Industrial Driver Power Electronics

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Lecture - 35

Vector Control of Induction Motor

Last class we found out the relation between the omega slip and the quarter age axis current that is iqs in the field oriented reference frame that is when the dq axis is oriented along the flux space phasor.

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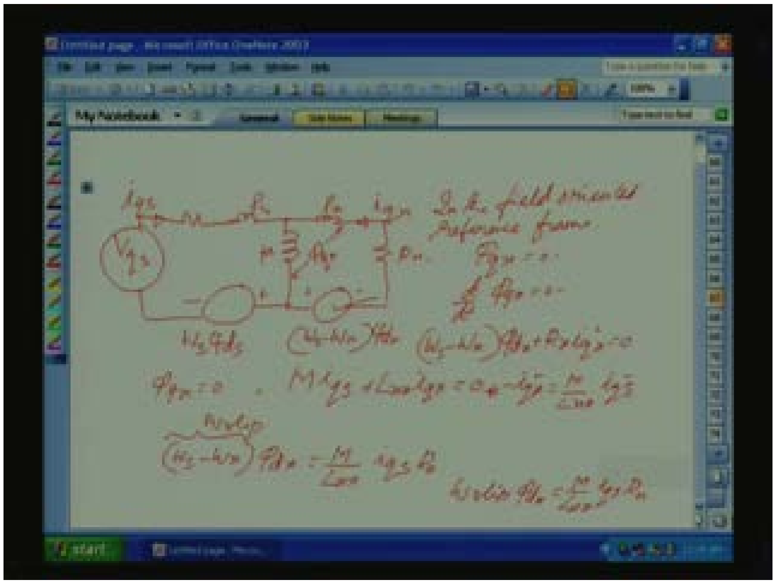

So, when we found when the d is along the flux space phasor, the imaginary component psi qr is equal to 0, so d by dt psi qr is equal to 0. So, from the rotor circuit, d by dt psi qr is 0, then the voltage coming across the Rr is the rotational voltage. So, that the equate it, then we found the iqr in terms of iqs that is from the flux equation, then we found omega slip is equal to proportional to iqs. So, under field oriented control, omega slip is proportional iqs and we know that for a motor, a torque is proportional to slip.

Now, let us take the d-axis equivalent circuit under field oriented control. So, we will go to the next page that is the d-axis equivalent circuit, equivalent circuit.

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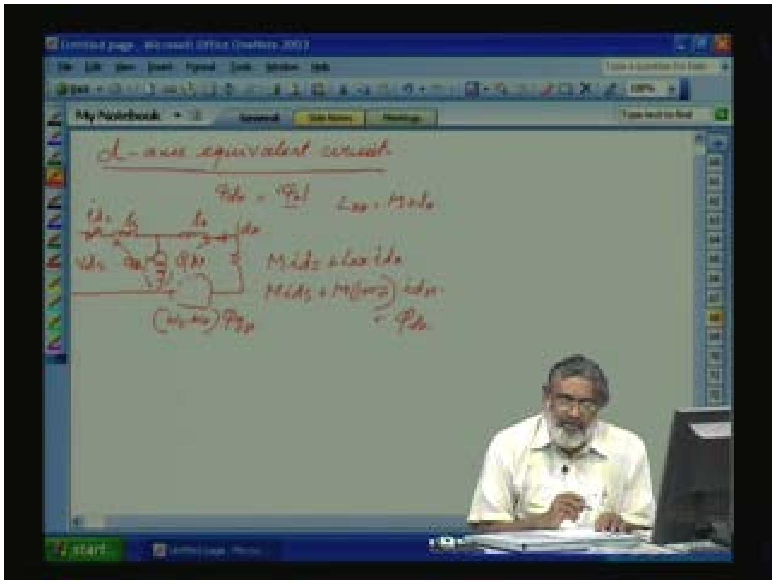

In the d-axis equivalent circuit, the psi dr is our psi r, flux phasor magnitude. Now, let us see the let us draw the d-axis equivalent circuit and from there we will derive the relations. This is mutual inductance, this is Vds, this is psi ds that is psi ds which couples this mutual and the leakage, leakage is equal to ls; this is mutual, phi ds, this the rotational voltage term that we have derived previously, this is equal to omega s minus omega r into psi qr, this is idr. Now, in this equation, psi dr is equal to psi r.

What is psi dr? Psi dr is equal to that is this one psi dr which couples the leakage, rotor leakage and the mutual inductance that is equal to this is ids. So, psi dr is equal to M into ids plus Lrr idr. See Lrr is, the term Lrr is mutual plus leakage lr. So, leakage we can always in induction motor equivalent circuit, leakage is represented as a fraction of the mutual inductance. So, this we can write as M into ids plus M into 1 plus sigma r, sigma r is the fraction 5% of the mutual inductance so that sigma is the fraction is the constant into idr, this is our psi dr.

So, if you see here, this flux is the combination of inductance plus current inductance plus current and we want this flux to keep the flux constant under field oriented control. So, let us say constant means now i_s we have to split along the dr and perpendicular to that one and as I told, when the parallel component, the component and the along idr when it is kept constant, the flux psi dr or psi r is constant because psi r is along dr axis. So, let us say the current which is responsible for the rotor flux, we can write as M into imr.

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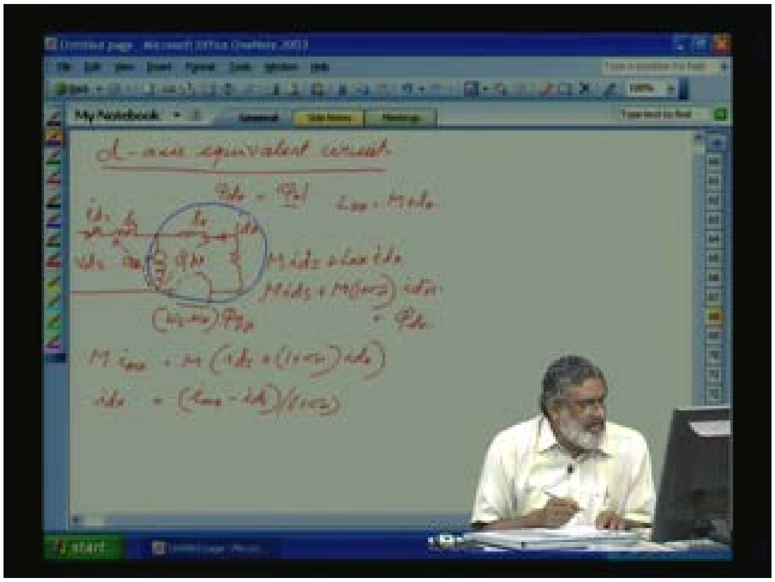

This is from this equation; this is equal to M into ids plus 1 plus sigma r into idr. So, from this equation, the idr which is very difficult to measure because we want all the quantities in terms of the stator quantities; idr is equal to imr, the flux producing component minus the stator ids by 1 plus sigma r.

Now, let us go back to our rotor side, d axis rotor side. If you see here, psi qr is equal to 0; under field orientation, psi qr is equal to 0. Now, dr we are keeping constant, so d by dt psi dr; so what is our current or what is the voltage coming across idr? idr is equal to sorry the resistance R is equal to d by dt psi dr because psi qr is equal to 0. So now, if you write down the voltage loop equation here, d by dt phi dr plus Rr idr is equal to 0; this is the voltage loop equation.

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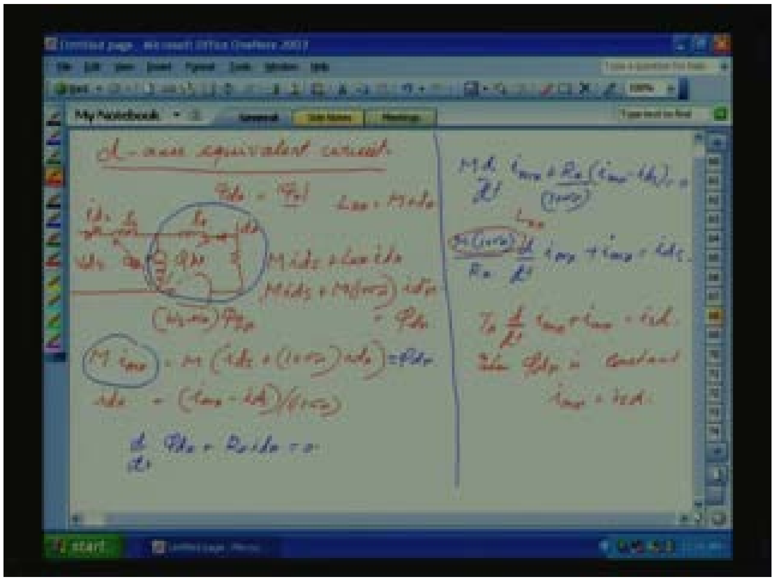

This is equal to, now psi dr we put as psi dr is equal to this is psi dr M imr; so d by dt, we can write it here, M into d by dt imr that is our psi dr that is we have got from this equation that is this equation. So, this is equal to psi dr. So, d by dt psi dr that is this one is equal to M into d by dt imr plus Rr idr that means plus Rr by 1 plus sigma r into imr minus ids is equal to 0. This we can multiply throughout by 1 plus six sigma r into Rr. So, this will be equal to M into 1 plus sigma r divided by Rr into d by dt imr is equal to plus imr is equal to ids, this the equation we get.

What is M into 1 plus sigma r? M into 1 plus sigma r is equal Lrr, this is Lrr that is mutual plus leakage. So, Lrr by Rr is the rotor time constant, rotor time constant that we can take as Tr into d by dt imr plus imr is equal to isd. So, if you see here, the imr, imr is equal to isd when the flux is constant that is when tr d by dt imr is equal to 0. When the flux is kept constant, imr is equal to isd. When phi dr is constant, d by dt imr is equal to 0; imr is equal to isd. Then why this first order equation happens?

This is why during the field weakening region, when we will slowly reduce the flux. So, when you slowly reduce the flux, the isd and the flux, the variation is proportional in the first order. Otherwise not in the flux weakening region that is in the constant torque region, imr is equal to isd that is below the base speed imr is equal to isd. So, this condition we will get. Now, we got the two equations. See, we have to control, we are injecting the current i_s into the machine and i_s we have split into two orthogonal components; isd into iqs and isd is placed along the phi r, rotor flux axis. If that is correct, the perpendicular component is proportional to slip and that will be proportional to torque and the parallel component, component along the psi r is the one which is responsible for the flux.

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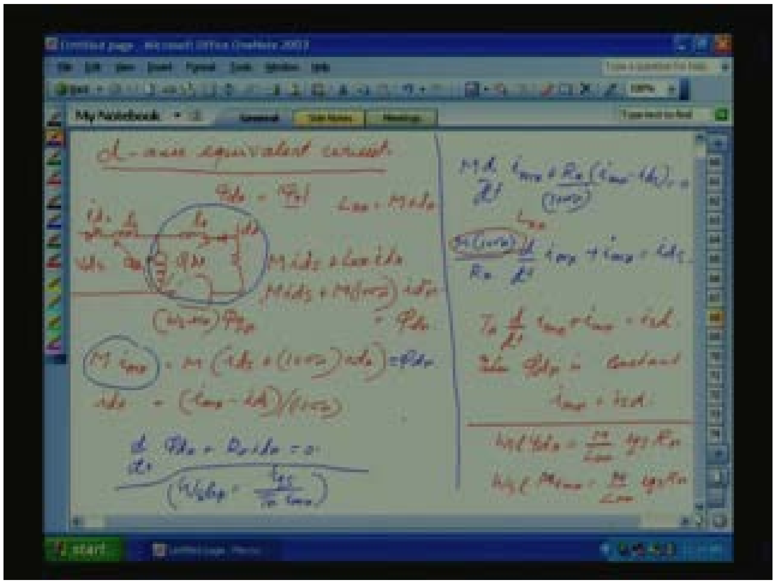

So, both equations under the field oriented control, the right equations, the current equation und field oriented control are let us write down the previous equation; omega slip into psi dr is equal to we got in the last class M Lrr iqs into Rr. Now, if you see here, psi dr is equal to omega slip into M imr is equal to M by Lrr iqs into Rr. Again, M imr, M we can cancel here in this equation, so M, M goes. So, what is omega slip? So, the final omega slip equation is equal to omega slip is equal to iqs divide by see Rr by Lrr that is one by Tr so that is Tr, rotor time constant into imr; imr is equal to ids when the flux is kept constant, so omega slip is proportional to iqs. So, we got the correct conditions for field oriented control.

Now, let us see under field orient control; how the machine, how the equivalent circuit, how the machine works? Machine model, if the field oriented control is correct, then the machine model is like this. See again, let us write our condition is imr is equal to isd, omega slip is equal to iqs divide by Tr ids.

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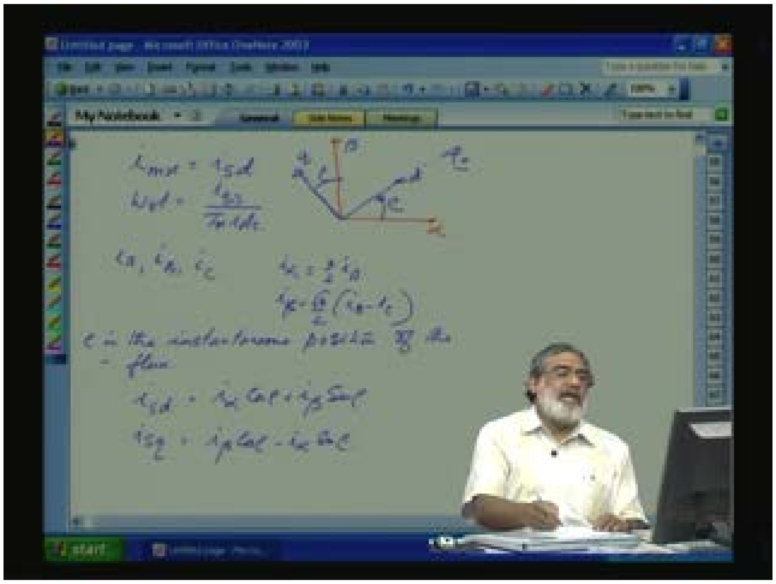

$i_{mr} = i_{sd}$

$\omega_{sl} = \frac{i_{sq}}{T_r i_{mr}}$

i_a, i_b, i_c

$i_\alpha = \frac{3}{2} i_a$

$i_\beta = \frac{\sqrt{3}}{2}(i_b - i_c)$

ρ is the instantaneous position of the flux

$i_{sd} = i_\alpha \cos\rho + i_\beta \sin\rho$

$i_{sq} = i_\beta \cos\rho - i_\alpha \sin\rho$

What we did? We put, if you see our reference frame, so our reference frame if you see here; this is our alpha, this is our beta that we are transferring to a general rotating reference frame that is our d and perpendicular to that one is the q. So, the reference frame axis is always we placed along the phi r axis, phi r flux space phasor. So, this is rho, instantaneous angle, this is also rho.

Now, if we know the abc component, we can find out the alpha beta component. See, we will be measuring i_a i_b i_c; from i_a i_b i_c, what is the alpha beta component? We know that i alpha is equal to 3 by 2 i_a, i beta is equal to root 3 by 2 i_b minus i_c. So, alpha beta component, how do you get d and q provider rho is known, rho means the instantaneous position of rotor flux is known?

Now, under field oriented control, rho is the instantaneous position of the rotor flux of the rotor flux. So now, for field orientation, we have to find out the id and iq. So now, our isd is equal to i alpha cos rho that is i alpha cos rho into plus i beta sine rho. From this equation, from this figure, i beta sine rho, this is beta axis, i beta sine rho that is this perpendicular i beta sine rho is this axis, this is our i alpha from here.

Now, isq is equal to i beta cos rho and minus i alpha sine rho that is minus i alpha and sine rho, minus i alpha sine rho that is from here, we can find out. See, i alpha into cos rho is compounded along this one; now this is i beta, i beta into sine rho, this is also rho. So, i beta into sine row is also equal to because this is parallel to, perpendicular to this one is over, parallel to this one. So, we can get this one.

Now, from this one, how do you find out the equivalent circuit? Let us try to draw the machine induction motor model under field oriented control. We will redraw the induction machine model when the correct field orientation is achieved. So, we are sending the three phase currents to the motor that is the i_R, then i_Y and then i_B.

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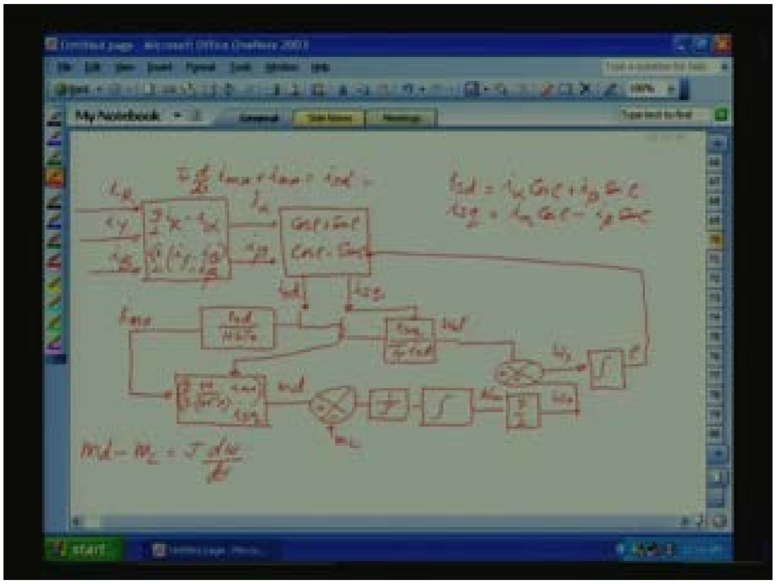

This, inside the machine if the field orientation is correct, the correct model under field orientation is this is 3 by 2 i_R is equal to i alpha and root 3 by 2 i_Y minus i_B is equal to i beta. So, we got i alpha and i beta. Now, if the rho information is correct, if you know the rotor flux position, instantaneous position of the rotor flux, rho is known; then using this transformation, cos rho plus sine rho and cos rho minus sine rho we will get isd and isq, isd and isq.

See, isd will be equal to i alpha plus i beta into sine rho and isq is equal to i alpha cos rho minus i beta sine rho; from the phasor diagram, we can derive this one. So, we will get isd and isq. So this isd, we know that isd imr tau r d by dt of imr plus imr is equal to isd. So, from this equation, imr when isd pass through a first order filter, you will get imr. So here, this one imr is equal to isd by 1 plus s torque. From this equation, you will get imr.

The moment imr is there, the torque equation we have derived, torque is equal to 2 by 3 M by 1 plus sigma r into imr into isq, imr into isq; isq we got here. This torque equation, this is md, driving torque minus load torque, this the load torque. We know how to relate the speed and the driving torque and the load torque, this equation we can use; md minus mL is equal to J, moment of inertia d into d omega by dt. So, this we can multiply by 1 by J, gain function. Then we can integrate it, here you will get omega mechanical speed multiplied by P by 2, P is the number of poles, you will get the omega r.

Now, from isq isd, we know if the slip is equal to, field orientation is correct, slip is equal to isq minus Tr isd, so isq is available here, so omega slip is available, omega slip plus omega r will give omega s that is the speed of rotation. When you integrate, you will get rho that is the rotor flux position. This rho, you will feed it here so that from the look up table we can generate cos rho sine rho. So, if the field orientation is correct, this is the machine model under field orientation. So, let us write the block diagram for field oriented control.

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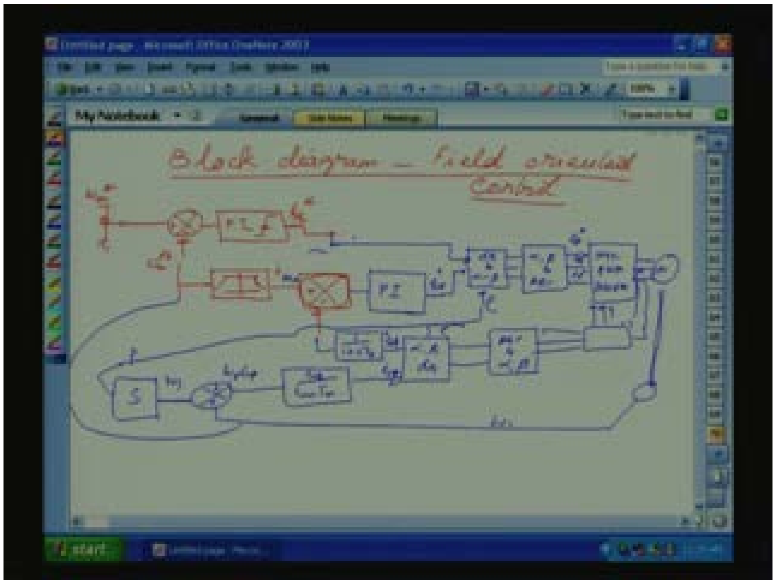

Block diagram, field oriented control or vector control. See, we are giving the omega m speed reference, omega m speed reference. This we will give it, so there should be a feedback, omega m feedback; that we can take it from taco or let us see. Now, whenever there is a difference between the reference and speed that means what it indicates? The driving torque is not equal to the load torque. So, that means we have to give the correct deriving torque that means it will point to the, torque means it will point to the isq.

So here, you have a controller, we will use let us say we are using PI controller. PI controller with saturation limit should be there that depends on the machine, how much isq plus or minus we can give it. So here, you will get isq reference; this isq reference, we got it. Now, let us say speed feedback; so speed feedback if you give it, till base speed, we will make our isd constant. After that, field weakening it will make inversely proportional, this way. So, this is our, we have a look up table here, this is our isd, isd is equal to imr. This again we will sorry we will compare with the feedback current. So, this is flux reference, so this is not isd, this is our imr.

So, here again, we have a PI controller. This PI controller, if feedback imr and reference imr and feedback imr is correct, then this will be equal to isd reference. So, we got isq and isd reference. So now, we can do the inverse transformation that is dq to alpha beta, dq to alpha beta again we can have alpha beta to abc. So, we will get the required i_a reference, i_b reference, i_c reference. This we can give to our hysteresis controller, hysteresis PWM controller and inverter and finally to the motor; this is our hysteresis PWM controlled inverter.

Now see, alpha beta, see here PWM you require reference feedback current also required. So, we can send this current. You know i_a plus i_b plus i_c is equal to 0; from this one, we can find out actual i_a i_b i_c, feed it here, again here i_a i_b i_c coming here. see one thing what we want see dq to alpha beta and this one you require rho here how to get rho we have we will come to that one. Now see, assuming rho is available see this three phase current again we are converting ABC to alpha beta we will convert it then alpha beta to provided d is known rho is known we will find out alpha beta to dq so dq we got dq this is isd actual current isd this is isq when why when we pass through 1 plus sTr we will get the correct imr that you feed it here now isq you got it

We know the equation isq divide by imr torque you will get the slip this slip is a taco for the machine from there you can get the omega r here you will get omega s you integrate you will get rho that rho you feed it here now this omega you can give as a feedback here also so our vector control is correct current his initially current hysteresis control we can use it because it will give fast response so high dynamic performance app application we can use this one this is the block diagram for a field oriented current using current hysteresis PWM control.

We can use also space vector PWM also then we can from the current PI control we have to get the required voltage control so this way we can get the field oriented controls block schematics for the field oriented control is like this so this we can simulate using MATLAB and Simulink before an actual implementation is being done. So, this is current hysteresis controller. Now, if you want to use voltage control, how it can be done? See, we got field oriented control; now how do you decide your controller for the separately excited DC machine? We have found out some set of rules to find out the PI controller.

So, let us draw the closed loop schematics; from there, same techniques what we use separately excited DC motor, we can use it here also. So, let us see the close loop controller block diagram.

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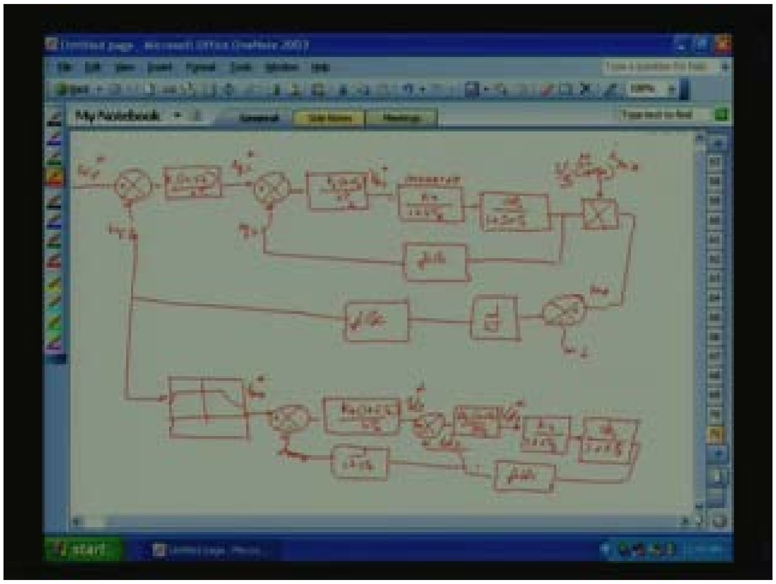

See, we have the omega reference and this is the omega feedback. So this, we will give to a speed controller, PI controller so that we will make it as K_1 into 1 plus sT_1 by sT_1; this is the

PI controller. This output will give our iqs star. This iqs star for a voltage control, we have check iqs and iqs feedback, it is coming here. This we will give it to current controller that is K_2 into 1 plus sT_2 by sT_2; this controller output if you use current hysteresis controller, this output iqs we can directly convert it to, using iqs and ids, we can directly control into ias reference, ibs reference and ics reference.

But if you want to, if you want to control a phase up to PWM, then we require the voltage reference. So here, we will have iqs reference and iqs feedback, then one more hysteresis controller, this output will give our Vqs reference. This feedback we will give to a PWM converter, so converter has to be or inverter, inverter we will again pass through; we will modulus a first order lack, so we will say inverter K_3 by 1 by sT_3, this the inverter, this is our inverter.

So, same like our PWM based, on the PWM frequency, we can find out approximate one sT_3. So this, it will go to the machine, machine again it will be same like separately excited DC motor 1 by Rs divide by 1 plus S leakage inductance, time constant due to the leakage inductance that is sTs we will put it; this we will give the output iqs. So iqs, may be gain and filter if is required, we have to put it here and feed it here. So, this current control, we can same like a current loop and outer speed loop.

So, this iqs multiplied by 2 by 3 M by 1 plus sigma r into imr is our torque, this torque md minus mL 1 by SJ, SJ the moment of inertia, you will get the speed feedback; speed feedback again if you are with a filter and gain that first order, we can model the first order. So, we will get outer speed loop and inner current loop same like in a separately excited DC machine. And for the dq axis d axis, see you have the current reference, under field weakening it will go inversely proportional both forward and reverse. So, this will give depending on the speed, our imr, imr reference plus minus imr feedback. This we will give to one controller that will give our ids reference that is K_4 into 1 plus sT_4 divide by sT_4. This will give our ids reference, ids reference minus ids feedback. If we are using a space circle PWM, then we require Vds, so one more PI controller.

So, this is K_5 into 1 plus sT_5, sT_5, this will give Vds reference; again the converter, Vds reference, the same converter, there is the same K_3 by 1 plus sT_3. It will pass through 1 by Rs. Here, this is not s sigma Ts because q axis because of the leakage time constant that and this is mainly the mutual inductance time comes. So, this is 1 plus STs, Ts is the stator time constant; this one stator, that mutual plus leakage because this is the flux producing component. So it will, mutual inductance time come into picture. So, this will come here and again if you are using a filter once again, you can feed it here; this is our current reference.

Now ids, 1 by 1 plus STr is our im. So, this loop also we can design if you know the input output relation, same like what we used for the separately excited DC machine or front end AC DC converter, you can use this one here. So, this way, we can have a vector control we can have it. The most important thing is the rho, instantaneous position of rho. If rho is correct, field orientation is correct, then we can only, then we can use this closed loop control for block diagram for designing the control parameters. So, the most important thing is finding out the rho.

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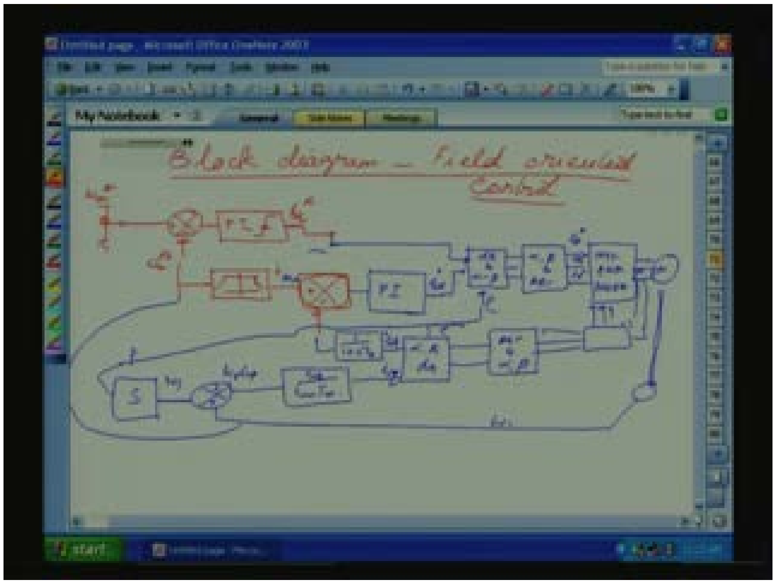

As I told before, a taco or a position encoder is required, then slip is required, slip you have to add and integrate rho we will get. But if you see, the slip is depending on the torque that is auto time constant. So, rotor resistance, it can vary with temperature. So, quite variation is possible here. So, many control scheme is available for parameter adaptation that how to control the rotor time or adaptation of the rotor time constant with respect to temperature is available, many literature, many paper is available in the literature. But we will not be dealing that one now.

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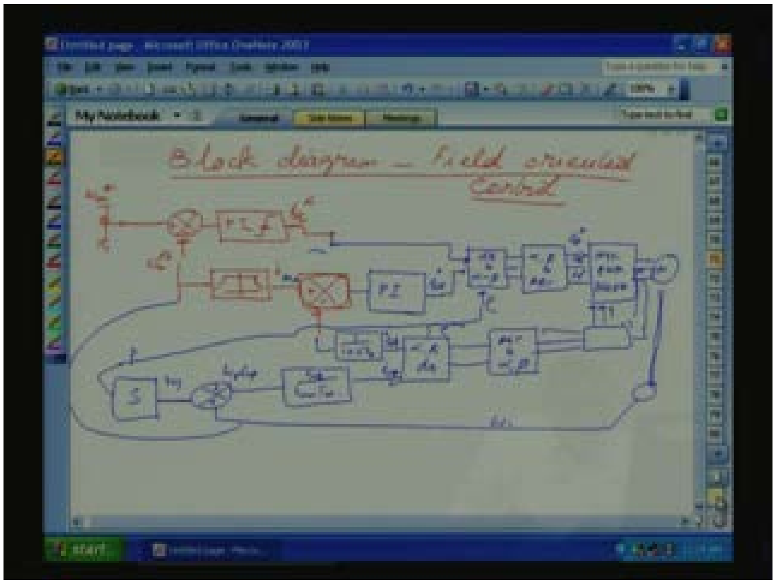

See, this field oriented control, we have used the current hysteresis controller that means here we have the isq and isd reference we generate; then using rho, we convert it into i alpha i beta then alpha beta to abc, then abc current and the abc feedback that is abc feedback we will is the simple hysteresis controller. But as I told, the problem with hysteresis controller previously, it is wide switching frequency variation and optimum PWM switching is not required.

So, instead of if you use a voltage control converter with a spacer PWM or sine triangle PWM, then we want the reference to the PWM is not current, the voltage. Then the field oriented control scheme will be the block diagram will be like this. We will go to that one now, next page we will go where the command voltage as the command variable for the inverter. So, field oriented control with a voltage as the command variable.

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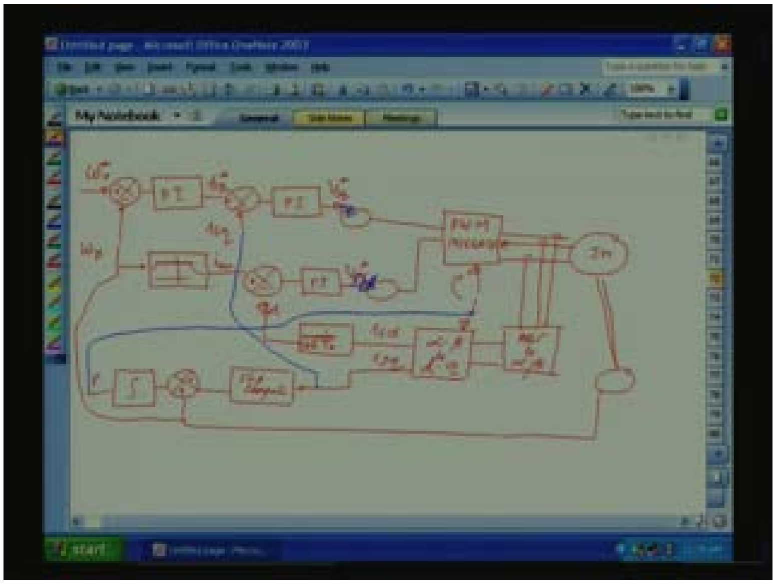

So, here also, we have the reference, speed reference, this is our omega r reference, then speed feedback is there that we will generate from encoder or a taco, then this PI controller output. As I told, any change in the speed, command speed and the reference indicates a difference in that torque command and the load torque. So, we have to give the correct isq which is proportional to the torque. This isq we will compare; see now, the voltage we are injecting to the machine using PWM control voltage we are controlling. So, we know with that correct isq is coming. So isq, this we will take it reference, isq feedback is required. So, this output PI controller, we will give our Vsq star.

Similarly, we have the speed feedback or speed reference, we have the look up table for imr, this is during the field weakening region, imr will come here; during steady state of an operation, imr will be equal to isd. So, we have the isd feedback here, isd. This is the PI controller, this we will give you our Vsq star. So, intentionally put this one; there is some more term also we need to add here. So, this we will talk about later. Let us say Vsq is coming, this Vsq will go to the PWM modulator and inverter, PWM, inverter and control.

We require the rho signal also, so Vsq Vsd we got it, here we require the rho also. This it will go to the motor induction motor; from the motor, we will send the current, all the three sensors are not required because ia plus ib plus ic is equal to 0. So, two current sensing is required. But for clarity, we have put three here.

These are in abc, so we will convert abc to alpha beta. Again, alpha beta to dq, here also we require rho information, this rho is required here also. Here we get isd feedback and isq feedback. We know that isd is equal to imr in the steady state if any transient flux weakening is there, this isd by 1 plus STr; this is the correct imr. So, we will leave it here. So, feedback and imr will be the same.

Now, this isd you know, how to compute the slip information. Previous block diagram, we have found slip is equal to find out slip computer, slip and we have the taco. This two added, we will get omega s. That integrate, we will get rho; this is the rho we will be feeding it here so and again this feedback we will close it, omega r.

Now this Vsq Vsd, this is coming from isq feedback, isq feedback here also that feedback term, we will close that one, it is coming from here. So, you will get how to compute Vsq Vsd? See, what is this one? See, any change in the isq and isq feedback, immediately it should reflect on Vsq. This shows that means Vsq is dependent only on isq and here this is not Vsq sorry this is Vsd and Vsd sorry this is Vsd, Vsd we are taking from the imr reference and isd feedback and the PI controller. That means any change in the isd reference and isd feedback should reflect to Vsd.

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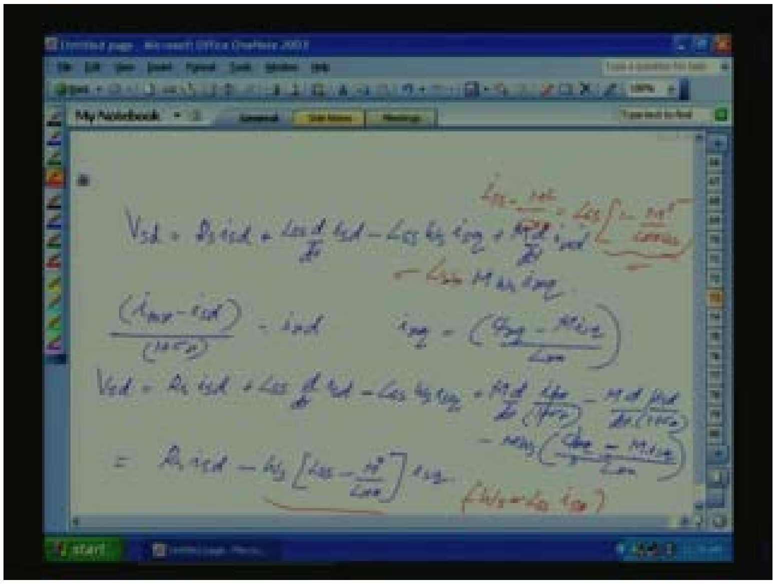

But if you see the actual Vsd Vsq equation, let us go back to the actual Vsd Vsq equation; here we can see Vsd is equal to Rs isd plus from the original, plus Lss d by dt isd minus Lss omega s isq. So, it shows Vsd, there is a isq; any change in the isq component, it will reflect on Vsd plus M into d by dt ird minus M into omega s irq. See, ird irq terms, the rotor currents we can represent in terms of isd and isq. We know that one imr minus isd divide by 1 plus sigma r is equal to ird. So, substituting this one here, also we know that irq is equal to psi rq minus M isq divide by Lrr and under field oriented control, psi rq is equal to 0. So, let us substitute this one and write Vsd.

So, then Vsd is equal to Rs isd plus Lss d by dt isd minus Lss omega s isq plus here we want to change ird, ird is equal to that is this term M into d by dt imr by 1 plus sigma r minus M into d by dt isd by 1 plus sigma r, then minus M into omega s into irq that is psi rq by psi rq minus sorry psi rq minus M into isq divide by Lrr. Psi rq is equal to 0 under field oriented control. Also, we can say during steady state, d by dt imr is equal to 0; imr is equal to isd, so d by dt isd is also 0 here, we can assume that one. So, this goes, then finally this will be equal to Rs isd, then minus omega s into omega s into Lss minus M by Lrr into, this M and M will come, M square into isq.

See, this Lss by Lrr, this term, this term, Lss minus M square by Lrr, we can write as Lss into 1 minus M square by Lrr Lss. So, this become a constant that we can say sigma Lss, this will become sigma Lss. So, this equation that is this equation, we can effectively write as minus omega s sigma Lss isq. So this, we will put as feed forward time in the controller here, isd term.

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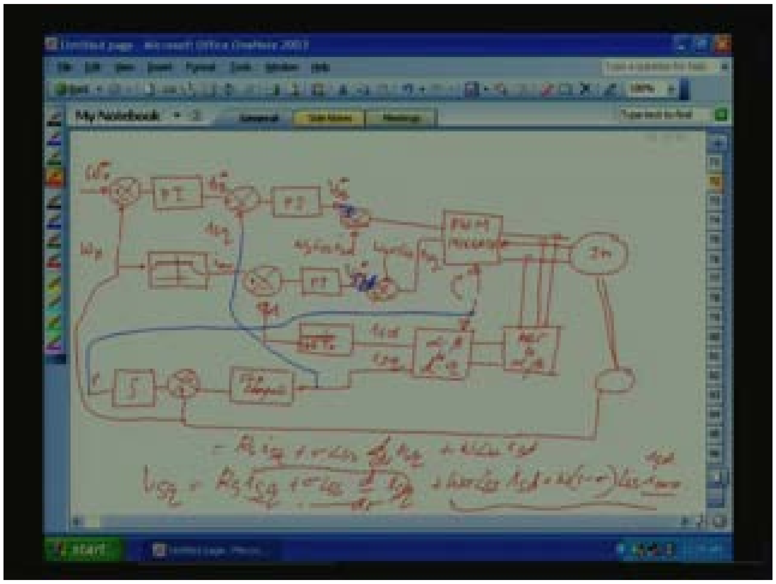

So, in the Vsq term here, there is a feed forward term. See already, isq we know it; so, we can use this one omega sigma Lss isq here, we can feed it here, omega s sigma Lss into isq. So, what is the advantage, this feed forward term? Then this PI controller has to change only for any variation in the isd only, any isq variation it will immediately affect through this one. Similarly, we can find out the feed forward term from the dq for the Vsq, we can find out from the equation, we can the same derivation and we can use it.

See here, we will see, if we go to the equation Vsq, Vsq is equal to Rs isq plus sigma. Finally, it will come sigma Lss d by dt isq plus omega sigma Lss isd plus omega into 1 minus sigma Lss r imr. If you from the matrix term that equation dq model if you get the Vsd equation, if you get finally, you will get this one. See here, omega imr is equal to isd; so sigma imr we can replace it isd in the steady state operation, imr is equal to ic. Finally, this equation will be equal to Rs isq plus sigma Lss d by dt isq plus omega plus omega Lss isd it will come because imr we are taking into isd. So, this term together, it will come here.

So this time, we can use a feed forward term here, this is also plus here, this is also plus here. So, here we can use the feed forward term from the isd that is omega s Lss isd here. So, what is the advantage? So, this PI controller has to vary, Vsq has to vary only if variation in the isq. So, the variation for the PI limit only due to the isq here and in isd variation, we have feed forward here. So, it need not come through the PI control, so it will also increase the response of the system. This way for voltage controlled inverters with voltage as the variable for the PWM, we can use these types of closed loop schemes for the vector control application.