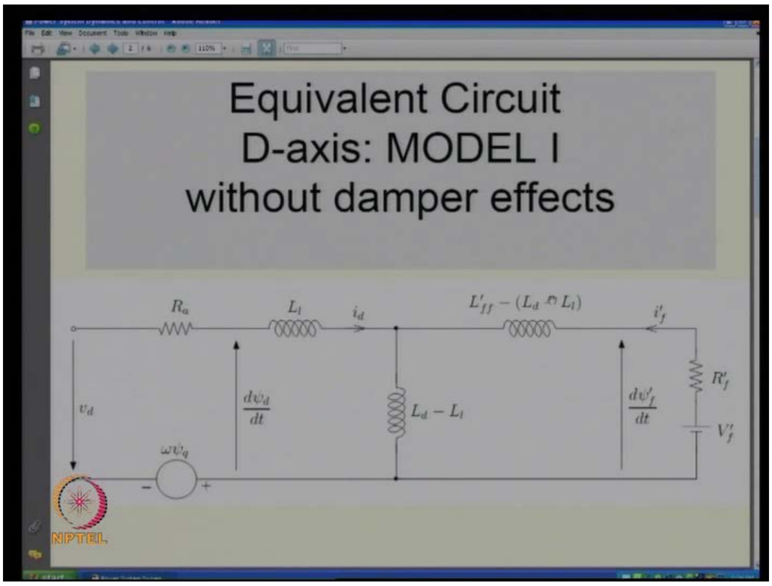

We come to this additional part in the circuit, so if you look at this particular circuit, the effect of this is this is what was there already and now we have got this additional effect of the field current.

So now, psi d for example, is L d into i d plus L d minus L l into i f dash, you can also verify that the differential equation of psi f dash also is consistent with what you have written down in our equations for example, d psi f dash by d T is equal to minus R f dash, i f dash plus V f dash. So, this is basically being satisfied, so the equivalent circuit in some sense is reflecting what the equation says.

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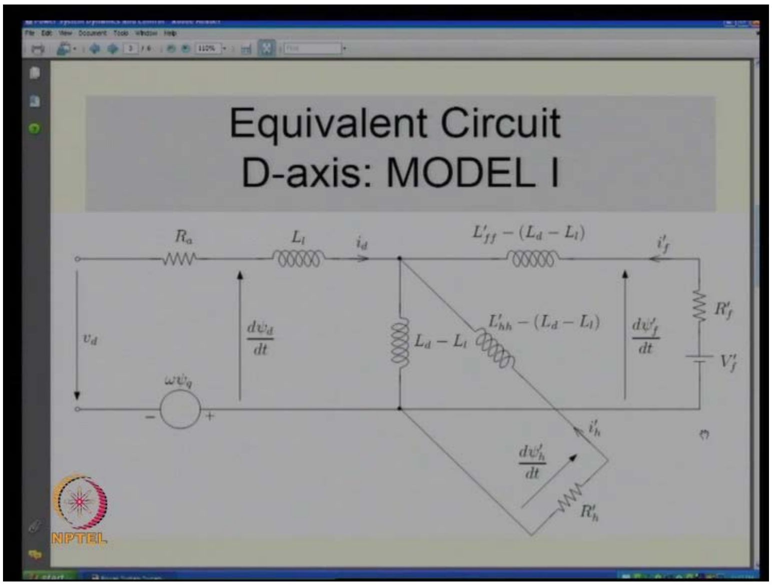

If we include the effect of the damper windings, this is what we get so we have got this now this additional branch coming here, psi d is nothing but, L l into i d plus L d minus L l into i d which is nothing but, L d into i d and since these currents i f dash and i g i h dash also getting into this psi d additionally is made out of L d minus L l into i h dash plus L d minus L l into i h dash.

So, so basically what this equivalent circuit is, just a way of representing the differential and algebra equations which we have just discussed, so you can well imagine that you can do the same thing for the q axis, for the q axis model is this, it looks almost similar to the previous thing only of course, you do not have a field voltage or no no extra voltage source on the damper windings.

So, this is basically what we have for the q axis in model I, remember that having an equivalent circuit is useful you can remember it very easily, there is another advantage if you can call it advantage, is that latter on, I mean if you look at for example, the literature on how you represent saturation, in fact what is assumed often in those models is that only this brand saturates.

So, by by kind of demarcating all these different inductances, in this equivalent circuit, which is of course, easy to remember, we can also you know demarcate this portion as being susceptible to saturation effects; of course, we have not considered saturation in a great you know we have not even discussed saturation so far but, if you happen to reach read more detailed literature on synchronous machine modeling, am sure you will be able to correlate with what am saying here.

Now, we move on to another model in fact you know the one of the steps which you have to undergo when you use model I is that you have to back calculate this L F f dash L h h dash, R g dash and R k dash and R f dash and R h dash from the original parameters, using those transfer function algebraic equations, which you relate the time constants to the various coefficients of the transfer function of the original model.

So, I hope you recall what I have saying you can just have a look at what am trying to say, so you know for example, T d dash, T d double dash, T d 0 dash and T d 0 double dash, from the measured values which are provided to you the standard parameters and from this you have to back calculate L F f dash, L h h dash, R f dash and R h dash.

So, this is what you have to do there are four equations and they are four unknowns and you should be able to obtain those, so this is one other thing which you have to do in model.

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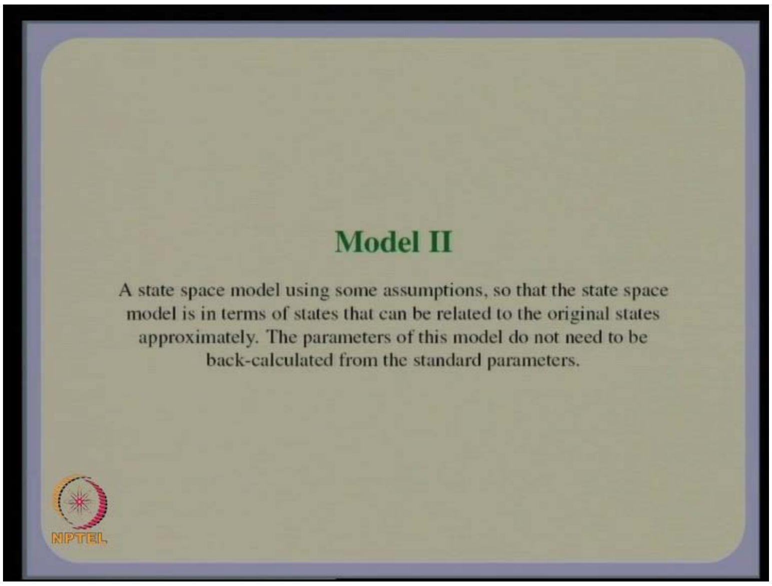

There is one important step, what I will show you is a quickly a model another model which uses a distinct approximation, this model is also useful in the sense it is going to be convenient for us to use this model, because in one step that is back calculating all parameters L h h dash, L g g dash, L k k dash and the resistances of the damper winding, that step is kind of a a rendered unnecessary if you use model II.

So model II is quite similar to model I but, the assumption made is quite distinct it is not the same assumption as before; so let us just quickly go through this model II, in fact then we will move on to the per unit system and then we will use exclusively model II, in the per unit system using per unit in all our future discussions.

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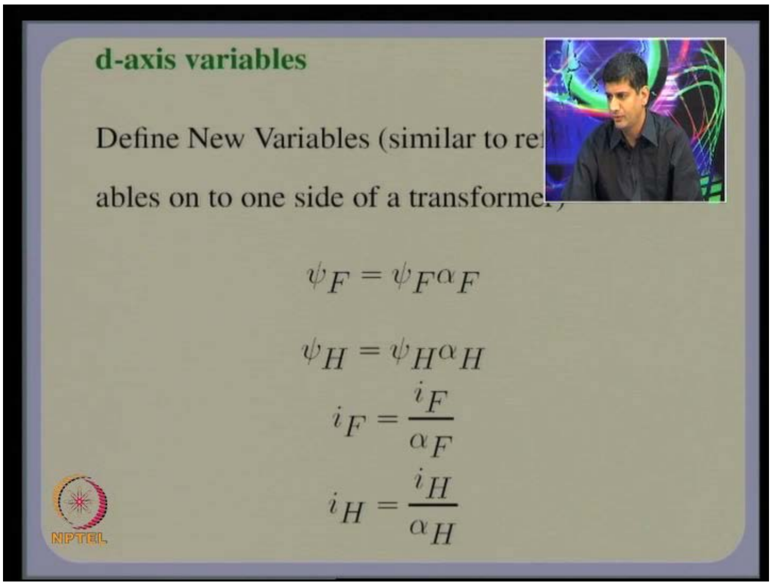

So, if you look at model II it is similar, to what we have in model I but, I have deliberately used upper case F H here, because I just want to make an important distinction that the alpha H and alpha F here, are distinct from what we have considered in model I.

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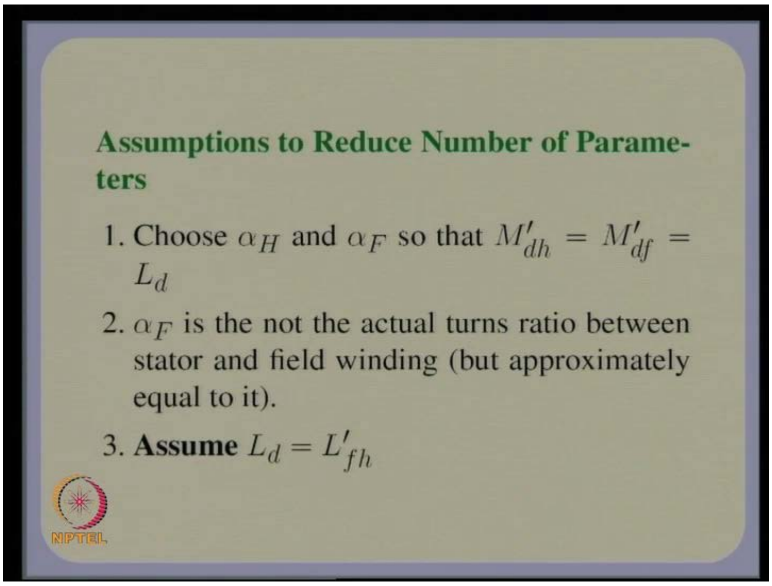

So, we go to the same steps as before, only the assumption made assumptions made are a bit distinct, so here, we choose alpha H and alpha F, so that M d h dash is equal to M d f dash is equal to L d, so this is the distinct as you know we we do out here alpha F is not the same as before, it is not the two turns ratio but, approximately equal to it; so it is approximately equal to the turns ratio, so we are not going to use alpha F as the turns ratio between the field winding and the d axis winding.

And the other assumption is of course, is regarding L f h dash we equated to M d f dash which is equal to L d, so remember here that, this model is distinct from the previous one we are choosing alpha H and alpha F, so that the first point here, M d h dash is equal to M d F dash is equal to L d is satisfied and just note this. So, this is this is a slightly slightly different model, it is not too different but, it is slightly different, remember that obviously alpha F cannot be the actual turns ratio, because you know M d f dash cannot be exactly equal to L d, because there is always some leakage.

So, there is an alpha H F cannot actually be the actual turns ratio but, it is approximately so assuming leakage is a small, then alpha F is actually the turns ratio but, it is not exactly the turns ratio, so that is an important difference from what we considered in the previous model. So, model II has got a distinct you know the approximations and the way of going about it is quite distinct but, both the models are still approximate, because leakages are assumed to be small.

So, it is not that, these approximations render the models useless.

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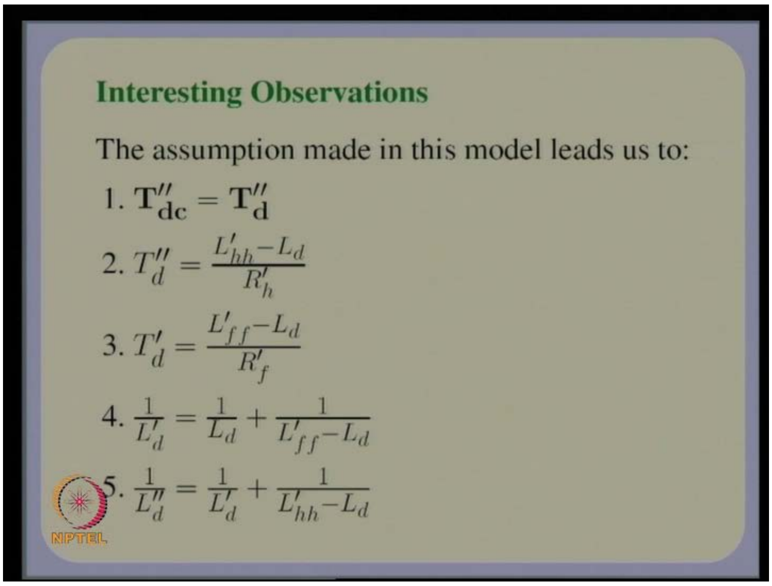

Now, this is something I state without proof, this is something you can try to prove yourself it requires a bit of a arithmetic ah some algebra you know if I have choose if I make these three point, the assumptions is basically L d dash is equal to L f h dash and I have chosen, alpha H and alpha F in this fashion then one of the important things; in fact I will identify this model by this important property, that this approximation renders T d c double dash approximately equal to T d double dash, I must at this point recall to your memory, T d c double dash is the is the time constant of the numerator of the transfer function between psi d and V f dash, V f.

So, remember that by making the approximations which you have stated here is equivalent to making the approximation T d c double dash is equal to T d by double dash, so I shall in fact always talk of this model as the model in which T d c double dash is equal to T d double dash, so I will be using this particular model.

Other interesting things is a are that T d the expressions for T d double dash, T d dash L d dash and L d double dash, become very simple they become very simple, in fact the relationships two to five are similar on the q axis as well you will get similar expressions on the q axis, very straight forward expressions for all these time constant and inductances.

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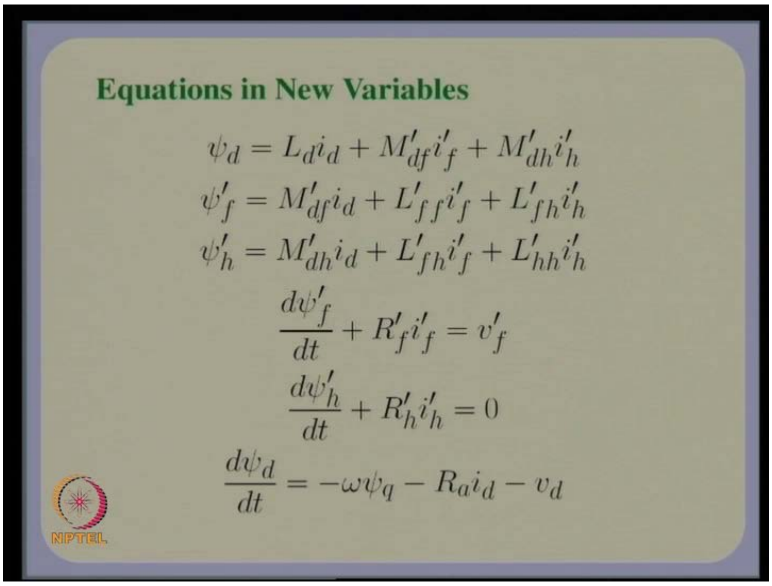

But, importantly T d is making the assumptions and making the choice of alpha F and alpha H in this fashion essentially results in making an assumption T d c double dash is equal to T d double dash, so that is an important thing you should remember.

So, if you look at the equations in the new variables they will look like this, so what do you notice is M d f dash, M d h dash, L f h dash are all replaced by L d, in fact there is one error here, no it is I think it is yeah. So what you have here is this, I will just check one thing and then we will continue yeah, so the variables of course, are I F I upper case F at H again remember, am using these upper case variables to emphasize the point that these are not the same as the original field flux you know field flux or damper winding variables the original ones.

But alpha F remember is not the actual turns ratio but, but approximately equal to it, so what you have here is, i F is in fact roughly proportional to the filed current.

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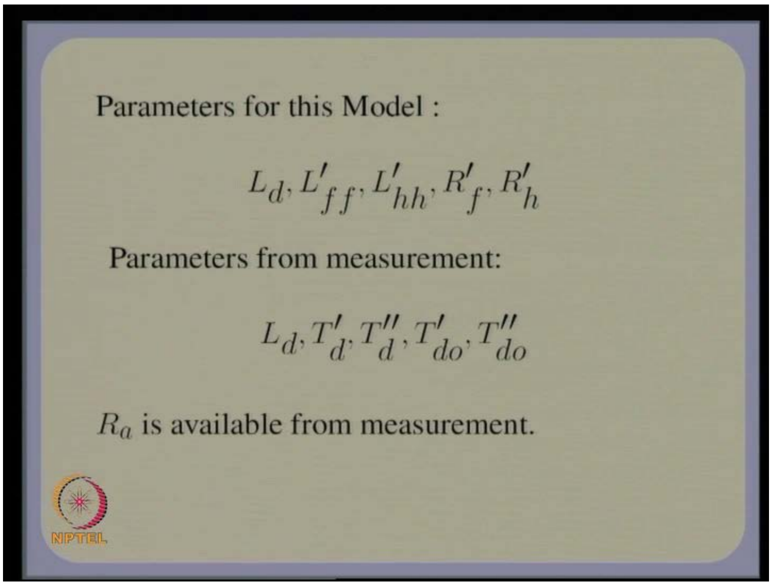

So, again the parameters required for this model are these and these, and the parameters obtained from measurement are these, so you should be able to form this model from the given data.

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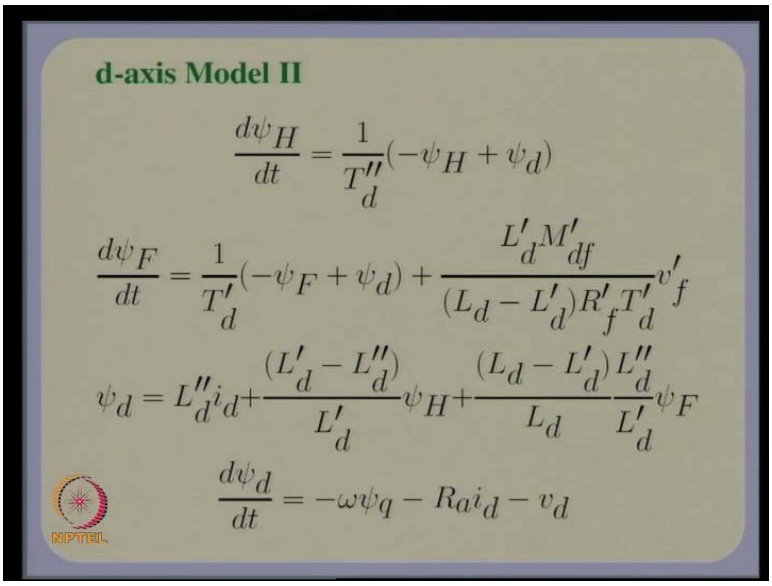

In fact, you can rewrite these equations, this is something I do not prove here but, whatever I have written before that is d psi F by d t and d psi H by d T this two differential equations here, you can substitute for the value of i F and i H in terms of psi d psi F and psi H and really get this differential equation model.

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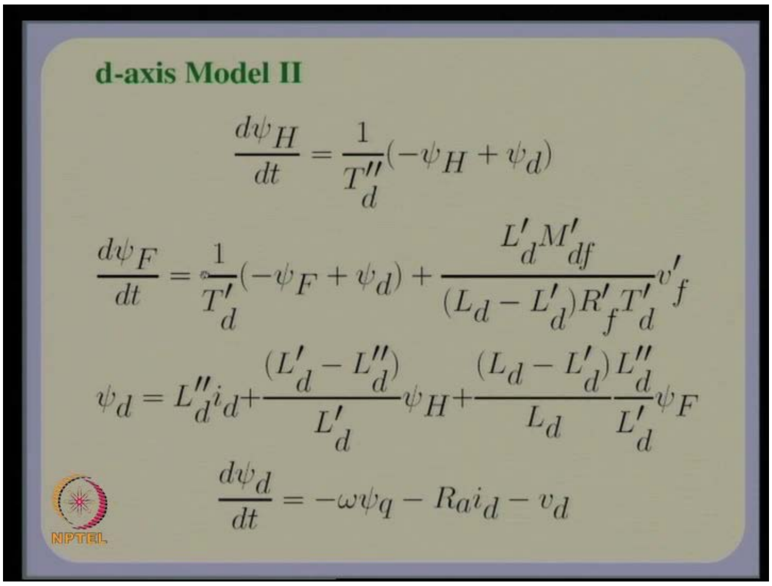

So, model II can be rewritten in this fashion, now what you notice is of course, is that you have essentially this psi F which is approximately proportional to the field flux and the input to that is V F dash, so this is our d axis model II. And the good thing about this model II which am talking of is talking of is in fact that is in fact that if I give you the standard parameters, I can directly form this model without having to try to back calculate all the values of L d, L h h dash, L f f dash and so on. I just, if am given the standard parameters the here is the model of course, this model involves an approximation but, it is very convenient to use.

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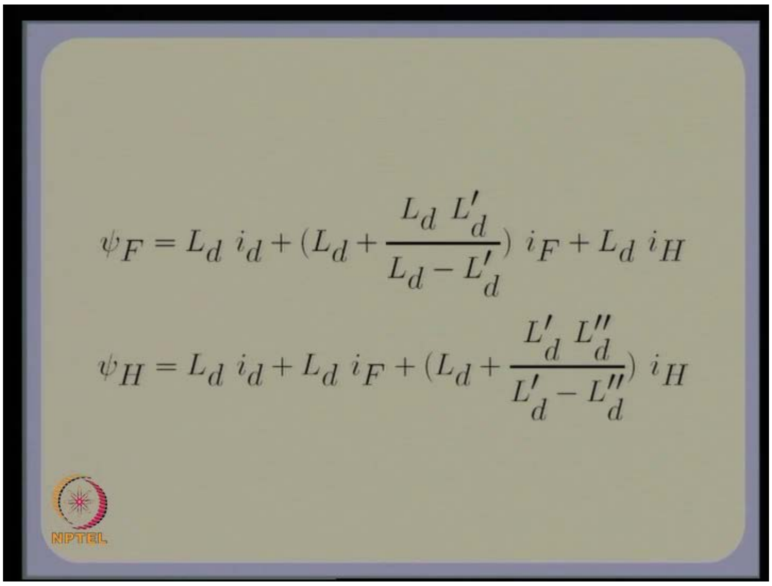

Another thing we which which effectively is inferred from this model is that, you can get a relationship between i F, i h, i d and psi F and the important thing is that, this can actually yield i F. In fact these equations are I have written them down the their, I have rewritten them in fact, because in a latter study when we talk about excitation systems we may require the value of i F which is approximately proportional to the field winding current.

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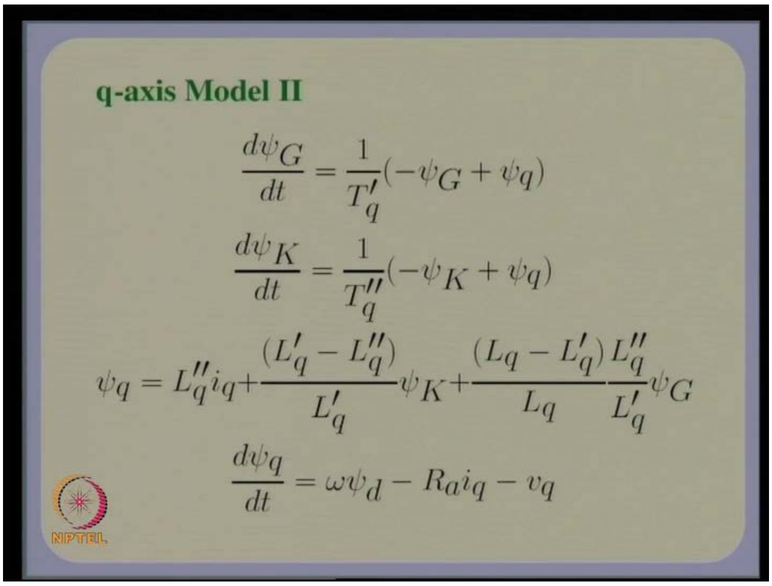

The q axis model II is similar of course; we do not have any input for this model.

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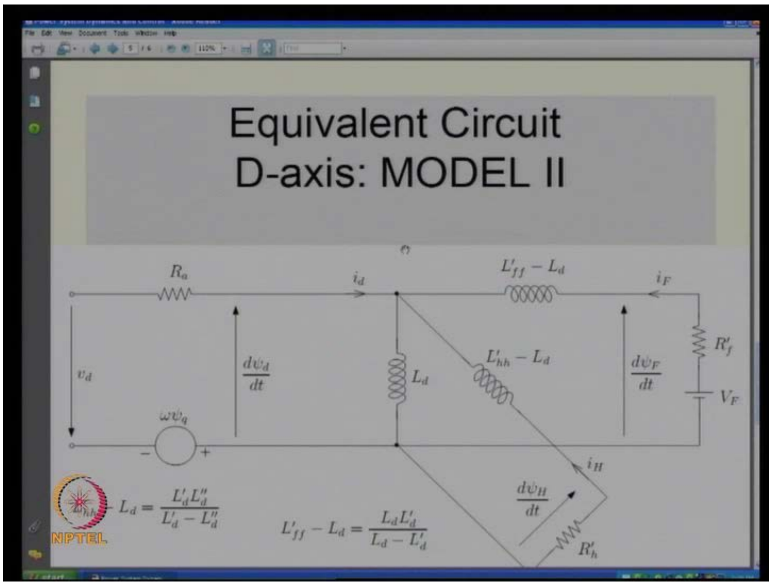

And if you look at the model II equivalent circuit it is quite simple, the model II equivalent circuit can easily be seen to be this, you can contrast it with the model I equivalent circuit we saw some time ago, it is quite different, it is somewhat different from what was discussed in model I, the equivalent circuit of model I. Very importantly the leakage effects are not considered and well it is not accounted for separately here, another thing is of course, that these leakage inductances are obtained using these equations.

So, L h h dash minus L d can be expressed in terms of the transient and sub transient inductance and similarly, L f f dash minus L d, which is the leakage inductance here can be a represented in terms of L d and L d dash.

So, this is the equivalent circuit for model II of the synchronous machine, if you look at the q axis similarly, this is what we get, so this kind of concludes our discussion about equivalent circuits, the advantage as I mentioned some time back about equivalent circuits is that, that you can kind of easily remember the equivalent circuit; you do not it may be more difficult to remember the equation but, because of this graphical representation, you can easily remember the equivalent circuit and there by obtain the differential algebraic equations, described in this circuit, so that is the advantage of remembering an equivalent circuit.

So lets us now, move on to, what is an important step that is getting into the per unit system, so if you look at the model which models which we have used, we have to introduce a per unit system, so that we can use this model readily for all our future studies in which all data will be given in per unit; so first step in defining per unit is define the base values.

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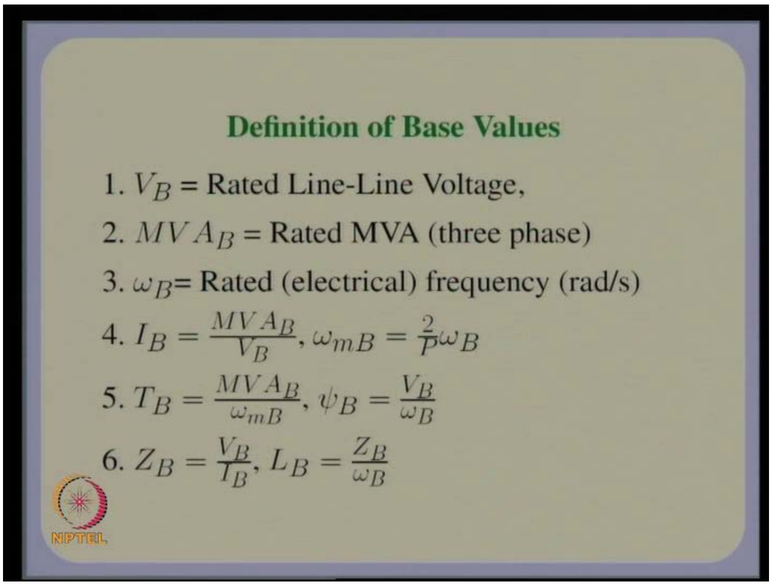

So, the typical base values used for a synchronous machine are V B is the rated line to line voltage, M V A B basis is of course, the three phase rated, M V A B of the machine omega B is the rated electrical frequency in radian per second, I all the rest of the base values are derived from these three base values. So I B, I base the current base is M V A by V base is quite different from, what we normally use in other studies, where there is a root three factor but, we shall show that if we use this consistently we will get very neat per unit equation which are self consistent.

Omega B, omega M B is the mechanical based frequency, which is nothing but, 2 by P times omega B, torque base is M V A base divided by omega mechanical base, flux base flux linkage base is V B V base by omega base and impedance base is V base by I base and inductance base is Z base by omega base.

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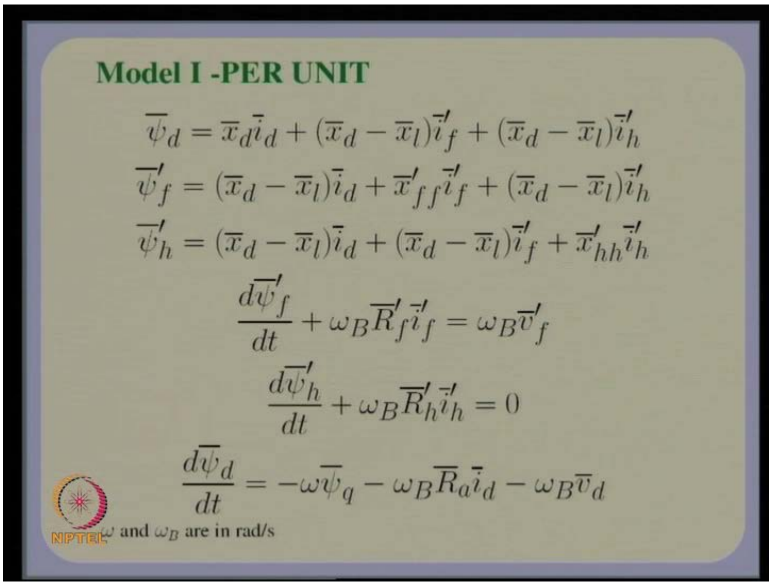

So, we will try to derive this model which is a per unit model, model I in per unit.

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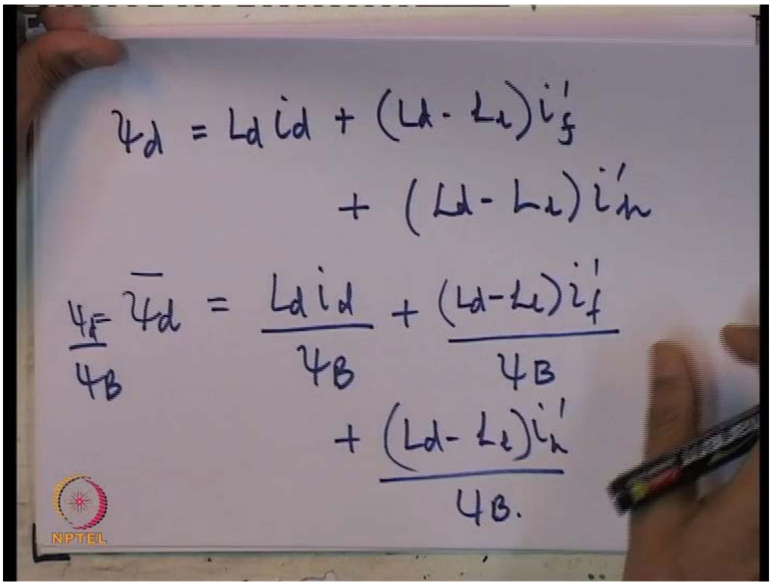

So, actually how do I get these equations for example, we had model I psi d is equal to L d i d plus L d minus L i i F dash plus L d minus L l into i h dash, now what you do is divide it by the flux the both sides, by the flux base. So, you will get psi d bar is equal to L d i d the psi base psi d is equal to psi d just divide it by see remember per unitizing is simply normalizing the equations, the original equations are not changed of course, they are simply you divide both left hand side and right hand side by the same value. So as long as we are consist, we do this consistently and mathematically, correctly there is no there will be no error, so psi B psi base.

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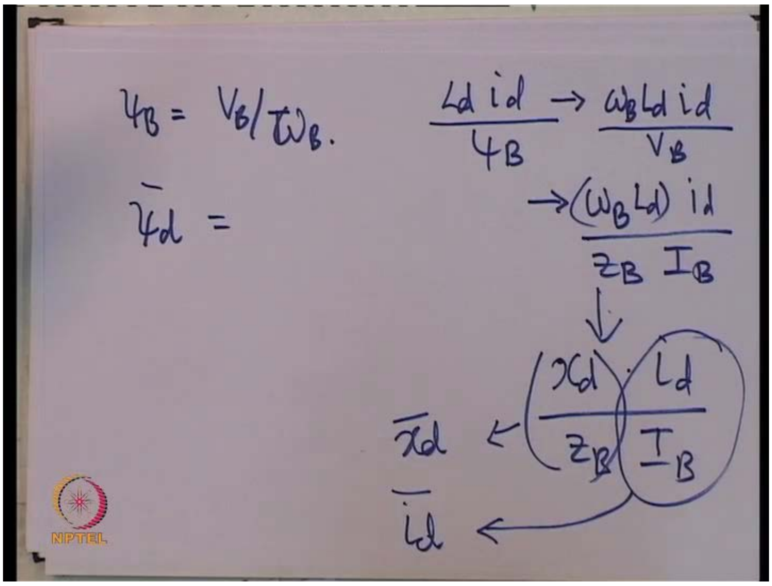

But recall that, psi base psi base is equal to V base V base by omega base, so what we have is now psi d bar is equal to L d i d divided by psi base will be yes, so it will be omega B L d i d divided by V base, which is nothing but, omega B L d i d into z base into I base, V base is nothing but, z base into I base. So, you will get from this this will be effectively x d into i d by z B into I B, so this is essentially x d, x d is a reactance and this is i d bar.

So, actually I will not write down all the terms, what if you look at the screen here.

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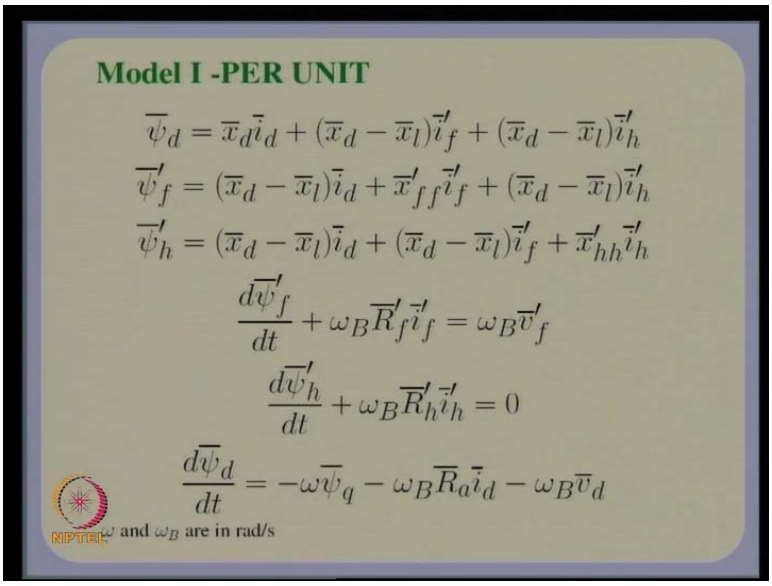

You will find that the first equation gets, become like this the second one obviously is going to be this way, so everything is in per unit this, over line over all the variables indicate that it is in per unit, so what about the differential equation.

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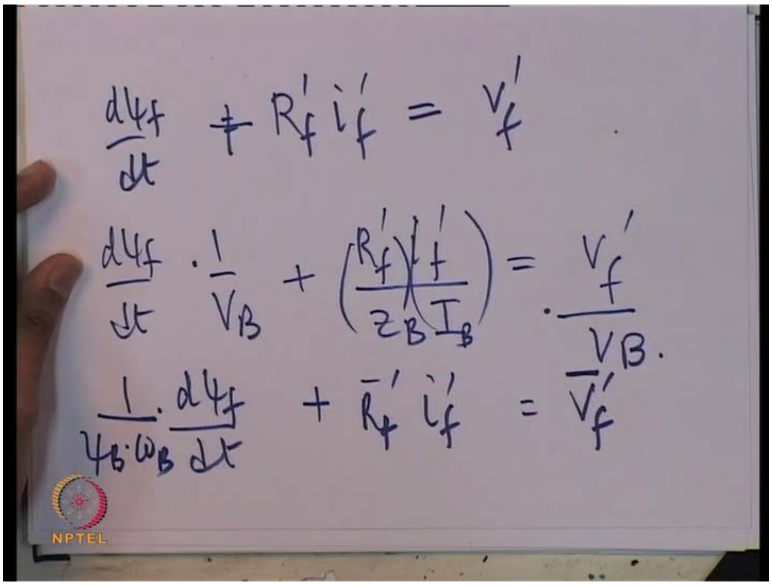

The differential equation if you look at for example, you have d psi f by d t is equal to this is the original variable R f dash sorry is a plus R f dash, i f dash is equal to V f dash, this is what we got these are in terms of the actual variables; now if you divide both sides by V base you will get d psi f by d t 1 up on V base plus R f dash i f dash V base is nothing but, z base I base so ill decompose it into this, is equal to V F dash up on V base. So, this becomes equal to V f bar over this over line or bar over bar actually denote that, this is in per unit this is R f bar i f bar, because this is per unitize and this becomes d psi f by d t and you know V base is equal to psi base into omega base.

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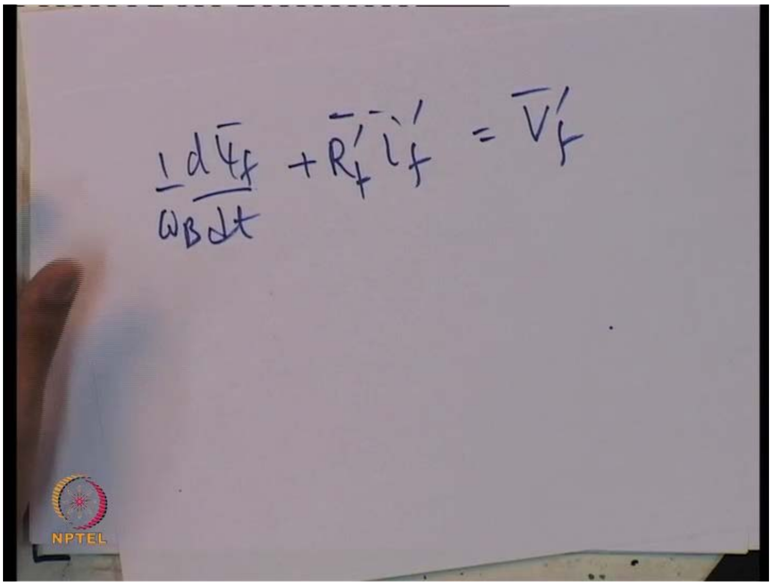

So, what you get eventually is d psi F bar by d T 1 up on omega B plus R f dash bar i f dash is equal to V f dash, so you multiply both, mean you multiply uniformly by omega B and if you look at the screen here, this equation becomes d psi bar dash f by d t plus omega B into R f bar dash into i f dash bar is equal to omega B into V f dash bar; remember that in, this as a important thing, that in these equations you can get you can per unitize all the equations.

Similarly, I will not go through all per you know writing down everything in per unit but, remember, that in these equations wherever omega B and omega appear they are in radian per second everything else in this equation, in these equations are in fact in per unit. So, omega B and omega in radian per second but, everything else in this equations are in per unit, this is an important thing we should you should remember.

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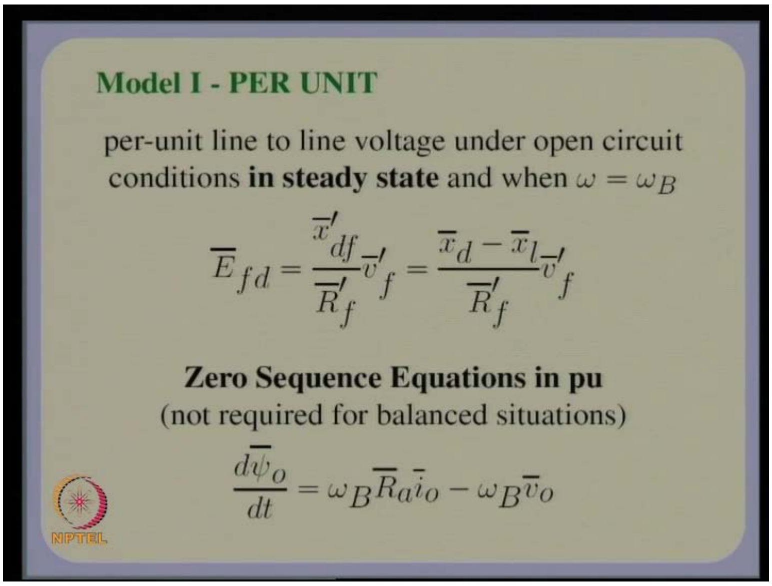

Often in our studies we do not directly, you will not be given what v f dash is, what is usually specified v f, that is a kind of an input for these equations, v f dash directly is not specified what is usually specified is, what is known as E f d bar. E f d bar is the per unit if you look at the screen is the per unit, line to line voltage under open circuit conditions in steady state and when the speed rotational speed of the machine is equal to the rated speed.

So, often what is done is that when you are analyzing a machine, no you will not be told what the field voltage v f bar is but, what will be instead told to you is that v f bar is such that, it yields so and so voltage under open circuit condition in steady state, when speed is equal to omega v.

So, often what people do is they specify E f d bar and not specify v f bar but, they are interrelated by this relationship, so it should not be difficult to actually get v f bar, so of course, if you know v f bar that sorry v f bar dash, you can get v f bar v f dash by using the base value of voltage v B. And once you get v f dash can you get v f well you can get v f, the actual voltage in volts, which is applied to the field winding if you know alpha F. So, alpha F has to be an extra data, which need to be given to you, if you want to actually know what the field voltage is going to be but, usually all our studies will be will be contained with being given only these, the value of E f d, E f d bar in fact or the per unit line to line voltage, under open circuit conditions in steady state and when omega is equal to omega B this is the open circuit voltage.

So, in let me repeat in most studies, you will not be too concerned in most studies, you will not be too concerned about what V f dash bar is you will be directly, rather I would not say you are concerned with you will be the voltage will be E f d will be specified to you not V f dash bar E f d bar is usually specified.

But this relationship if you keep in mind, there is no ambiguity and you will know what exactly we are talking about of course, all throughout our discussion, we have been neglecting zero sequence equation, assuming that machine is going to be operated in balance conditions, this is not necessarily so; none of our you could have situations where machine is not operating under balance situations, in that case of course, if you if you need to use it the equations of a the zero sequence equations are given.

So, the model I in the q axis is again looks like this, it looks very similar to the d axis, so the q axis, this is the d axis per unit model, E f d is usually specified E F d bar is usually specified the per unit value of the open circuit voltage. In fact, what I should say here is the per unit line to line voltage, which would have existed under open circuit conditions in steady state and when omega is equal to omega B, this is what is specified E f d bar is this the voltage, open circuit voltage, which would have existed.

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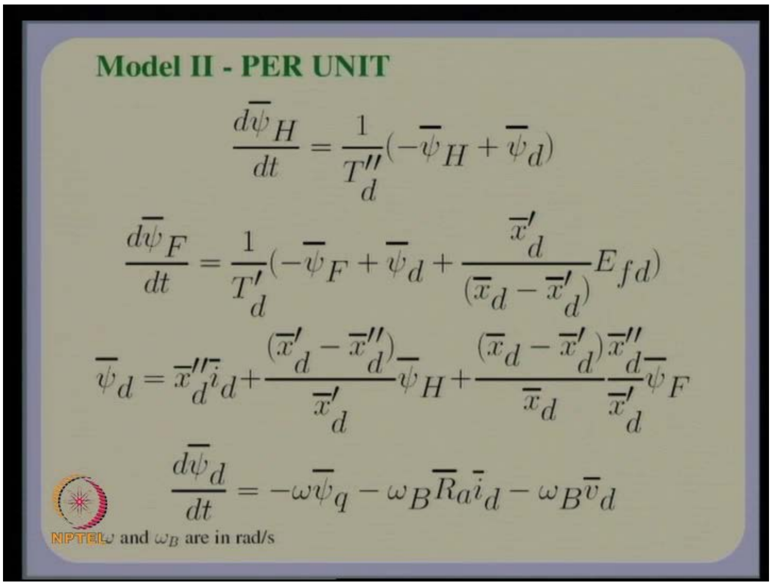

Model I per unit q axis is given by this way, if you look at model II, model II looks like this, it is not difficult to obtain it from the original model II equations the actual values, we can get the per unit model in this fashion.

Again if instead of E f d in these equations actually, there is a mistake here, this E f d in this equation the second differential equation, E f d should be replaced by E f d bar, so there is an error here.

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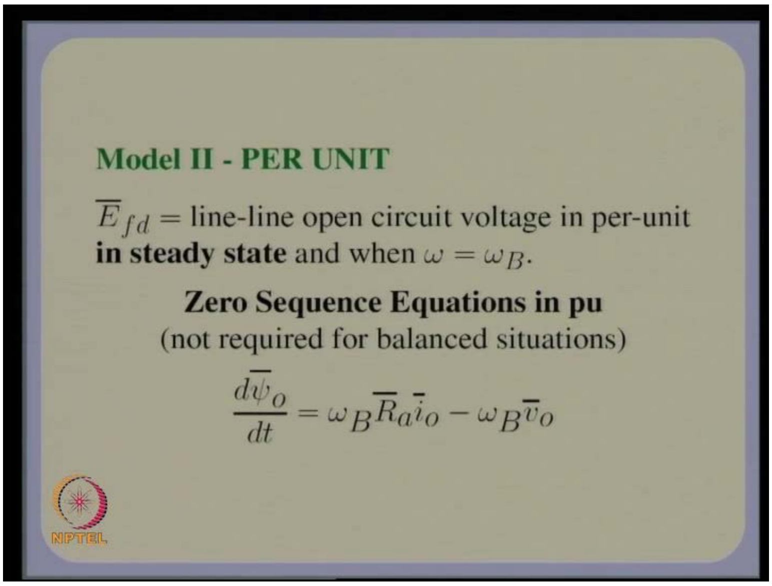

E f d bar it is a per unit value E f d bar is the line to line open circuit voltage in per unit, which would have existed or the line to line voltage which would have existed, under open circuit conditions in steady state, when the machine is rotating at omega is equal to omega B, again we have got the zero sequence equations per unit.

So, let me repeat model II looks like this, the input to this model is of course, are of course, v d bar and E f d bar E f d bar is the field voltage v d bar is the d axis voltage applied to the d axis winding, E f d bar again let me repeat the second equation should read, should use E f d bar not E f d this should be E f d bar and E f d bar is the voltage which would have existed under open circuit conditions, the line to line voltage in per unit under steady state and when omega is equal to omega B.

So, this model uses E f d bar not E f d this should be E f d bar and E f d bar is in fact the field voltage but, specified in an indirect fashion, remember that under open circuit conditions the voltage which appears across the stator winding is directly proportional to the field voltage and then the speed.

So, specifying E f d bar is is acceptable because it is a kind of a the voltage which would have existed under open circuit condition, so we know effectively what V F bar is, V F bar dash is, so any way. So, model II per unit of the q axis looks like this, it is quite straight forward there is no input field voltage input here, these are just damper windings.

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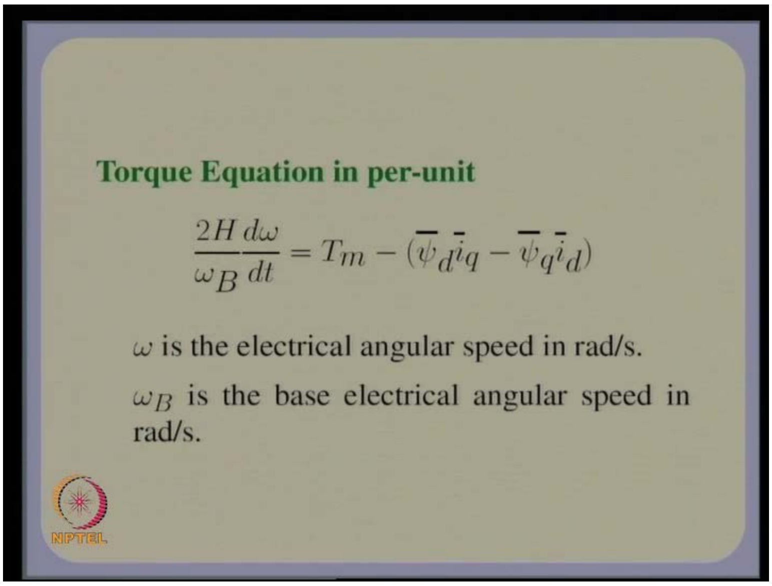

Now, coming to the torque equation, recalls that our equations the equation which we have used do far.

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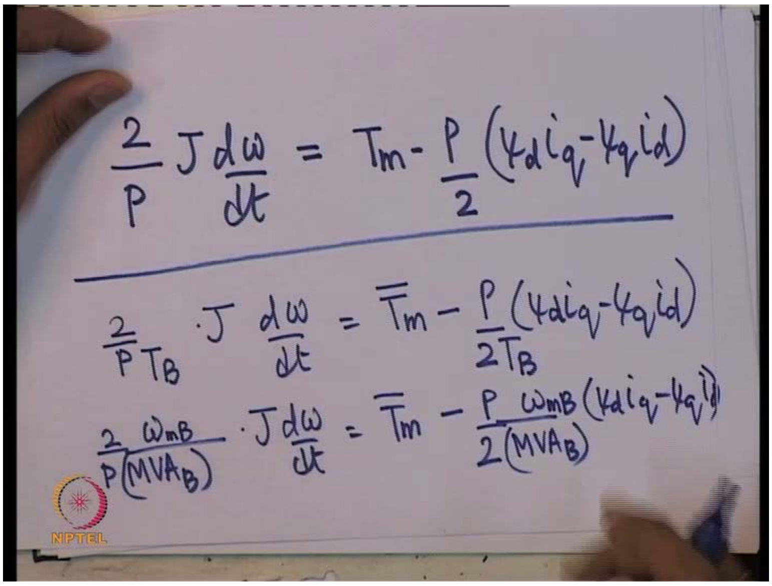

Is if omega is the electrical frequency in radian per second, this is the torque equation omega, here is of course, the electrical speed the electrical speed in radian per second, so if you want to write this down in terms of per unit. So let us, divide both sides by torque base, so you will get 2 by p torque base J d omega by d t is equal to T m bar minus p by 2 torque base psi d i q minus psi q i d and torque base is nothing but, M V A base mechanical speed base; M V A base divided by mechanical speed base is torque base, T m bar is of course, not the base speed base torque p by 2 M V A base omega mechanical speed base psi d i q minus psi q i d.

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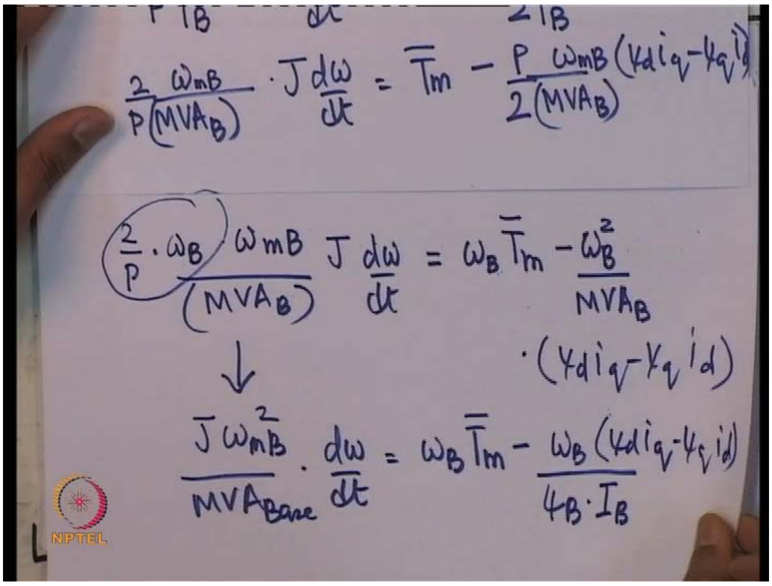

So, if you keep this like this, you will get 2 by p, you multiply both sides by omega omega base, so you will get 2 by p into omega base into omega m B by M V A base into J d omega by d t am multiplying both sides by omega electrical base, omega base T m bar minus, this is omega square, because p by 2 p by 2 omega B is omega B and you am also multiplying omega B on both sides into psi d I q minus psi q i d.

So, this becomes J see if you look at this this omega mechanical base square by M V A base into d omega by d t is equal to omega B T m bar minus, I will write this as omega B M V A is nothing but, voltage base into current base and voltage base is voltage base divided omega base is flux base; so I will call this, becomes flux base into current base into psi d i q minus psi q i d.

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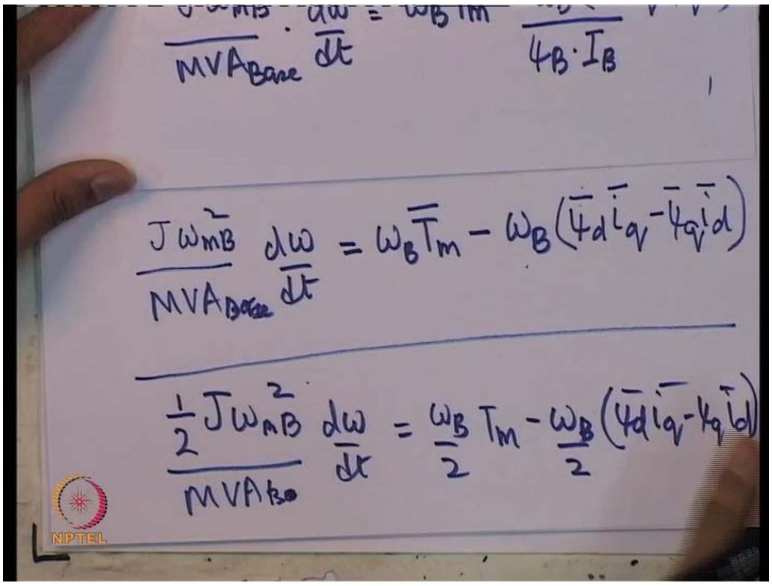

So, what you get eventually is J omega m base square by M V A base d omega by d t is equal to omega B T m bar minus omega B and since psi d i q is here and you have got psi B into i d effectively this gets normalized into per unit in per unit form, so you will get i q bar minus psi q bar i d bar.

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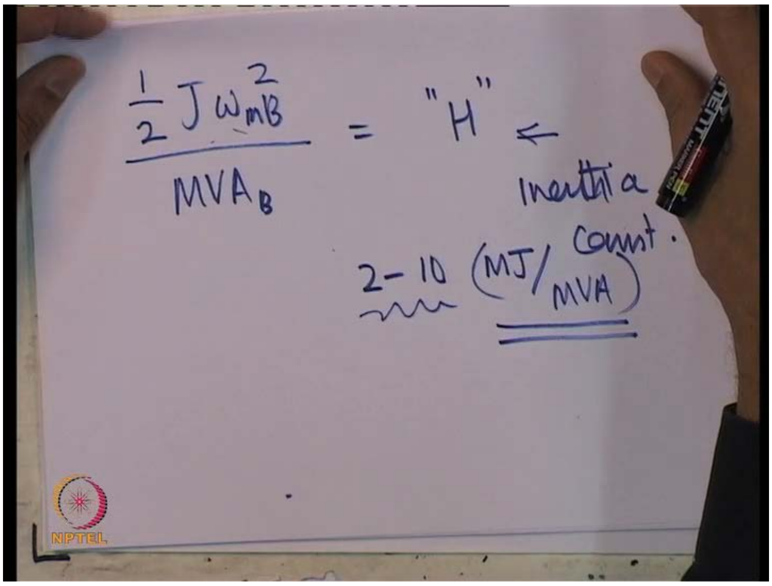

Now, what is usually done is we if we multiply both both sides by half again, we will get half j omega m B square by M V A base ops it goes down here, base base omega base d omega by d t is equal to half omega B by 2 T m minus omega B by 2 psi d i q minus psi q i d bar these are all in per unit.

So, this is in per unit form the whole equation in fact half j omega m B square, this is the mechanical base speed rated mechanical speed square M V A base is a quantity which is known as the inertia constant is H, for a wide typically inertia constant and it is typically for machines could be between 2 to10 the units of course, are mega joules per M V or you know seconds but, this is the more evocative use M j mega joule per M V A.

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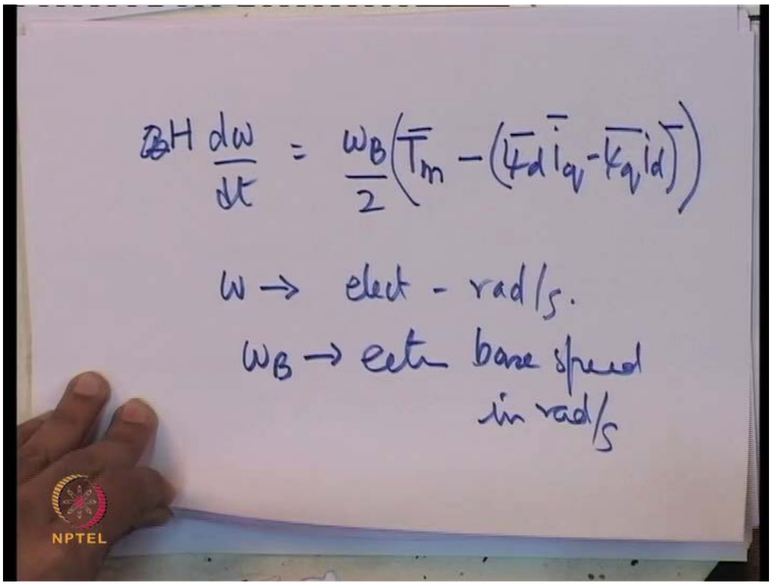

So, this is the typical value of H, so H is nothing but, this kinetic energy you can say under rated speed conditions divided by the M V A base, so our equations become we can rewrite these equations 2 H, what we get is H d omega by d T is equal to omega B by 2 T M bar. In an earlier equation I forgot to put this bar here, this these are the equations of the machine omega remember is the electrical speed in radian per second, omega B is the electrical base speed in radian per second, everything else that is T m here, other than this is actually in per unit.

So, what we have here is the equation, torque equations in per unit 2 H by omega B, I will just rearranged the equation, if you look at these what I have written down, just rearranged everything 2 H by omega B by d t is equal to T m omega B and omega R in fact in radians per second.

Now, to conclude before I conclude this lecture, I end this lecture let me point out one important thing what we will do now, in future is use model II you have in fact derived model A, model I and model II you can use any of these three models, all are based on standard parameters. Model A requires the standard parameters but, effectively requires T d c double dash also and the standard parameters and it it is terms of fluxes; which or it is in terms of state, which cannot be easily related to the original states model I is a model is in which the state rotor flux states; which are the states which are used, the rotor fluxes, which are used in fact are some kind of referred fluxes it involves an approximation it is a very popular model used in the literature.

Model II is also uses distinct approximations, the different approximation but, it is also a valid approximate model you can use it there is no issue, the good thing about model II is directly you can write down the equations in terms of the standard parameters, you do not have to do this extra back calculation step. So I will be using model II in all the studies hence forth but, remember that you can use model I or model A as well model A of course, requires T d c double dash, model I and II do not require T d c double dash, T c in fact model II you can show effectively assumes that T d c double dash is equal to T d double dash, that is what we just mentioned, when we saw the proper T’s or rather the effect of the approximations we are making.

So, if we assume T d c double dash is equal to T d double dash, you can use model II the states used there are approximately for example, the rotor states used there are a approximately proportional to the original states, the proportional by some proportionality constant alpha upper case F and alpha upper case H.

So, we can use model II it is a convenient model to use but, in books, in other books and in the literature often people use model I, so do not get too perturbed too both of them involves certain approximations, we have written down the equations of both models in per unit I have told you how to obtain the parameters of model I model II is directly in terms of the standard parameters.

So, do not feel uncomfortable or you know do not get too perturbed, if you find in some book they are using exclusively model I, you can use model I also both of them involves certain approximations. Model I as well as model II, model A will require T d c double dash and another problem is that the states there cannot be directly related to the original flux, the rotor flux states; so directly I mean it is not an easy easy proportionality relationship of course, there is a relationship.

So, let me just put this to summarize the model which will be used in all for future discussions, will be as follows this is the model II in per unit, one of the things which I have done here now, is remove all the over bars. So, this is the per unit model but, just for notational simplicity and you know, otherwise you will keep for getting put put these over bars but, this is implicit in this model that everything is in per unit except omega and omega B which are in radians per second.

So, I have removed the over bars for notational simplicity, except omega and omega B which are in radians per second all other fluxes currents and voltages are in fact dimensionless they are per unit in per unit. E f d is the voltage which would have appeared under open circuit conditions, across the line to line voltage, so instead of specifying the field voltage you will be directly giving E f d.

I have removed the over bars and this is per unit model, so I will be exclusively using this model but, remember I have discussed the other models too, especially model I, which is which is the model which is most often seen in the literature and model A, which is which is in fact appear very much in the literature.

So model I and model II are the two models, which you can use if given the standard parameters of course, remember if somebody gave you all the inductances and resistances directly, you would not have to worry about using these models, you could have used original model in terms of basic parameters directly but, in our discussion remember, we will be using model II which is per unitized as shown here.

So, with this we conclude our discussion of the modeling of the synchronous machine it has been a bit tedious but, you can go back through through the previous lecture, once or twice and I am sure you will get everything clear in your mind. One important point which you should remember in any kind of modeling especially modeling, which you are able to identify transfer functions, by measurement the coefficients of transfer functions or the time constants or gains of transfer function from measurement that, there is no unique steady state space model which you can derive. Of course, if your measurements give you adequate number of parameters, you could be able to derive the state model which you desire in terms of the states which you desire.

But in synchronous machine unfortunately, you will be given standard parameters which will enable you to get a model, which effectively gives you, which is in terms of in some faces the referred states, referred onto the stator side. So, these are the referred states and the parameters of course, are the what are known as the standard parameters so with this this with this statement, let me conclude this particular lecture, in the next lecture, we start really looking at the consequences or the inferences which can be drawn from the equations of a synchronous machine more very importantly you will be able to understand how one may you know do a short circuit analysis of a synchronous machine, what is the responses and we can really start building up the base for doing a realistic study; so, with this we will conclude this lecture.