Power System Dynamics and Control
Prof .A.M. Kulkarni
Electrical Engineering Department
Indian Institute Of Technology, Bombay

Lecture No: # 13
Modeling of Synchronous Machines (Contd.)

In the previous class we derived voltage equations of a synchronous machine. In fact, we applied Faradays law and we got the relationship between voltage and fluxes. And of course, the relationship between fluxes and the currents also we tried to get the relationship. In fact, that relationship is the inductance matrix which turns out is position dependent that is theta dependent. Remember, an important thing is that theta is continuously changing in a synchronous machine. So, that inductance matrix is time dependent, it is dependent on the theta position.

Now, in today's lecture what we will do is the lecture is continuation of the modeling of a synchronous machine. We will introduce you to a transformation of variables called the T q transformation or parks transformation. In the previous lecture, we kind of concluded at a point where we derived the equation of torque in terms of the current; we will just redo that again at the beginning of the lecture just to refresh your memory and I will introduce the transformation which I just mentioned. Now, if you recall what we did last time for the mechanical equations of a synchronous machine.

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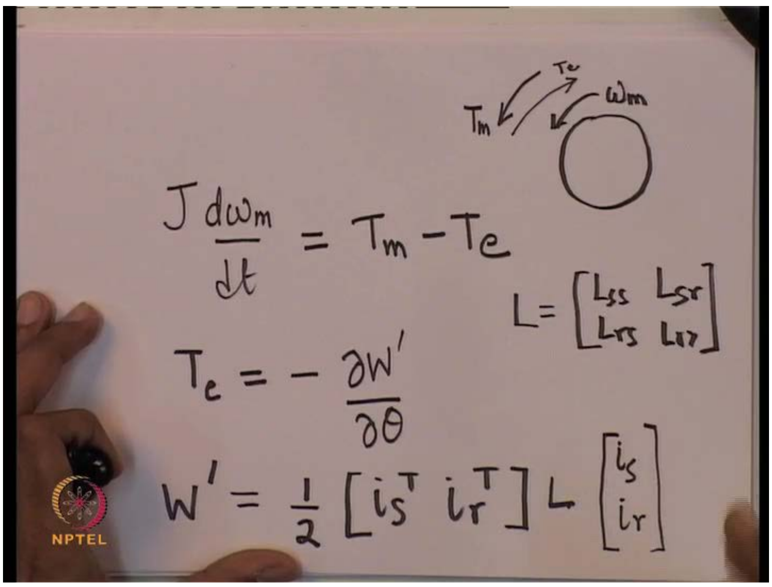

So, if you have got a synchronous machine moving in this direction with the mechanical speed of omega m and it has got electromagnetic torque which of course, opposes the motion, and the prime over torque T m. So, if you look at the equations of this system you have J is the moment of inertia in kg meter square. So, this is the well known equation which describes the rotation.

And the electrical torque the basic electromagnetic energy conversion formula tells you the electromagnetic torque is given by partial derivative of the co energy with respect to theta. So, the torque in this direction and remember theta is measured in the anti clockwise direction. So, in that case you have this. So, the co energy is of course, the function of the currents. So, when I take the partial derivatives I should take the currents constant. The co energy is defined as half of i s transpose i r transpose; i s and i r are the L inductance matrix of the system. We already derived what is L matrix is in fact, the three of its sub matrices are functions of theta. So, L is made out of sub matrices L s s, L s r, L r s and L r r; out of which L r r is not theta dependent, but all the rest are theta dependent. So, this is what we have done before; i s remember denoting the status current, i r is the router current.

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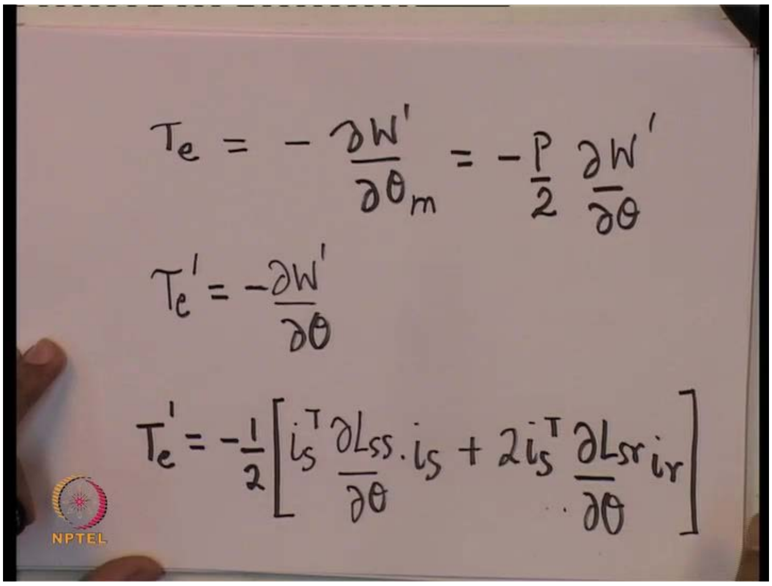

Now, T e which is nothing, but minus d omega dash by d theta. In fact, only for the two pole machines remember that the correct formula in general is T e is negative of the partial derivative of d w dash is the co energy with respect to the mechanical angle. So, please remember that this is the mechanical angle.

Of course, when we derived L, it is a function of theta where as this is theta m. So, just remember that. So, what we have is theta m which is nothing, but minus P by 2 d w dash by d theta. Now, if we define T e dash to be equal to minus of this we can show of course, that your T e dash will be equal to minus of half i s transpose. And as I mentioned last time, you would not find L r r coming in these equations because the partial derivatives of L r r with respect to theta will be equal to zero. And we have already made an observation that L r s transpose is equal to L s r. So, we just get one of them you know this simplifies to this.

So, this is what we did last time; we got a torque expression for T e dash.

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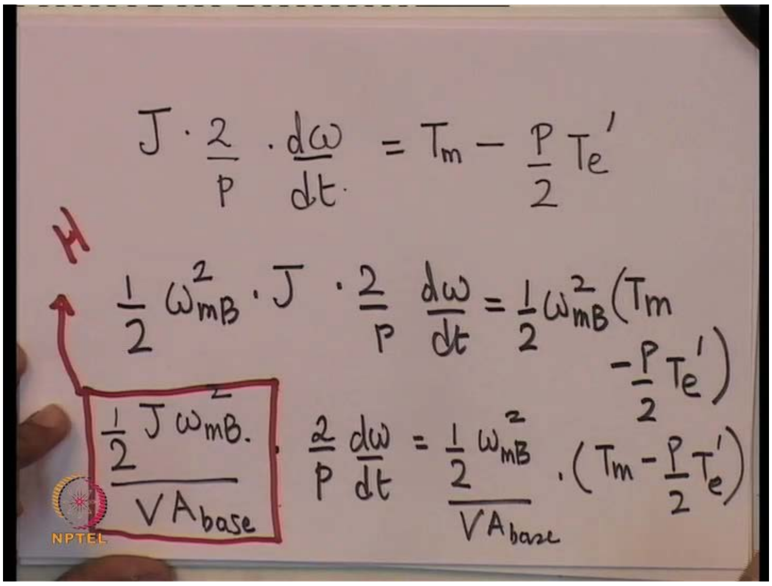

And once you of course, do that you can write your equations as J into d omega m by d t. Just again one small point which I wish to emphasize this is the angular speed. So, you can write this as 2 times p times the rate of change of electrical speed is equal to T m minus T e which is nothing, but this is basically what we have and remember T e dash is this.

So, we have got the relationship between the currents and the torques. So, In fact, just to correlate something we have done some time back. Let me just multiply both sides by half omega m square. So, I will do half into omega m the base value of the speed or the rate value of that speed into J into 2 by P d omega by d t. So, I have multiplied it there; is equal to you multiple this side also.

You will get half of omega m B square into T m minus P by 2 T e dash. Now, what I will do next is divide both sides by the volt ampere base of the machine. Remember, omega m base is the mechanical base frequency; angular frequency. So, it is usually the rated mechanical angular frequency of the machine.

So, that is one thing which you should remember. So, actually if you divide by volt ampere base you will get half J omega m B square divided by volt ampere base into 2 by P d omega by d t is equal to half omega m B square by volt ampere base into T m minus P by 2 T e dash.

Now, a few things this is what is commonly known as H or the inertia constant of the machine; and it is units are joules per volt ampere or mega joules per mega volt ampere. So, this is called the H of the machine. So, you have basically if you look at this particular equation I will rewrite it.

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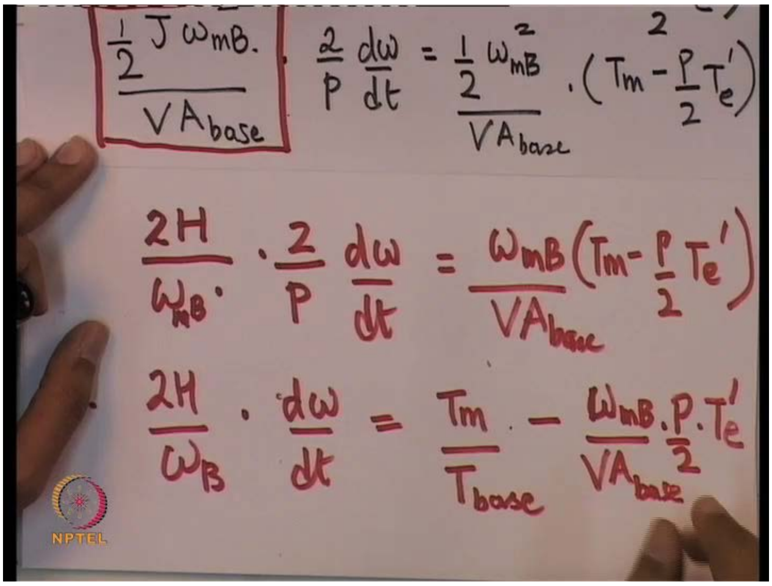

So, you can actually write it as we will get 2 times H you get his two onto this side.

Two times H I got this 2 onto this side; I will take one of these omega m B is out of this side into P into d omega by d t is equal to omega m base divided by volt ampere base into T m minus P by 2 T e dash. If you actually look at how these omega m mechanical base into P divided by 2 would actually give you the electrical radians per second base value. You will have 2 H by omega base; omega base is the radian frequency base value of the machine.

If you look at this, it is the mechanical torque base. So, you have got T m is the mechanical torque divided by the torque base of the machine minus what you have is I will get rewrite it here. So, that it becomes easy what I am doing base into P by 2 into T e dash; just check if it is volt ampere base into P by 2 into this.

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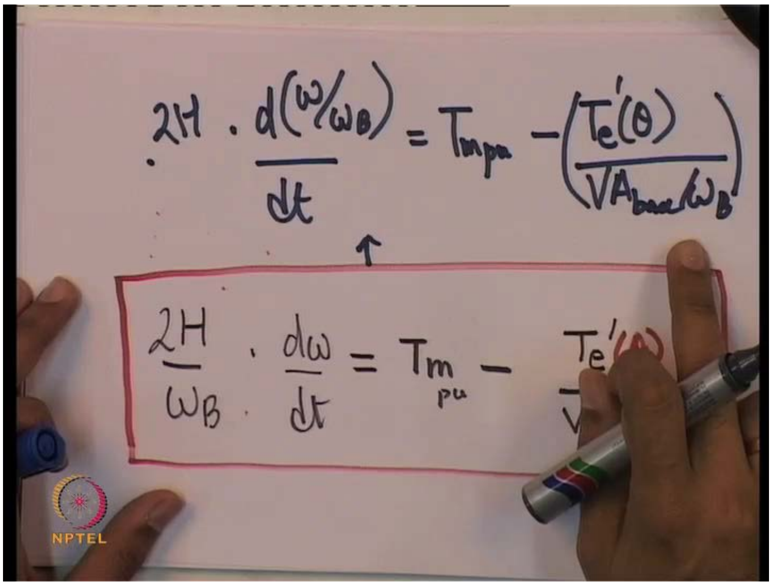

Finally, what we get is the torque equation of the machine is 2 H by omega B into d omega by d t is equal to T m per unit minus T e dash divided by volt ampere base divided by omega base; the electrical base. So, this is the final equation of the torque of the machine. In fact, you will note that T e dash will be the function of theta, you know the inductance matrix will be actually functions of theta whatever we have derived earlier functions of theta.

So, in fact, if you look at the interesting thing about the number of poles, it does not appear in this equation. So, when you write this thing per unit you will not find the number of poles. In fact, we will express this T e in terms of fluxes and the currents and the inductance is the function of theta volt ampere base and omega B, but you will not get P exquisitely. Actually, when you go to the per unit system normally you can actually be blind to the number of poles working into the per unit system.

Of course, if you actually want to get the mechanical speed; if you know the electrical speed then you do the required the number of poles. So, that is of course, something which you should remember. In fact, you can write this 2H into d omega by omega B. So, in fact, I call this as a per unit equation; everything is in per unit.

Rather we have not really this T is not in per unit, but divided by volt ampere base by omega base. So, eventually of course, after sometime I will show how everything in this also can be expressed in per unit. So, this is the final equation we used sometime back in our earlier lecture that this is the original of this particular equation.

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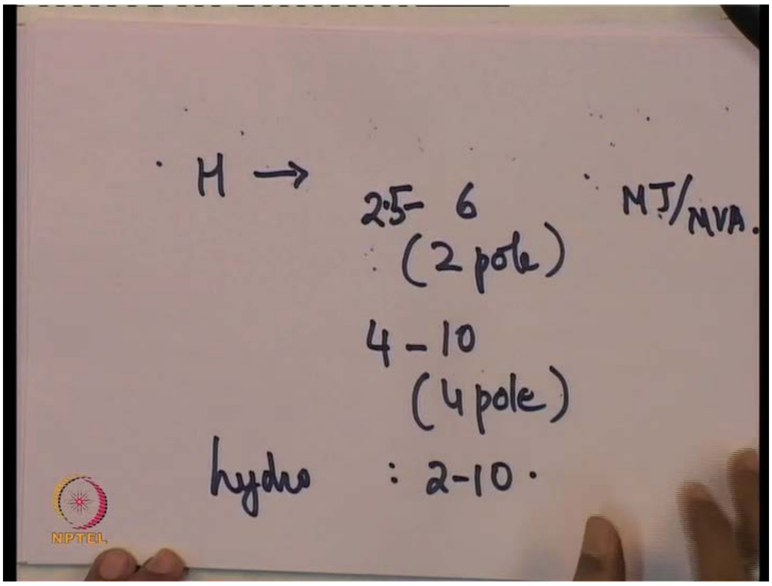

Now, moving on a bit of course, move on let me tell you know the typical values of H for at thermal unit can be between 2.5 to 6. This is of course, for a two pole machine these values I have taken form Kundurs book for a four pole machine. And for hydro units it is usually 2 to 10. And of course, I have not written the units they are mega joules per M V A or joule per volt ampere.

So, the unit of H is mega joule per M V A. Now, one of the things if you recall the equations of the synchronous machine you will get the rate of change of flux is you know dependent on v.

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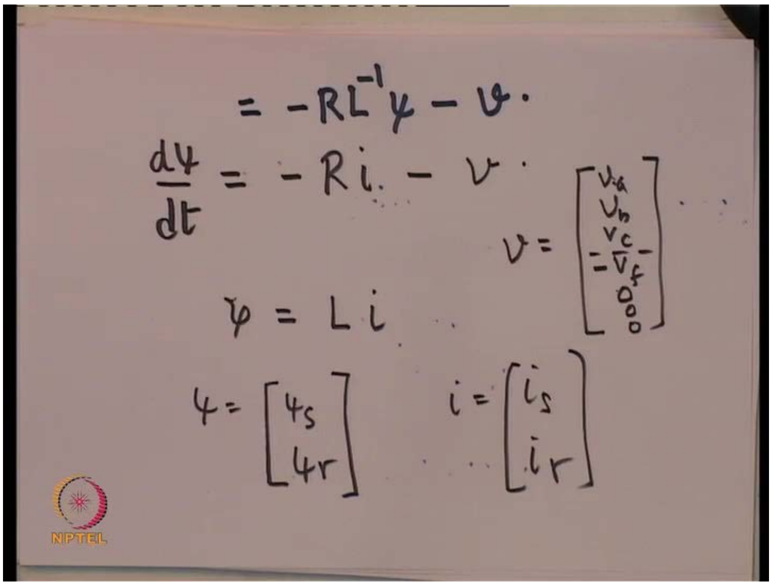

In fact, if you recall the formula which we had written last time;the general form is d si by d t is equal to minus R into i minus v and if you recall si was nothing, but L into I; si is of course, made out of si s and si r and i is also made out of i s and i r; and v is nothing, but v a, v b, v c then minus v f is made out of the rotor end state voltages zero zero zero.

So, this is something we did in the previous class. In fact, you can replace instead of writing it as this way; you can replace this by minus R L inverse si minus v. So, the only complication when we are trying to solve this equation is this actually looks like a linear equation.

Even if you assume that rate of change of theta is a constant, speed of a synchronous machine is constant. Remember that this L will be time varying. In fact, if you just look at these flux equations they are linear time variant equations. So, if I want to get the solution of this particular equation, well I cannot use directly the Eigen analysis techniques to solve this equation.

Again I repeat this inductance matrix is time varying, it is not a linear time invariant system; it is a function of theta. Even if you assume that theta rather the speed of the machine is constant still you will get a time variant set of equations. So, that is why it will be good to see how you can explore ways to analyze this.

Now, one of the most powerful ideas which have you used before is to use the idea of a transformation. We have used transformation; transformations is like analyzing a system x dot is equal to a x; we tried to find out the transformation which would diagnolize the matrix. The idea was of course, diagonal matrix implies there is no coupling between the states.

So, if I have got x dot into diagonal matrix into x, there is no coupling between the coupling states and you can easily get the solution in terms of the exponential functions. Now, here we can use again the idea for transformation, but right now we limit ourselves to try to make these time variant set of equations into time invariant set of equations. So, what we will do is try to get a transformation of variables. So, that we will get this as our objective. Now, of course, how do you get the transformation? What I will do is introduce the transformation directly and see what its consequences are; i am not going to derive the transformations for you.

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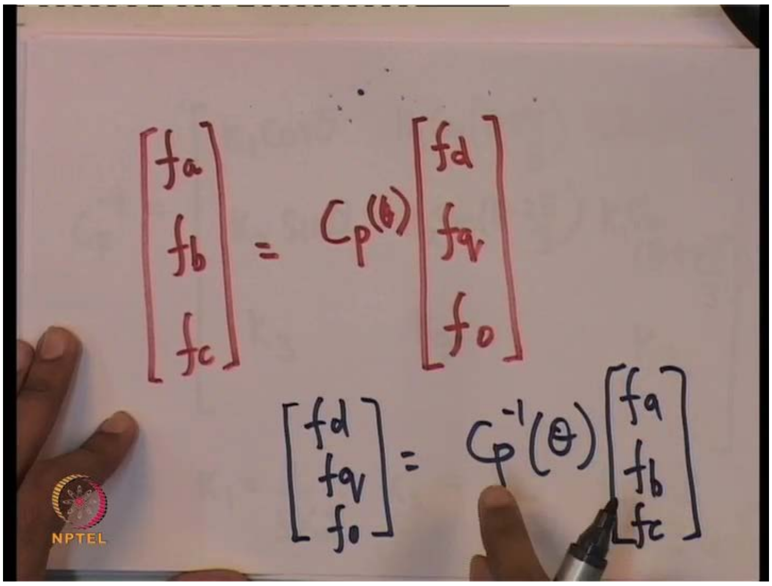

So, just let me introduce it to you directly without any further delay. This transformation is called parks transformation. So, instead of looking at the differential equations in the variables i a, i b, i c or v a, v b, v c or si a, si b, si c; this f could denote any three phase variable; I will look at the variables f c, f q and f 0 using the transformation C p, this is a matrix which is dependent on theta.

So, that is an important point you should keep in mind. Now, what is this transformation? Of course, this whole key is what is this transformation? It turns out that this is really a very useful transformation.

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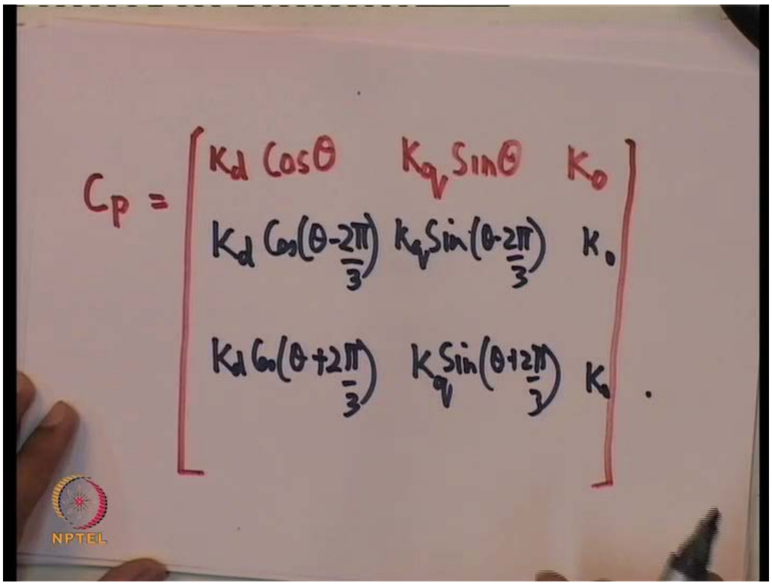

So, C p is equal to I will just define these transformations; it is a three by three matrix. Something you may have guessed that I am applying transformation only to a b c variable and not to the field you know d, f and j variables. In fact, the a b c quantity we are applying this particular transformation. Now, in fact, just recall it is just the interesting correlation which you should recollect the currents on the router become constants in steady state; where as you know those currents in the stator or voltage in the stator or three phase sinusoids. In fact, for balanced condition we get three phase balanced sinusoids.

So, if I am going to try to make what do you call in a time variant set on equations one can kind of guess very intuitively that you have to apply transformation only to the a b c variables. So, indeed that is the case. So, this particular transformation which I am going to talk about actually is applied only to the stator variables a b c variable. So, the interesting thing about the transformation even without going further is that it is inverse

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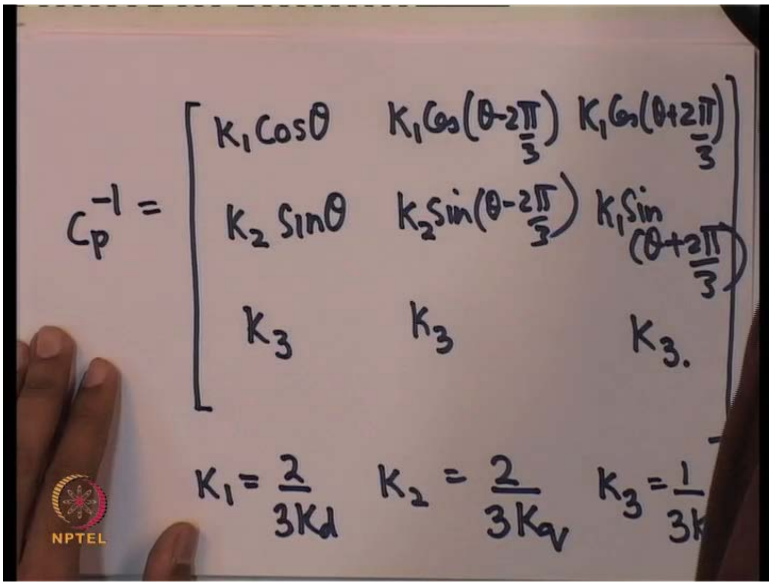

C p inverse always exists unless you choose K d, K q, K 0 you know any of them zero. So, K d K q and K 0 are non zero then you can actually get a transformation C p inverse which is we is we find like this. It has this form K 1 cos theta plus 2 pi by 3; we will show this side. This is K 2 sine theta minus 2 pi by 3 K 3 and K 1 sine theta plus 2 pi by 3; this is K 3. Where K 1 is equal to 2 by 3 K d; this is something which you can work out I am not working out for you, but in fact, one simple thing you can do is just multiply C p and C p inverse and just verify that it is actually giving an identity matrix. Note that there is a minor error here; the two three component of C p inverse should be K 2 and not K 1. C p inverse comes out to be this. Why we need C p inverse? The point is whenever we need any kind of transformation analysis remember that if I define a transformation of variables, if we want to know what the old variables were eventually I would need the inverse transformation.

So, in fact, f d f q and f 0 is equal to C p inverse theta. So, actually a transformation makes sense only if you can go back and forth between the old and the new variables. So, it is important that C p should be invertible, but it turns out the C p is actually invertible unless you choose K d, K q and K 0 is equal to zero. So, C p inverse turns out is invertible. Another interesting thing you will notice before we go ahead is that the structure of C p an C p inverse looks similar; I mean if you look at the structure of C p and C p inverse, look at C p this constants along this columns sine thetas along this cos theta here of course, the constants are K d, K q and K 0 whereas, if you look at this the cosine functions are here; the sine functions are here; this is constant.

So, you can guess that for some you know the structure it looks like transpose C p inverse. In fact, for special values of K d K q and K 0, this is indeed true. So, for you actually let you out one this K d K q and K 0 is root two by three and K 0 is 1. So, if K d is equal to root two by three and K 0 turns out to be one by root three. In that case, C p will be equal to C p transpose. So, that is one important result which you should keep in mind.

Some special values of K d and K q, C p transpose and C p inverse are equal. Now, the main utility of the transformation can be seen if you look at the transformation of flux linkages.

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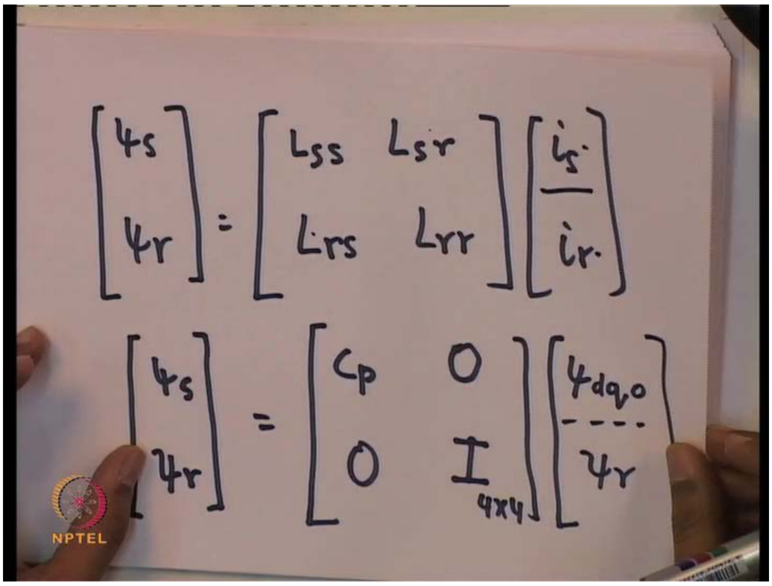

For example, if you have got you know we have done this before si s and si r is equal to these are functions of theta. Now, if I use a transformation remember I only have to transform the stator fluxes and the stator currents.

So, suppose I define as before this is three by four matrixes full of zeros and this is an identity matrix I; this is four by four identity matrix; si I will call this d q and 0 and si. So, what I am doing is I am not transforming si this is just say si r is equal to si r I am just transforming si a si b si c into si d q zero. So, that f variable I mean I have applied whatever transformation to flux si a si b si c. So, if I define a transformation of this kind in fact, similar transformation can be applied to i s and i r.

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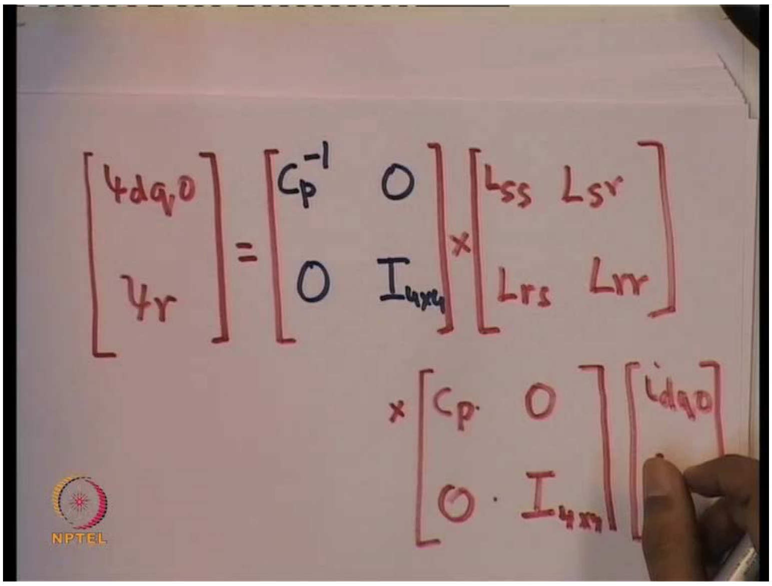

So, in that case it is easy to see that the final equations relating si d q 0 and si r and i r are si d q zero si r is equal to L s s, L s r, L r s and L r r into C p matrix is zero zero and this is identity matrix of size four into four into i d q 0 and i r. So, what I have actually done is I have replaced i s and i r by this i d q and i r. So, i s and i r is equal to C p into i d q 0; i r is equal to i r. So, I have just replaced this by this then you have got L r r, then you have got this L matrix. So, I will just repeat what I said; I have replaced I s and I r by this. Then of course, L s s, L r r also comes here well show this again. So, this is what we get and of course, we get C p inverse here zero zero I four into four matrix. So, actually if you get it to this side you get si s into si r. So, basically what I have done is I have taken this equation here you have got a b c a b c this has been replaced by d q zero here. So, what you need to do is of course, I will re write this well get

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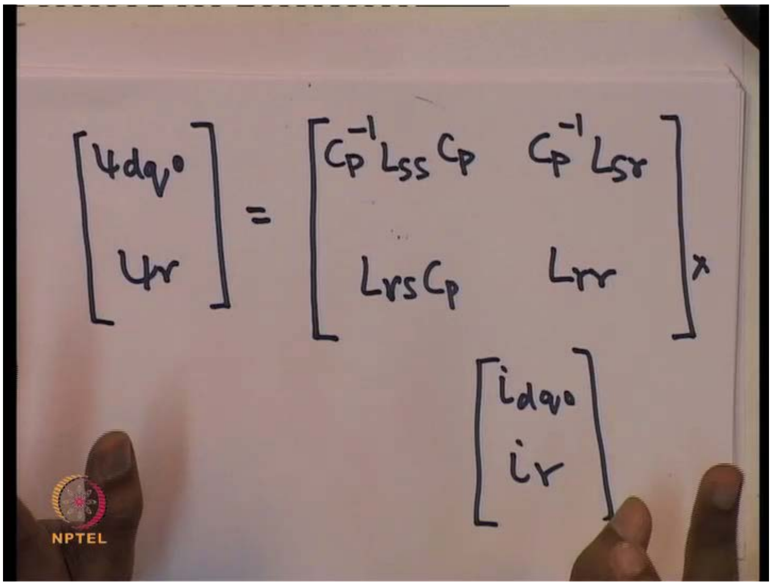

Si d q 0 si r is equal to finally, C p inverse L s s C p, C p inverse L s r L r s into C p and L r r into this is multiplied by i d q 0 and i r. So, this is what we get finally. Now, let me just give a sneak preview of what we are going to get? What we intend is we intend to get try to see if this is actually not going to be function of theta. So, what we are trying to do is see the relation between i d q 0 and si d q 0 i d q 0 and i r; and si r and i r. Now, a nice thing it would be nice to find if all these terms came out to be independent of theta. So, in fact, let me just try to show it at least for one term for example, if I want to do I will just show it for one term I request you to go and do it for each and every term.

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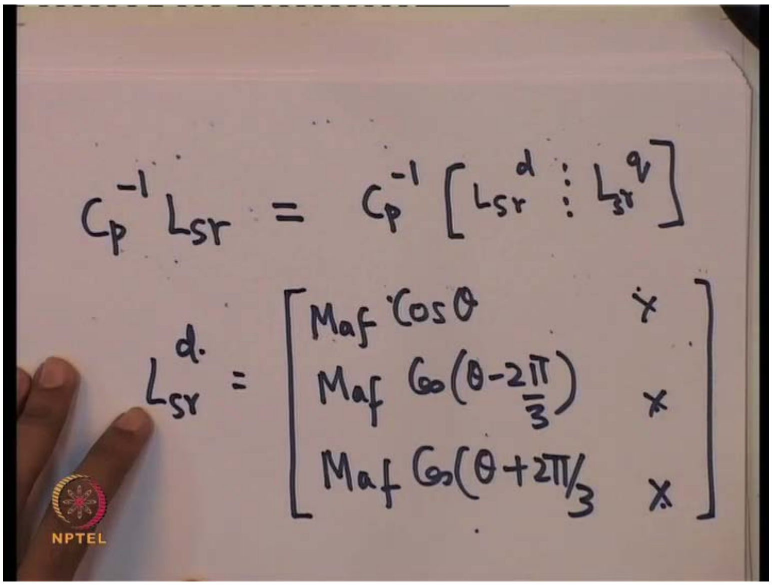

So, what it turns out is that for example, C p inverse L s r. So, let me try to compute this. So, what do you mean by L s r recall what L s r is L s r is C p inverse; please look into sometime what we did last class L s r is equal to L s r transpose this is nothing, but L r s. If we partition this into two parts L r is d L r is q L r is this as this form and L r s d has this form. So, for example, if I use C p L s r d and L s r q. So, if I actually apply this transformation what is L s r d? I will just write it down again M a f cos theta, M a f cos theta minus 2 pi by 3, M a f cos theta plus 2 pi by 3 then you have got another column; I will not write down that column this is nothing, but L s r d.

So, in fact, there is another column I have not written it down. So, you have got terms here and here also. So, if I do C p inverse of L s r d you know what C p inverse is? This is what C p inverse looks like have a good look at this because we need to fit all our manipulations on a small sheet of paper. So, if you have got C p inverse into L s r. So, C p inverse into L s r d; I am not showing the derivations for all terms I will just showing it for one term. So, you do C p inverse into L s r d.

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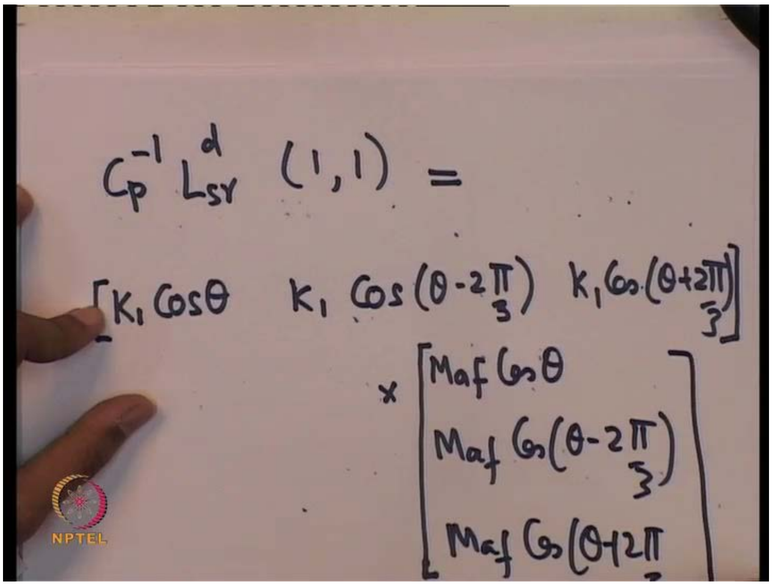

The first component of C p inverse L s r d that is one one component you can easily find out that it will be basically the first row of C p that is K 1 cos theta K 1 cos theta minus 2 pi by 3 and K 1 cos theta plus 2 pi by 3.

So, the first term of this complete matrix is nothing, but the first row of C p matrix into the first column of L s r d. So, the first column of L s r d is M a f cos theta, M a f cos theta minus 2 pi by 3 and M a f plus cos theta 2 pi by 3. So, if you multiply these two you will get the first term of this. I am just doing it only for the first term; I hope you will be follow up on the other terms.

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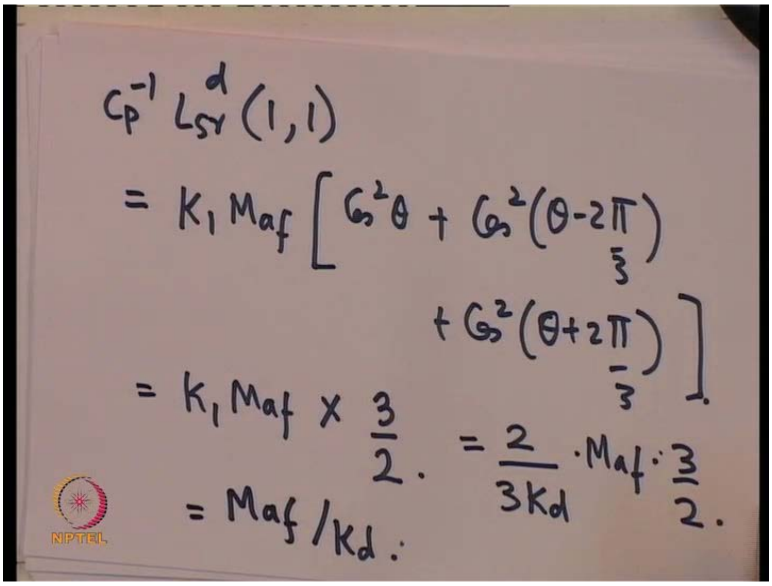

So, what you will get if you that will be C p inverse L s r d the first term is nothing but I will just work it out; you will get K one which is going to be common.

M a f which is going to be common and you will get cos square theta plus cos square theta minus two pi by three plus cos square theta plus two pi by three. So, what you have got is this is the first term of C p L s r d. So, remember just before you lose track; let me just recall what we are doing? This is the final relationship between the d q fluxes and d q currents and of course, the router currents. This has to be evaluated remember that C p is the function of theta; L s r, L r s, L s s are functions of theta.

What I am just trying to show you is the derivation of one term that is first term rather the one comma one term of this matrix. And I leave of course, the computation of all other terms to you as an exercise; so, I will just do it for one term. So, that term comes out as to be K one M a f into what should it be? Now, this you must have learnt trigonometric identity cos square theta minus cos square theta minus two pi by three cos square theta plus two pi by three is a constant. In fact, it is equal to three by two. So, what we find here effectively is that the first term is this. In fact, we have already defined what K 1 is; K 1 is nothing but two by three into K d; K d is of course, defined in the transformation C p into M a f into three by two. So, what you get is a very convenient kind of number that is equal to M a f divided by K d.

So, this is the first term of this matrix. So, let me just show it this to you again. So, what we are doing is we have got the first term of this. In fact, it is not a function of theta right M a f by K d, it is the constant.

So, it turns out all the terms of this matrix are in fact, not functions of theta. So, that is one very interesting effect of this transformation. So, if I look into the flux and current relationships in these new variables in the d q variables you will find that. In fact, they are not functions of theta.

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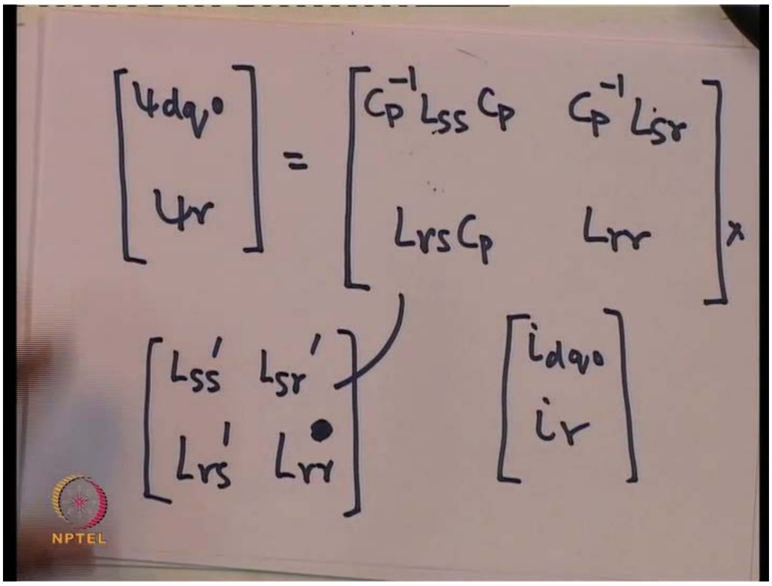

So, if you look at this particular matrix here I will just may be call it some name; let us just say it is terms are L s s dash; this is L s r dash, L r s dash and L r r dash of course, L r r and L r r there is no dash here; this is simply L r r, because L r r does not get transformed at all. Then it turns out that all this sub matrices are in fact, not functions of theta.

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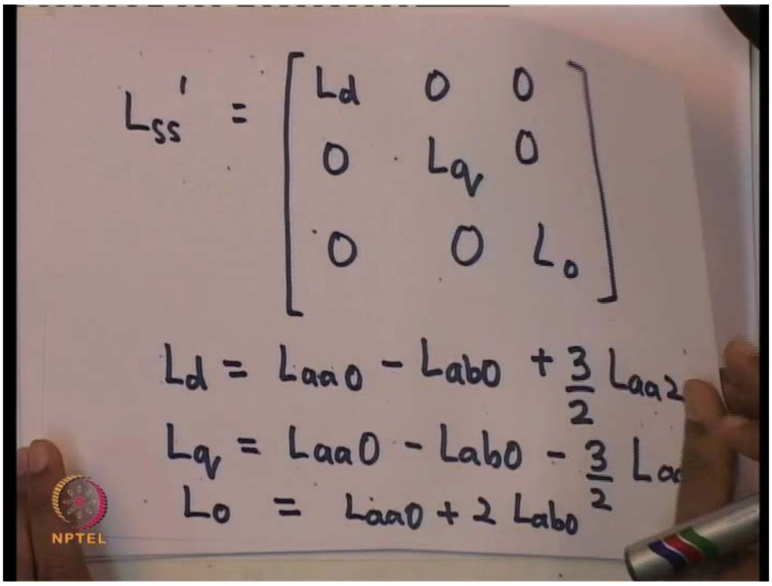

So, an interesting if you really sit and derive it you will get L s s dash is equal to in fact, it turns out to be a diagonal matrix where of course, L d is nothing, but written in terms of the what I can call as the primitive parameters L a a zero, L a b zero plus three by two L a a two. What are these L a a zero, L a b zero etcetera? Please recall that our L s s was made out of you know this L a a two, L a a zero's and L a b zero's; this whole L s s matrix was made like this.

So, L s s dash which is the relationship between the transformed flux and currents are in fact, related by this and L q is equal to L a a zero minus L a b zero minus three by two L a a two and L zero is nothing, but L a a zero plus two L a b zero.

What you notice here? Of course, if L a a two is equal to zero; L d and L q are equal. So, in fact, when does this occur this occurs if there is no saliency? So, in fact, L a a two will become equal to zero if there is no saliency. So, what you get is L a, L d and L q will become equal of course, in general it is not true because this is non zero.

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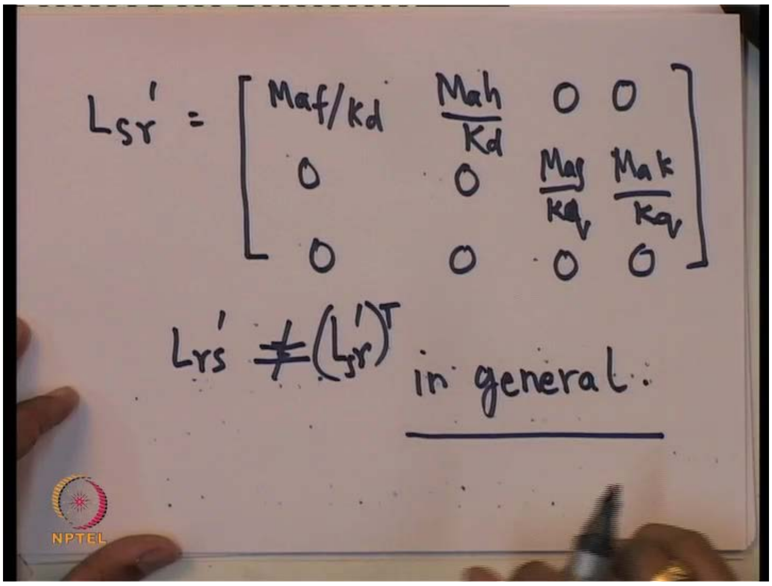

So, one of the important things are it is not only time, it is not a function of theta; L s s is not a function of theta, but it is also diagonal. So, that makes it very neat. Similarly, L s r dash is nothing, but M a f by K d, M a h by K d, zero and zero and you will have zero M a g by K q, M a k by K q and zero zero zero and zero. And L r s dash is equal to L s r dash transpose. In general, it is not that is one interesting point.

So, all though L r s and L s r are transpose of each other; this is not true in general. I should show you that it can be made true if you for a certain choice of K d and K q. So, in fact, I have not defined what K d and K q are. So, they are just arbitrary constants.

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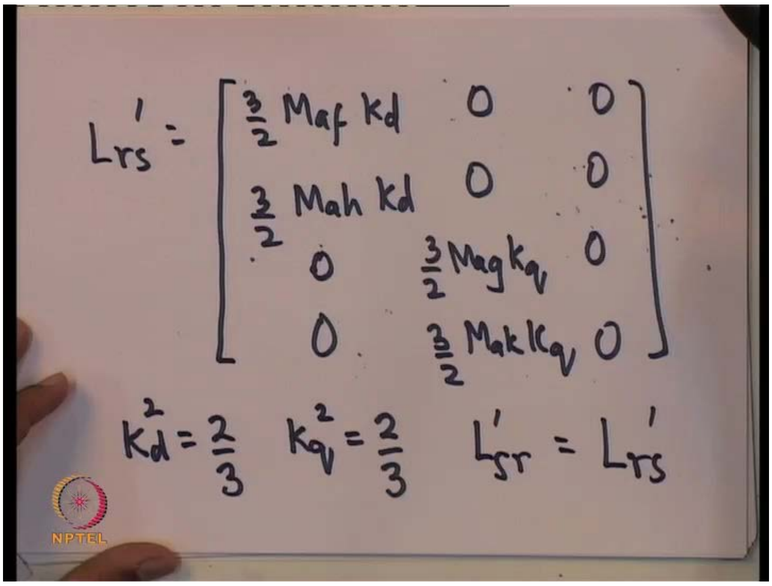

So, actually L r s dash turns out to be three by two times M a f K d and three by two times M a h K d and zero zero zero zero; three by two times M a g K q and three by two times M a k K q; and this becomes zero zero zero zero. So, if you look at this and this, it is not true in general.

So, in general this and this will not be true; they will not be transpositions of each other, but if I choose K d, K d square is equal to two by three and K q square is equal to two by three. In that case only it turns out that L s r is equal to L r s transpose.

So, this is special values of K d and K q. So, of course, one thing you should see right away that L s r dash and L r s dash are not functions of theta; that is something which you should immediately see.

And L r s dash is equal to L s r transpose dash only if for a certain values of K d and K q. Now, you should recall just remember that the fact that the relationship between si and i is not dependent on theta; si d q zero, i d q zero is not dependent on theta; is not affected on what value of K d and K q or K zero you use?

So, this value of K d, K q and K zero whatever value you choose except zero of course, if you chose it as zero you will not be able to invert C p. So, in that case whatever I am saying is not true, but any non zero value of K d and K q will lead you to this relationship matrix; this is the inductance matrix in the d q zero variables which is not a function of theta. So, what value of K d K q you chose or K zero you chose does not alter the fact that by using this transformation you can get flux and current relationship which is not dependent on theta. So, that is one important thing which you should keep in mind.

I have not actually derived all the terms of this matrix, it can be quite tedious. But remember, that in case I encourage you to sit and derive every term of this matrix I just showed you the derivation of the first term of L s r dash, but you can actually take out the whole matrix which is in fact, a seven by seven matrix which has 49 terms from first principles and you actually obtain the expressions for each element in that matrix.

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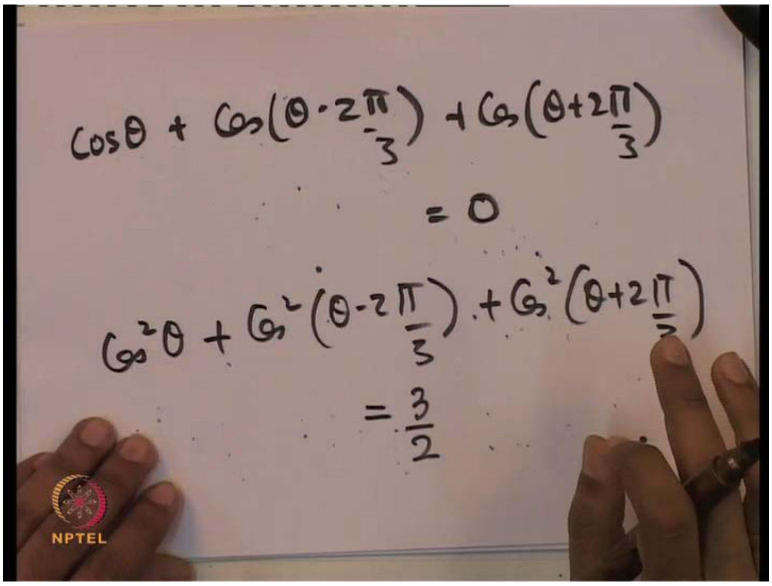

In fact, what will help you in doing that would be the trigonometric identities cos theta plus cos theta minus two pie by three plus cos theta plus two pie by three is zero. Similarly, sin theta plus sin theta minus two pie by three plus sin theta plus two pie by three is equal to zero and cos square theta plus cos square theta minus two pie by three plus cos square theta plus two pie by three is in fact, a constant not dependent on theta equal to three by two; the same applies if you replace this cos by sin.

So, these are the four in fact, if you take the sin identities also these two cosine identities and the corresponding sin identities will help you to get all the terms in this matrix; and you will see that they are not functions of theta. They are functions of K d and K q and for special values of K d and K q you can ensure that the L s r dash and L r s dash are transposes of each other.

So, what we really see is we have applied the d q transformation this called the park's transformation or d q transformation matrix. And what we have achieved here is make the flux and the current relationships in the d q zero frame independent of theta.

Now, of course, that does not end our work is to look at also the differential equations as defined by Faraday's law. So, what were the differential equations of our machine?

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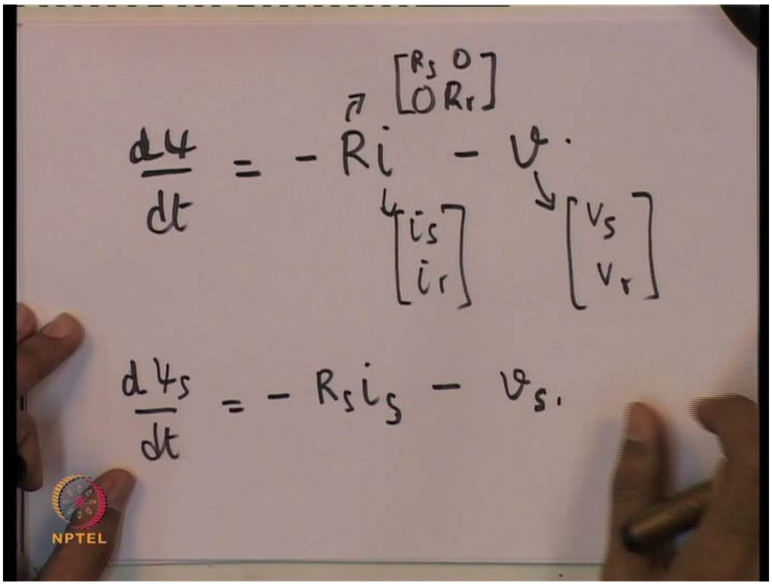

In fact, there were d si by d t is equal to minus R i minus v. So, that was our equation. In fact, this is a composite equation I told you that this i is nothing, but i s and i r. So, this is i is nothing, but i s i r; v is nothing, but v s and v r and so on.

So, if I just write the stator equations there will be d si s by d t is equal to minus r s i s. In fact, R is a diagonal matrix consisting of R s and R r. So, you will get R s i s. So, I can write the component I mean this is actually I am just writing down the stator equations minus v s.

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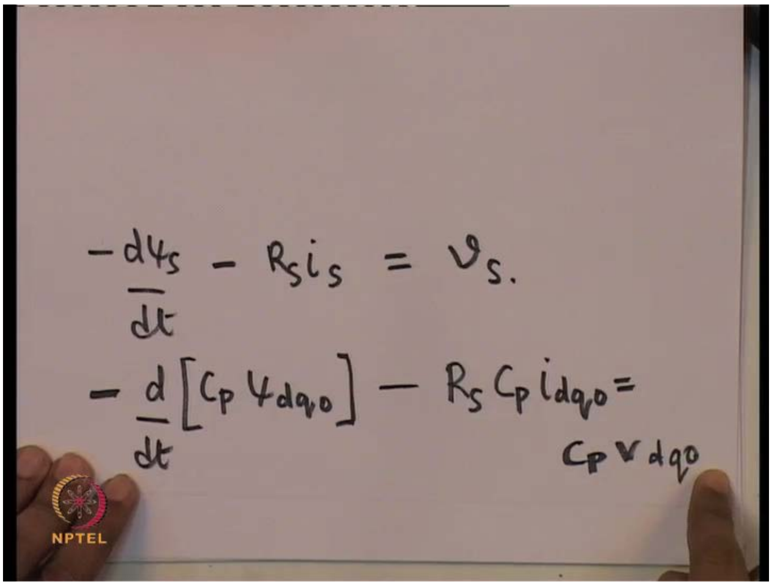

So, if I apply suppose if I want to write these of these are of course, derived in a b c frame of reference. So, these are a b c variables. So, if I will rewrite these equations first I will write it as minus d si s by d t minus R s i s is equal to v s.

So, I can rewrite this as minus of d by d t of C p times si d q zero minus R s into C p times i d q zero is equal to C p times V d q zero. So, all a b c variables are converted to the d q zero variables. So, I will just read out this is C p into V d q zero; this R s into C p into i d q zero; C p is a matrix, R s is a matrix.

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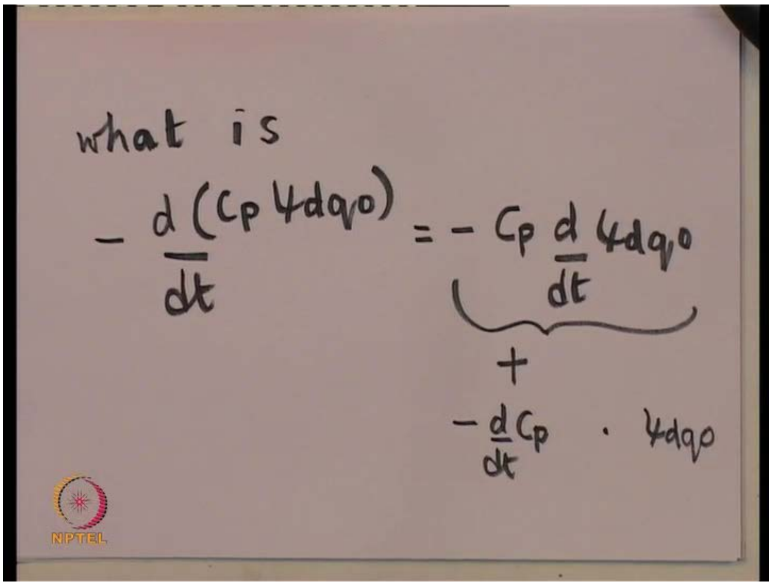

Now, before we do further manipulations one interesting point which I need to emphasis here. What is minus d by dt C p si d q zero? It is nothing, but minus of C p times d by d t into si d q zero. No, it is not correct. Remember, that C p is also a function of theta. So, the correct expression would be this minus of d by d t of this C p itself into si d q zero.

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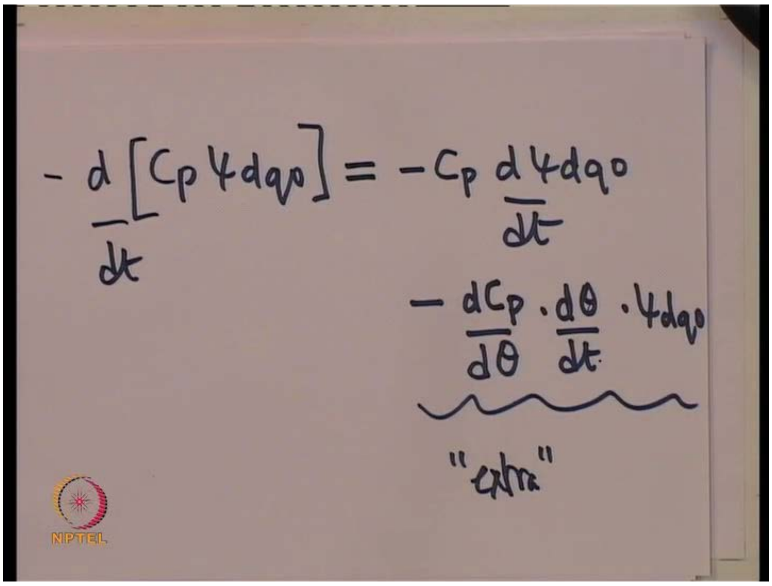

So, what you will get is I will just rewrite it minus d C p si d q zero; just remember that you have to just take into account this is equal to minus C p into d si d q zero by d t minus d C p by d theta and then do d theta by d t; and this is multiplied by si d q zero.

So, what we have this last term which I wrote down here you know will be equal to this last term of the previous equation will be equal to this. So, what we get is the final relationship which we get is this d theta by d t is the electrical speed of this machine.

So, the key difference between what we have done the transformation which we have used before and now is that it is a time dependent transformation; this is dependent on theta. Theta itself is dependent on time; because it is a rotating machine, theta is continuously changing it is a function of time. So, what we see is that when you are taking the derivative of C p into si d q zero we have to take the derivative of the transformation as well.

This was not the case when we did use the linear time invariant systems with constant transformation matrix; this is not a constant transformation matrix. So, you get this extra d theta by d t term when we take this derivative. So, this is some kind of you know extra term or extra speed dependent term which comes as a result of applying a transformation. In fact, one important point which you should note is that if we consistently and correctly apply the mathematics you get this term. In fact, it cannot be reasoned out you know why we get a speed dependent term in the differential equations when you do the transformation cannot be reasoned out in any other way than mathematically.

So, although one can try to give what is known as a physical interpretation to the d q transformation, it is a good idea to first how first of all work out all the mathematics correctly and then interpret what we are getting.

So, let me just again repeat when you apply a time variant transformation like C p on a differential equation; remember that you will have to take the derivative of the transformation itself and as a result of the transformation derivative of this transformation C p, you get speed dependent term which also called the speed e m f. So, we will continue of course, with this derivation we are coming to the close of the basic modeling of a synchronous machine, but still we have a few things to work out. So, we will work out those things in the next class.