Advanced Electric Drives
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Lecture – 12

Hello, welcome to this lecture on Advance Electric Drives. In the last class we were discussing about the air gap flux oriented vector control of indexing motor. We have seen that in air gap flux oriented vector control of indexing motor, the torque and flux are not inherently decoupled, in fact they are coupled. So, if we want to vary the torque by changing the torque component of current, the flux does not remain constant, so we will discuss more on this topic today, that is air gap flux oriented vector control of indexing motor.

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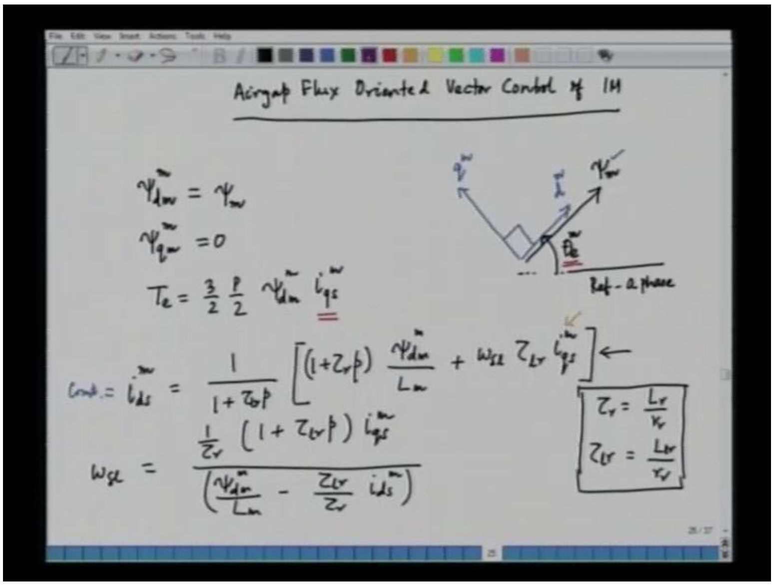

Now, we have already seen that in air gap flux oriented vector control, the d axis of the reference frame is oriented along the air gap flux vector. So, what we do here is the following, that this is the reference axis, reference of phase a of the indexing machine, and let this be the air gap flux vector, and that we symbolized by psi m. And what we do we orient our d axis along the air gap flux vector, this is our d axis, and we call this to be d m and the q axis is right angle to the d axis.

This is the q axis and we call this to be q m, and due to this we can see that the angle between the reference f s, and the air gap flux vector or the d axis of the reference frame is theta e m. So, this is the angle of the reference frame theta e m, theta e m is angle between the air gap flux vector and the phase a axis. Of course, the air gap flux vector is rotating in the space with synchronous speed, we must understand that in an indexing machine all flux vectors are rotating in synchronous speed, that it be rotor flux vector or air gap flux vector or the stator flux vector.

However, the angle of the flux vector with respect to phase a axis is not the same, they all rotating synchronously in the space, the relative velocity between all of them in the steady state is 0, but they sustain different angle with phase a axis of the machine. So, this angle that is the angle of the air gap flux vector is theta e, which is different from the angle of the rotor flux vector, and what we do here we have oriented the d axis along the air gap flux vector.

So, due to this special orientation, what we obtain is the following that psi d m, the air gap flux in the d axis in the reference frame oriented along the air gap flux vector, that is equal to psi m is the total air gap flux. And psi q m in the air gap flux reference frame is equal to 0, because in the q axis there is no component of the air gap flux, if we project this psi m this is our psi m along this q axis, since this angle is 90 degree psi q m will be equal to 0.

So, this is what we have seen in the last lecture, and due to this we can see that we have something like decimation like torque equation, the torque equation that, we have seen T e is equal to 3 by 2 into p by 2 into psi d m into i q s f. And this equation reassembles that of a decimation torque equation, and we can control the torque either by controlling i q s or by controlling psi d m or the air gap flux in the d axis. However, we would like to keep the flux constant, because it is known that if we change the flux, there will be delay the flux cannot be changed immediately, there will always be a delay accompanied by the change of flux.

So, we would like to keep the flux constant, and we would like to change the torque by changing the torque component of current, this is call the torque component of current. But, we will see actually in the last lecture, in fact we have already derived this equation, and we have seen that when we change the torque by changing i q s the flux is also change.

So, in face psi d m and i q s in the air gap flux reference frame are coupled, they are not decouple variable although they 2 are in 2 different axis, they are mutually coupled if we want to change i q s psi d m is affected. So, we will just rewrite the equation that we have derived in the last lecture, so in the last lecture what we have obtain is the following, that i d s m is equal to 1 by 1 plus tau r p into 1 plus tau r p psi d m by L m plus omega s L tau L r into i q s.

And here tau r is the rotor time constant, that is equal to L r by r r and tau L r is the rotor leakage time constant, that is equal to L l r by r r. So, this we have already seen in the last lecture, so if we see this equation, this equation if we see now in this equation, you can see this suppose we would like to keep psi d m constant. Now, if we want to keep psi d m constant, if you want to keep this flux constant let us say, and we can change the torque by changing the torque component of current, say for example, we would like to change this quantity.

Now if you change i q s we have to also change i d s, i d s can no longer be constant, we have to change i d s to keep the flux constant. So, in other words if we want to change the torque, you should also change i d s in association with the change in i q s, to ensure a constant flux, so this has to implemented to ensure that that is a decoupling between the torque and flux. So, although there is no inherent decoupling, because if you do not take care, suppose you would like to in this case say for example, you would keep this constant. Let us say we do not vary this, if we assume that this is constant, let us say and we go on changing i q s.

Now, if i d s is constant, and we change i q s ((Refer Time: 08:32)) psi d m will no longer be constant, this shows there is a coupling between i q s and psi d m in the air gap flux reference frame. To cancel this coupling what we have to do, we have to change i d s when we change i q s to control the torque. Now, this is one of the equation, the second equation that we derive to the equation for slip speed, the equation for slip speed that we have obtained in the last lecture, was omega s L that is equal to 1 by tau r into 1 plus tau L r p into i q s m divide by psi d m by L m minus tau L r by tau r i d s.

So, usually when we want to transform the d q variable into a b c variable, in this case the variables are in air gap flux reference frame, we have to use a angle of transformation. We have to transform the variable in the d q frame into the actual variables in a b c frame, and in this case the transformation angle is theta e m, that we have already discuss that this is the angle of the transformation.

So, this angle of the transformation has to be obtain, and to obtain this angle of transformation we have to find out the speed of the air gap flux vector, in the speed of the air gap flux vector is omega e m. And obtain this omega e m we have to have a knowledge of the slip speed, and omega e m is obtain in the following fashion, you want to find out omega e m that can be obtain by adding the slip speed with the rotor speed.

The rotor speed can be measured using an encoder or a speed sensor, and the speed can be calculated, we can calculate the slip speed using equation, and if we add this two, we get the speed of the air gap flux vector. And integration of that will give us the angle of the air gap flux vector with respect to the stationary phase a axis, and this angle can be use to transform the d q variable, in the air gap flux reference frame to the physical variable of the machine that is a b and q.

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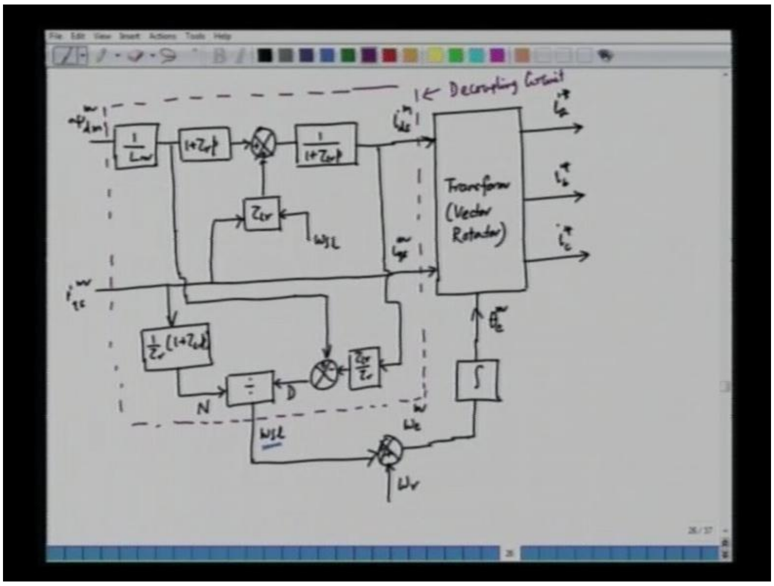

Now, you will see that how we can implement that in case of a block diagram, so we will take an block diagram q, so this can be implemented, so what we have here, we have to use a transformation. This is our transformation block, in which we can feed our i d s m and i q s m, now this we can call transformation block, sometimes is also call vector rotator, because it rotate the moving variable in the stationary variable. And then the output of this would be the current physical current, so this is i a star, i b star, i c star, the reference current of the machine, the 3 phase machine.

And to have this transformation we have to use the transformation angle that, we are just discussing in the transformation angle is theta e m, but how to obtain i d s m and i q s m. I q s m is the torque component of current that can be obtain from a torque controller, so this can be obtain from the external source, so we can obtain this i q s m, but obtain i d s m we have to take the help of the flux.

So, we have to keep the flux constant, so what we do here we have psi d m and psi d m we can divide by L m, so what we are trying to do here, we are essentially trying to implement this equation. We are trying to find out i d s from this equation, so we have to keep this psi d m constant, so this has to be kept constant and i d s m becomes a function of psi d m, which is this quantity. And then omega s L the slip speed and, of course i q s m is the torque component current.

So, when we want to evaluate i d s m we have to take psi d m omega s L and i q s m to find out i d s, so that is what we are implementing to this block diagram. So, from psi d m we divide the L m, and then we multiply by a gain block and this is 1 flux tau r c as per the equation, then we have some more and then we have again a gain block that is 1 by 1 plus tau L r p, this is i d s.

And here we have to add also a component of i q s as per the equation, so this is tau L r and this is coming from i q s m, and then the slip speed also involve here, so we can add the slip speed, but first of all we have to evaluate, what is the slip speed. So, the slip speed is evaluated in the following fashion, we have a block which will have this value 1 plus tau L r p, and this is our i q s, and we have a divider block here. This become the numerator, and we have the denominator, which is calculated as follows, now what we are trying to do we are trying to find out the slip speed by this equation. This equation will give us the expression for the slip speed, so when we wants slip speed the slip speed can be in the first equation.

If this is our equation number 1 and this is equation number 2, the first equation to find out i d s m we needs slip speed, so we have to evaluate slip speed. So, this is how we are evaluating the slip speed, and this will be coming from the flux, and then the other component is coming from i d s. We have again gain block here tau L r by tau r that is obtain from this gain block and this is i d s m, which is paid from the offer current at the flux component of current, and then this becomes the denominator.

So, what we are doing here, we are basically evaluating the denominator that is psi d m by L m minus tau L r by tau r into i d s m, that is what we are evaluating here. And then this becomes the slip speed the result here is the slip speed, and when we have slip speed we can use this slip speed in various base, first of all this slip speed is taken and we can add to this slip speed the rotors speed.

We can add here the electrical speed of the rotor omega r, and what we obtain here is omega e m with the speed of the air gap flux vector, and when we integrate this what we obtain is theta e m. So, this one when we integrate this 1 we can have a integrator block here, we can integrate this speed to obtain the angle of the transformation that is theta e. And this slip speed with is which is calculated here is also use for evaluating i d s m, because we have seen that the slip speed in this case is required to evaluate i d s m.

So, in this we can take this slip speed and put the slip speed here that we are evaluate here, we can in the block here we can multiply this slip speed in this case, we have a gain block. And then finally, this is helpful in evaluating the flux component of current, that is i d m, now this is the block diagram of air gap flux orientation. Now, we must understand that air gap flux orientation is computationally intensive, because this requires lot of signal processing.

And this block which is shown in a dash enclosure, we can show the in a dash enclosure this part of the circuit can be turn as decoupling block. So, we can say the as a decoupling circuit, because this decouple the inherent coupling present between the torque component of current and the air gap flux. So, if we have this signal processing outside the transformation block, we can cancel the coupling that is present in case of air gap flux orientation. And when we chase the torque or the torque component of current the flux can be maintain constant, so what you have to do is that if you want to keep flux constant.

We can say that these our flux, so we can say this remains constant, so we can keep this constant, and we can go on changing the torque component of current, this is our torque component of current. So, we can change i q s, and if we give a constant flux common flux will be constant, because the decoupling network or the decoupling circuit take care of canceling the coupling present inside the machine.

So, of course, we have already understood that, the air gap flux easy to measure, but the price that we have to pay here is that the coupling is present, and to cancel the coupling inside the machine, we have to use a decoupling circuit or decoupling network. We can go one step ahead the argument is we can orient the reference frame with respect to the rotor flux, we can orient the reference frame with respect to the air gap flux, why cannot we orient the reference frame with respect to stator flux.

There are some researcher, who have tried to do stator flux orientation, the advantage of having stator flux orientation is that the stator flux is the easiest flux to be measure. The measurement of stator flux is the most easy, so this is one of the motivations to go for stator flux orientation, so here after this will be discussing about the stator flux orientation.

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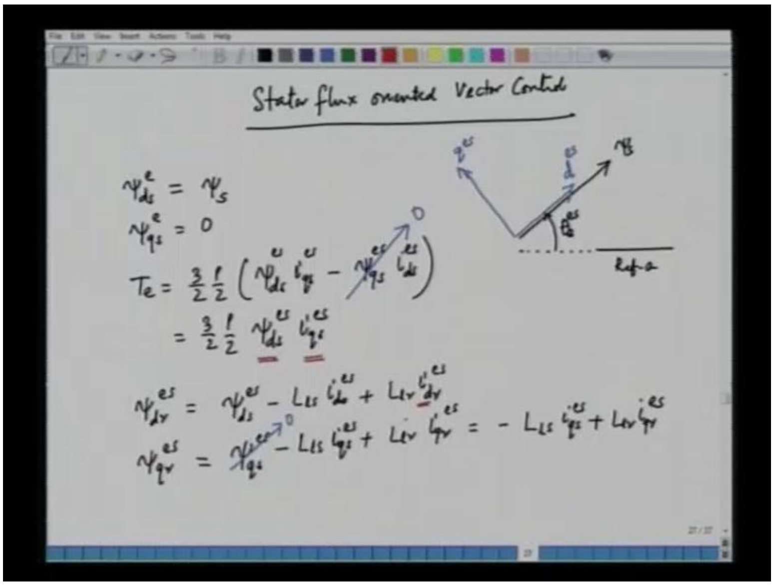

Stator flux oriented vector, now in this case also we can say that, if this is our phase a axis is the reference a and what we are doing here, we are tracking for the stator flux. This our psi s and what we do here we orient our d axis along the stator flux vector, so we can orient our d axis along this, so we call this to be d e s, symbolizing that this is a rotating reference frame, and this is a stator flux reference frame. And the q axis is orthogonally oriented along the with respect to the d axis, so this is our q e s, and if we see this is our reference frame or the this is the reference phase a axis, and this angle is theta e f, this is the angle of the stator flux vector with respect to the stationary phase a axis.

So, here also we can vary comfortably say, because of the orientation we can directly say, that psi d s e is equal to psi s total stator flux vector, and psi q s e is equal to 0, due to the proper orientation we know that that is no component along the q axis. And the torque can be written in the following fashion T e is equal to 3 by 2 into p by 2 into psi d s e s i q s e s minus psi q s e s into i d s e s, and we have assume that this is equal to 0.

So, if we assume this psi q s equal to 0, we can write this equation as 3 by 2 into p by 2 into psi d s e s into i q s e s, and this also resembles the torque equation of that of decimation, so this equation has got only 2 variable that is psi d s and psi q s. So, we can keep psi d s constant as we have seen in case of air gap flux orientation, we can keep psi d s constant and we can change i q s to control the torque, but; however, in this case also just like our air gap flux orientation.

The torque component of current and the flux are inherently coupled, it means we cannot control this 2 variable independently, if we control i q s psi d s will be altered. So, we have to have a decoupling circuit to cancel the inherent decoupling present in the torque component of current, and the stator flux in the d axis. So, likewise, also we can derive the equations, and the equations can derived in the following fashion, that we can first we can write down the expression for the rotor flux in the d N q axis, in stator flux psi d s e s minus L l s i d s plus L l r i d e s. And similarly, we can write down the rotor flux, in the q axis in terms of the stator flux.

Now, this is necessary, because we target the stator flux vector L l s i q s plus L l r i q, so what we are trying to do here, we are trying to write the rotor flux in terms of stator flux psi d s and psi q s. Now, we know that psi q s is equal to 0, so if we substitute, this in this case we can get the following expression for psi q r L l s i q s plus L l r i q s. Now, similarly we can also write down the expression for the rotor current, in this equation the rotor currents are not known.

So, this currents are not known here, so the we do not know this current i d r we also do not know i q r, so we have to express this rotor current in terms of stator current and stator flux.

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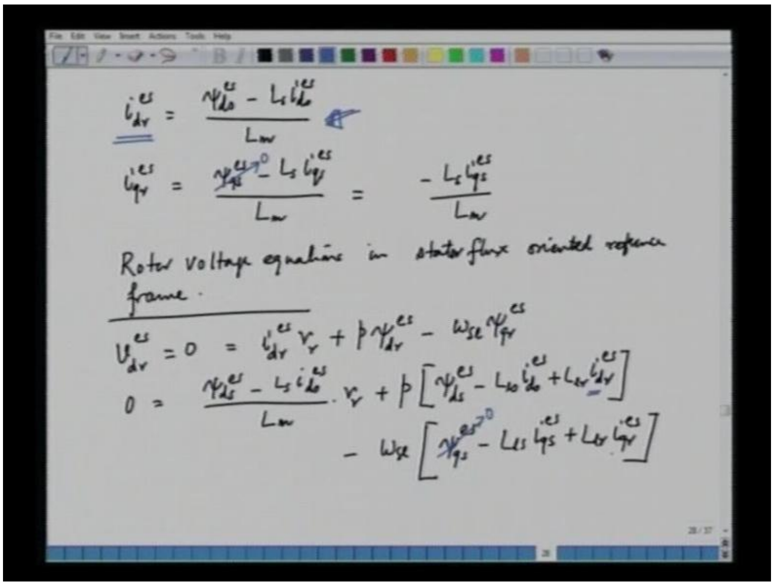

So, we can write down expression for i d r and i q r in terms of stator flux and stator current, so we can do that in the following fashion, i d r e s that is equal to psi d s e s minus L s i d s by L m. And in the similar fashion we can say that i q r e s that is equal to psi q s e s minus L s i q s e s by L m, and we know that this flux does not exist, this equal to 0, so we can for the simplify this equation for i q r, that is equal to minus of L s i q s e s by l.

So, we have a expression for the rotor fluxes, we have expression for the rotor current, now we can derive the equations starting from the rotor voltage equation. So, as we have done in case of an air gap flux oriented control, similarly we can derive the expression for the flux component of current and the slip speed for stator flux oriented vector control. So, we can start that from the rotor voltage equation, so we write down the rotor voltage equation, in stator flux oriented reference frame, and here we can start with the d axis v d r e s that is equal to 0.

And that is equal to i d r e s r r plus p psi d r e s minus of omega s L into psi q r e s, so this is as we have done, in case of rotor flux oriented vector control we can write the similar equation, but we have to express psi q r in terms of psi q s. So, here in this equation what we do, we do 2 things, first of all we take this first term, i d s e s and this i d r, in fact we do not know, we have to express i d r and i d r expression is already available here, already we have the expression for i d r.

So, we can have the expression for i d r and write this i d r here, that is psi d s e s minus L s i d s e s divided by L m into r r, and what is psi d r, psi d r we can express it in terms of psi d s. That is psi d s e s minus of L l s i d s e s plus L l r i d r e s, and then we have psi q r and psi q r can be written in the following fashion omega s L into psi q s e s minus L l s i q s e s plus L l r i q r e s. So, this equation can be simplified, and just cope of simplification exist here, what we can do in this case is that this quantity does not exist, so we can put that equal to 0.

And we can substitute for i d r i d r is not known, so i d r can be written form this equation. And then we have to substitute for i q r and i q r is given by this expression, so we can substitute for i d r and i q r for the simplify this, and we get the following expression.

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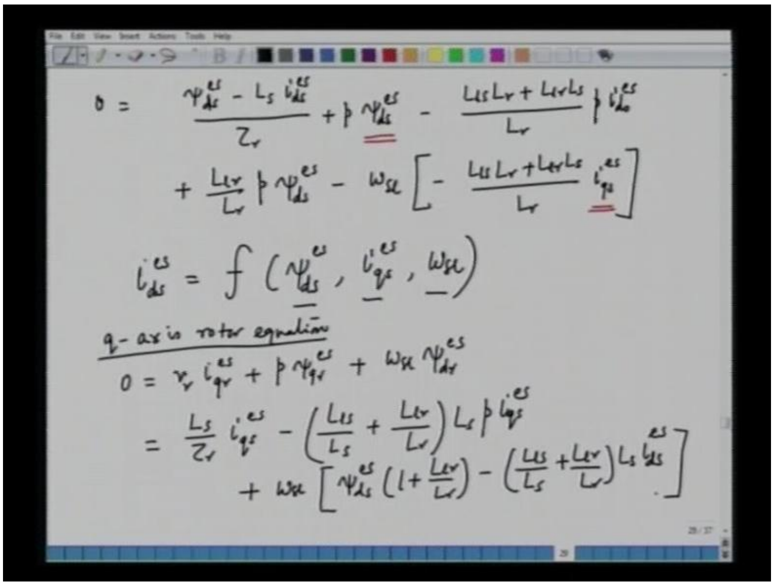

So, if we simplify this what we obtain is the following, 0 equal to psi d s e minus L s i d s e s by tau r plus p psi d s e s minus L l s L r plus s L r L s by L r into p i d s e s plus L l r by L r p psi d s e s minus of omega s L into psi q s vanishes. So, we have minus of L l s L r plus L r L s by L r into i q s e s, now this equation shows that exist a coupling between i q s and psi d s. Now, suppose we would like to keep psi d s constant, now if you want to keep psi d s constant, and if this quality is kept constant, but yet we have to control the torque we can control the torque by increasing or decreasing i q s, i q s is the torque component of current.

Now, if we keep this or if you change i q s, and we would like to keep the flux constant, we have to change i d s, unless we change i d s as we change i q s the flux i d s will change. So, what we do here to keep the flux constant, we have to change i d s as a function of i q s slip speed in this equation.

So, what we have to do here is the following we can write down from this equation i d s as a function of psi d s i q s, and the slip speed which we can easily write as we have done in case of an air gap flux oriented vector control. So, if we obtain psi d s i d s as a function of psi d s i q s, and omega s for a given i q s or given psi d s we can evaluate what should be i d s. Similarly, if we take the q axis rotor equation, in the stator flux reference frame we get the following after simplification.

So, what we can do here, that this is the rotor flux rotor equation plus p psi q r e s plus omega s L psi d i e s. Now, we can simplify this, now once we simplify, we get the following result L s by tau r into i q s e s minus L l s by L s plus L l r by L r L s p into I q s e s plus omega s L into psi d s e s into 1 plus L l r by L r minus L l s by L s plus L l r by L r into L s into i d s e s. This equation is definitely more involve, because this has got the derivative term by what we see here, this also has got the expression I mean the variables like i q s, variables like i d s.

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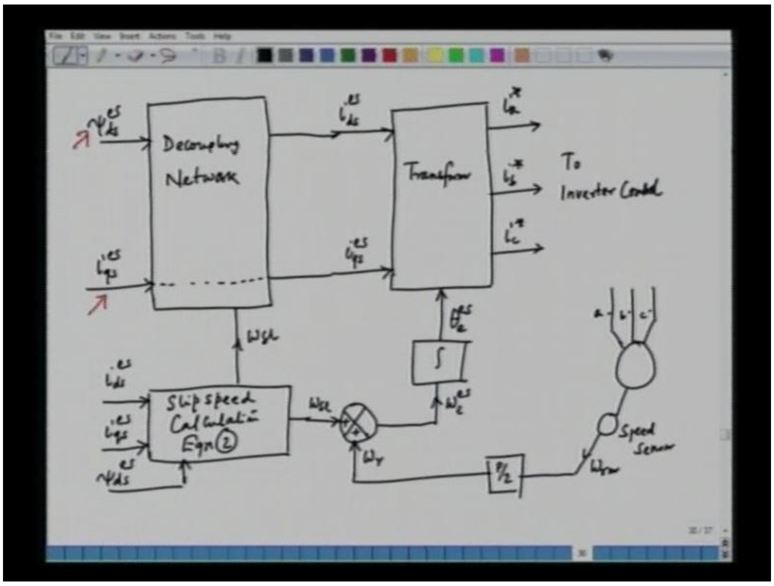

So, this equation after simplification we can get the expression for omega s L, so from this equation we can evaluate omega s L, so what we have to do here is that, we can evaluate omega s L from this equation. So, this omega s L can be evaluated from this equation, and after we evaluate omega s L from this equation is omega s L can be used to compute the speed of the stator flux vector, which will be use for the transforming i d s and i q s into i a i b.

We are discussing about the stator flux oriented vector control, and we have seen that that is inherent coupling between the torque component of current, and the stator flux. So, we have to cancel the coupling by having a decoupling network, we have 2 equations here, this is the first equation we can say this is the equation number ,1 in which we can obtain i d s in terms of psi d s i q s and the slip speed, that is omega s L. And we have the second equation here, which will give the expression for the slip speed that is this quantity, so from this we can evaluate what is the slip speed.

So, we can use this 2 equation to implement air gap flux oriented. stator flux oriented vector control, so we can see how it is implemented. So, what we have to do here is that, we have to transform the variables from the stator flux reference frame, and here we have i d s and i q s and we have to view the transformation here. And this transformation is basically done using the angle of the stator flux vector that is theta e e s, now if we see this angle that we are talking about. This angle is use to transform the variables in the stator flux reference frame into the, variable in the stationary a b c reference frame that is phase a, phase b, and phase c.

So, we have to find out this angle and to find out this angle theta e, we need the information about the slip speed, so this is evaluated by integrating the speed of the stator flux vector, that is omega e e s. And that is obtain by the summation of the actual speed that is omega r, and the slip speed that is calculated using equation 2 by using this equation. So, we can calculate the slip speed using this equation, and this slip speed can be used to compute the synchronous speed that which the stator flux vector is rotating in the space, we have to use here what is called the sweep computation block.

So, this is the slip speed calculation, and this be write this equation 2 that, we have previously shown we have the equation 2, this equation 2 will give us the expression for omega s L. And what are the inputs here, input to this slip calculator and the slip calculation block are i d s i q s, and of course psi d s and then we have here a decoupling network as we did in case of an air gap flux oriented vector control.

So, this is the decoupling network and this decoupling network is basically obtained from equation 1 i d s is evaluated as a function of the d axis stator flux. The q axis current in the stator flux reference frame that is i q s e s, and the slip speed that evaluated using the slip calculator. So, we can use that in the decoupling network, so what we have here is psi d s e s, and if you want to keep it constant, we can give a constant reference here. And then here we can have the i q s, this is a torque component of current, this usually this current usually comes from a speed error.

So, we have a speed error and then we have a PI controller, which basically gives us the torque component of current i q s, And psi d s we can choose the keep this constant, if you want constant flux operation, we can keep this constant, and what are the other inputs here. The other inputs input is slip speed that is omega s L, because we have we have been able to evaluate i d s as a function of the stator flux psi d s i q s and omega s l.

So, these are the input to this block, and that is called the decoupling block, and out of that we obtain i d s and i q s goes directly in this case that is no transformation. So, were the i q s is constant, and then after this transformation form i d s to i q s using theta e what we obtain here is the reference 3 phase current i a, i b, i c. They are the reference current, so we can denote them as i a star i b star and i c star, and the reference current that we have can be impress on the machine using inverter. So, here what we have here 2 inverter control, so we can use a voltage source inverter, we can have an indexing motor here, and these are the 3 different of the indexing machine.

So, we can have this inverter, and this inverter will this i a star i b star and i c star to the 3 phases of the machine, they are phase a, b and c. So, we can have a sensor here, we can have a speed sensor, and the speed sensor will be giving us the mechanical speed, omega r m. And this we can multiply by the number of polyair p by 2 to get the electrical proof and this is paid here, and this is added with the slip speed to obtain the speed of the stator flux vector that is omega e super script e s.

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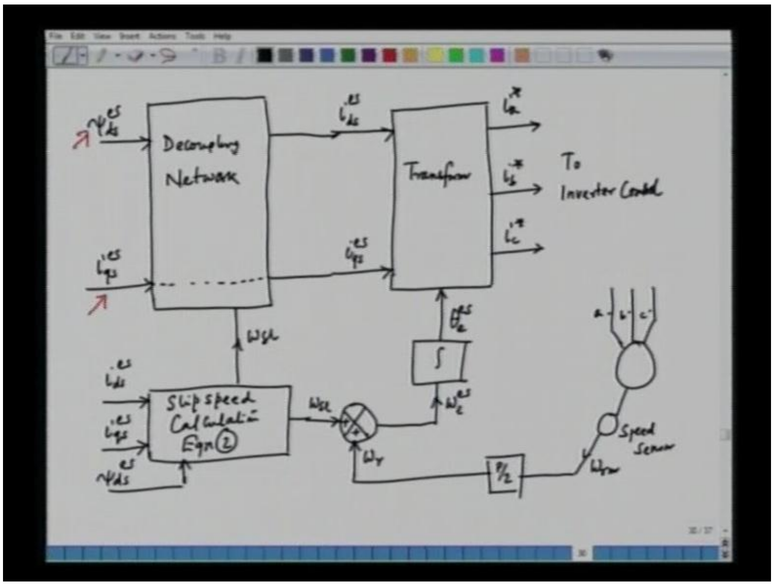

And integration of that will give a the angle of the stator flux vector, and the angle in this case can be use to transform i d s and i q s into i a, i b, i c, which will be impress on to the machine by using the invert. So, this is something similar to that of the air gap flux oriented vector control, and this is also little bit more complex, because you know that we have to use this decoupling network.

So, unless we this 3 coupling network, we cannot go for vector control using stator flux reference frame or air gap flux reference frame, and this decoupling network makes it computationally more intensive. So, what we have to have, we have to have a very fast online processing of all the signals, we have to have a digital processor to process the signal in real time, so that this can be over, so quickly that the controlled is implemented with within a short time.

So, this is about the stator flux oriented vector control with requires or decoupling network, we will now discuss about a interesting area of modern AC drive control that is the speed sensor less control. And we will see how this speed sensor less control can be implemented in an indexing machine, of course whenever we wanted drive we have to have very often, in face we go for a close to speed feedback. We want to variable speed drive we would like to control the speed as we want, and for that we have to have a close to speed feedback.

And for the close to feedback, we often use a speed sensor, which could be a encoder as well, but the speed sensor makes a system less robust, and in many industrial application the speed sensor may not be desirable.

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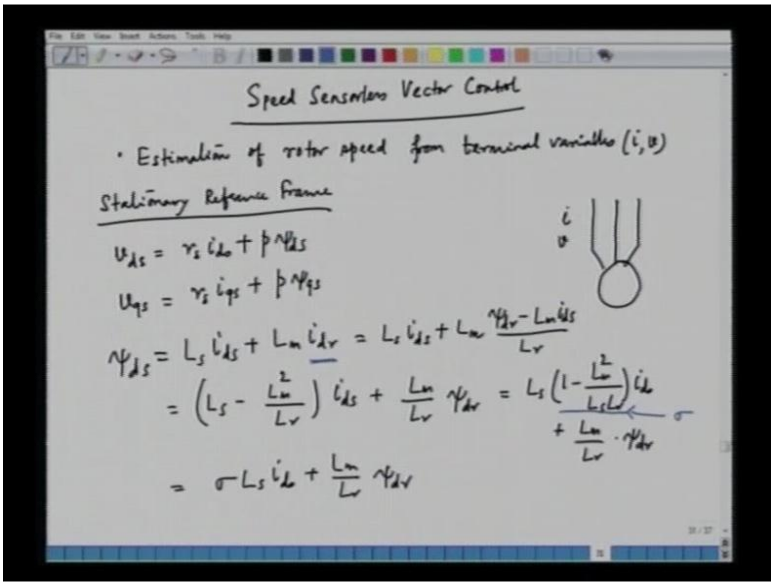

So, we will be discussing the speed sensor less vector control, so the objective in this case is that we have to eliminate the speed sensor; that means, it is called speed sensor less. So, we have to estimate this speed, so the basic idea in this case is estimation of rotor speed, and how do you estimate the rotor speed, we estimate the rotor speed from terminal variable. Now, what are the terminal variables, suppose we have a indexing machine and these are the 3 phases of an indexing machine, and what is available to us is the 3 terminal, and in this case we can have the currents and the voltage.

So, the terminal variables are, in face the current and the voltage, so we have to estimates the speed from current and the voltages of an indexing machine, now to be able to do that we have to have some equations. So, we will derive some equation and, so how we can go for speed estimation from voltages and currents, so the first 1 we will take a stationary reference frame, and we can write down the equation of the voltages in the stator.

This is the d axis stator voltage v d s equal to r s i d s plus p psi d s and v q s is r s i q s plus p psi q s, and we can express this flux in terms of current. So, what we can do here is that we can say for example, in the d axis we can say that psi d s equal to L s i d s plus L m into i d r, and what is i d r. Again, we do not know what is i d r, i d r is the rotor current, and the rotor current is not easily available to us, so we have to replace for i d r. So, this i d r has to be replaced as we have got before, that is equal to L s i d s plus L m into i d r is psi d r minus L m i d s by L r, so this is our i d r.

Now, if we simplify this we can get the following expression L s minus L m square by L r into i d s plus L m by L r into psi d r, this is what we obtain here. And then as before we can say that that is equal to L s into 1 minus L m square by L s L r into i d s plus L m by L r into psi d r. That is equal to the leakage factor sigma into L s into i d s plus L m by L r into psi d r, this quantity is called the leakage factor this is called the leakage factor, because this is actually at index or a major of the leakage inductance of the machine.

If the leakage inductance is 0 or the coupling is side between the stator and the rotor, the leakage factor would be 0, which of course, hypothetical that is always some leakage inductance, the sigma is the small value it is called the leakage factor.

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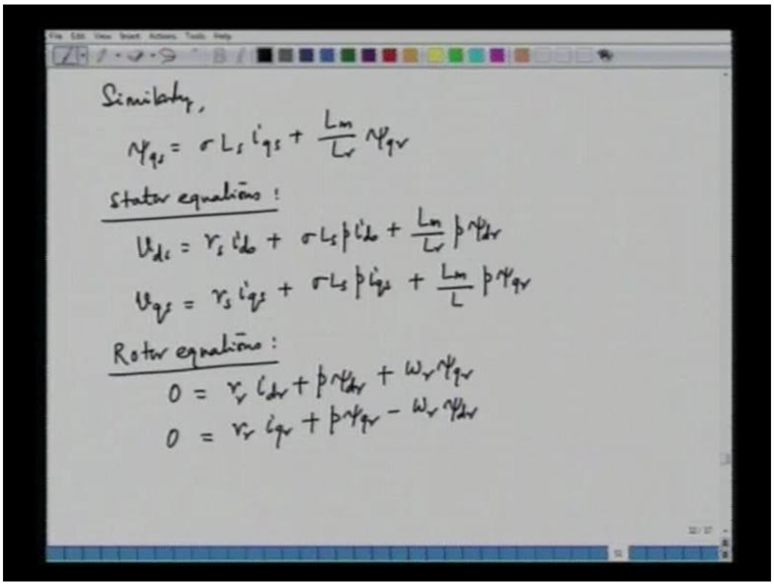

So, exactly in a similar way we can write down for the q axis, so we can say here that in the similar fashion, we can say here psi q s is equal to sigma into L s i q s plus L m by L r into psi q r. So, we can substitute this in the stator equation and simplify the stator equations, so we can say the stator equations that we have already written v d s is equal to r s i d s plus p psi d s. So, we can replace for psi d s as we have derive, so that is equal to sigma L s p i d s plus L m by L r p psi d r this for the d axis, and similarly in the q axis we can say that v q s is equal to r s i q s plus sigma L s p i q s plus L m by L r into p psi q r.

So, these are the 2 equation for the stator, and similarly we can write down the equation for the rotor, the rotor equation in the stationary reference frame would be 0 is equal to r r i d r plus p psi d r plus omega r into psi q r. This in the d axis similarly, we can have in the q axis as well 0 is equal to r r i q r plus p psi q r minus omega r psi d r.

So, this is these are the 2 equation in the rotor, so what will do again we can eliminate the rotor currents, these are not known to us i d r is not known and i q r is also not known. And then we will do some simplification and to the stator and the rotor equation will try to estimate the rotor speed that is omega r.

So, in a way what we are trying to do here, we are trying to estimate rotor speed in the terminal variable, in the terminal variables are the voltages v d s v q s and i d s and i q s. In a next lecture we will see that, now we can have a block diagram. How we can implement this in the form of a block diagram to estimate the speed from the terminal variable v d s, v q s, i d s and i q s.