Advanced Electric Drives
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Lecture - 13

Hello and welcome to the lecture on advanced electrical drives. In a last lecture we have just started the speed sincere less vector control of induction motor. The basic motivation behind the speed sincere less control is that, in many industrial applications speed sincere is not a very essential requirement. So, for example in underground mining when you use a drive in underground mining; the speed sincere with the speed sincere the drive becomes less robust. So, to make the industrial drive more robust over the ideal situation is to go for a drive without a speed sensor.

So, the speed sincere less control has become our D facoto industrial slandered, we can go for a drive without any speed sincere. So, if you do not have the speed sincere how can we go for close to speed control, there made be any speed sincere. But speed can be estimated from the terminal variables.

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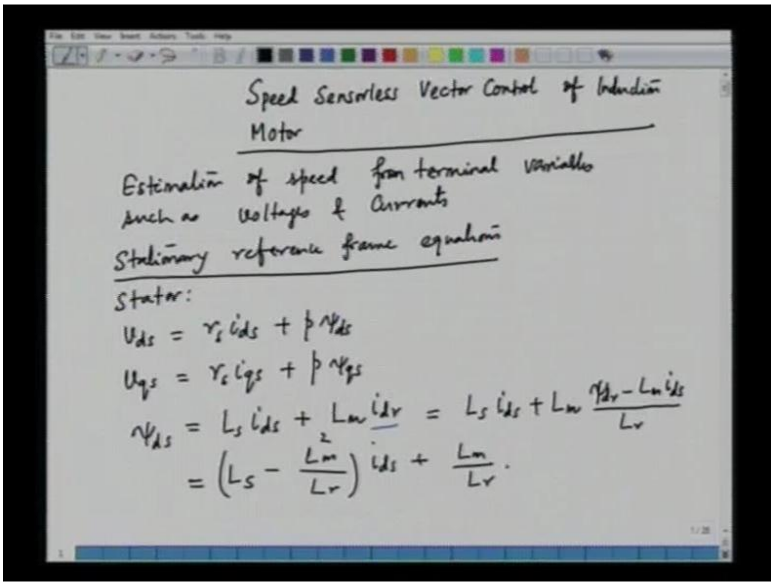

So, today we discuss about the speed sincere less vector control of induction motor. Now, where we do not have a speed sincere we have to estimate the speed from voltages and current, this voltages and the currents is the terminal variables. So, what we have to do is to estimate the speed from the terminal variable. So, estimation of the speed from terminal variables such has voltages and currents. So, we will first derive the equations for the speed sincere less control. And then by mean to the block diagram will try to see how this can be implemented. So, we will write down by the equation in the stationary reference frame for the induction machine. So, we are taking a stationary reference frame equations.

So, we will first talk about; the stator the stator equation are v d s equal to r s i d s plus P psi d s is the d axis. Similarly, in the q axis we can have v q s equal to r s i q s plus P psi q s. And we can also write down the expression for psi d s; psi d s equal to L s i d s plus L m i d r; as we have already seen that i d r it is difficult to measure. So, we do not have any idea about rooter current. So, we have to estimate this current or we have to express the current in terms the stator current and sum other variable. So, we can replace i d r an i d r is replace in the following fashion; so, i d r minus L m i d s i L r. So, we have to able the replace the rooter d axis current by the following expression. Then if we simplify this what we get is following L s minus L m square by L r into i d s plus L m by L r into psi d r.

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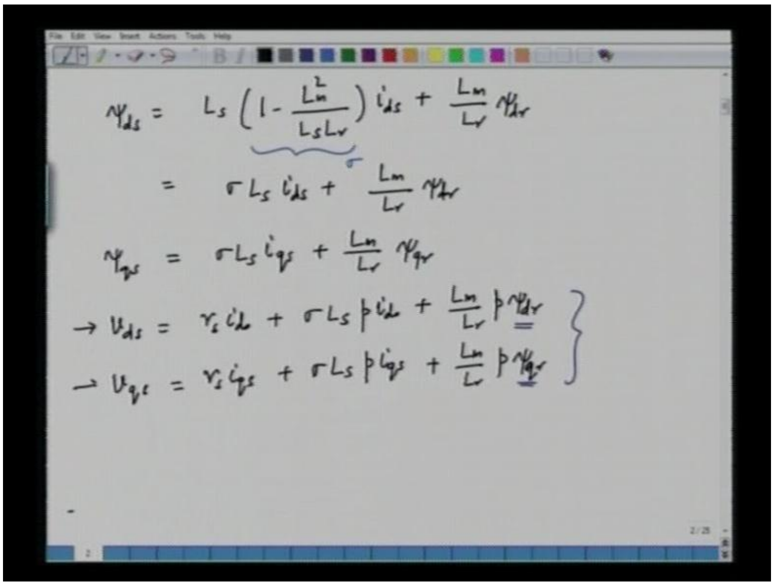

This can further be simplified of follow psi d s is equal to L s in to 1 minus L m square by L f L r in to i d f plus L m by L r in to psi d r; these are all in the stationary reference scheme. Now, this quantity is called the leakage factory or sigma this is a measure of the leakage sigma indication of the machine. So, if sigma equal to 0; the leakage intoxication of the machine it is also equal to 0. So, we can further item this is sigma in to L s in to i d s plus L m by L r in to psi d r.

Similarly, in the q axis we can write down by the expression for by psi q x it will be similarly, to what we are waiting sigma L s into i q s plus L m by L r into psi q r. So, this we can substitute back in the voltage equation that we are already seen that these are the 2 voltage equations. So, we can substitute for psi d s and psi q respectively and simplified. So, if substitute this back in the voltage equation; we get the following v d f is equal to r s i d s plus sigma L s p i d s plus L m by L r into p psi d r this in the d axis.

And, similarly in the q axis we can apply the equation v q s; that 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 d r. So, the important of this equation are the following if we know the voltage, if we know current; we can estimate the rotor flux. So, this equation this to equation shows that we can estimate psi d r and psi q r form this 2 equation. So, we have psi d r in the first equation and psi q r in the second equation. So, we can estimate psi d r and psi q r form v d s and v q s respectively.

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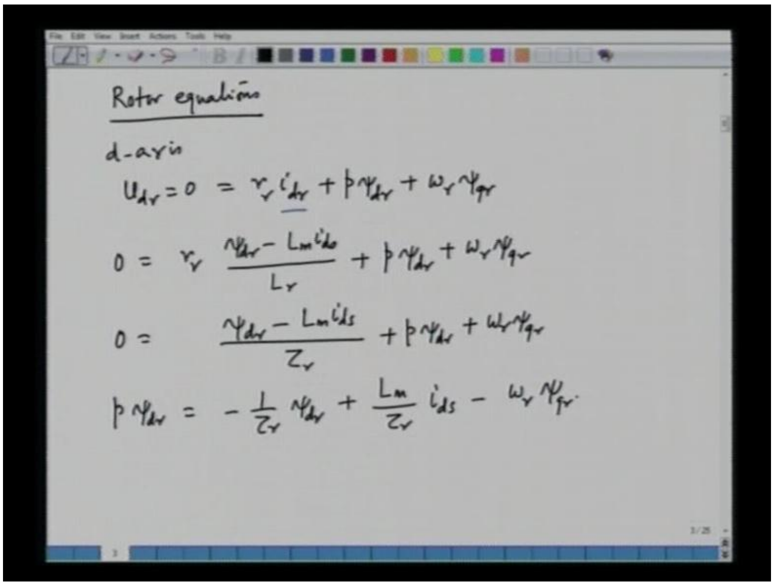

Now, let us write down the expression for the rotor in the similar fashion we can write down the rooter equations. So, in the rooter we can start with the d axis equations the rooters are sort circuited. So, we can start with the v d r equal to 0; so v d r equal to 0 that equal to r r i d r plus P psi d r. And then you know we are talking about stationary reference frame; the stationary reference frame means the speed of the reference is equal to 0. So, we have rotationally in to c m f. But that will be appearing as omega r in to psi q r. So, we have in the fifth block omega r in to psi q r. Because the reference frame with the velocity that equal to 0; we are talking about the stationary reference form this equation we can as we already done this i d r difficult to measure.

So, we can replace for i d r. So, we can say 0 equal to r r; i d r can be returning terms of psi d r. And i d s psi d r minus L m i d s by L r plus p i d r plus omega r psi d r this can further be simplified; we know that L r by r r is now what? So, 0 equal to psi d r minus L m i d s by tau by this is the rooter time constant tau is the rooter time constant that is divided here plus psi d r plus omega r psi q r or we can say that P psi d r is equal to minus of 1 by tau; psi d r plus L m by tau r into i d s minus omega r psi q r. So, this is equation in the p axis. Similarly, we can write down the equation in the q axis.

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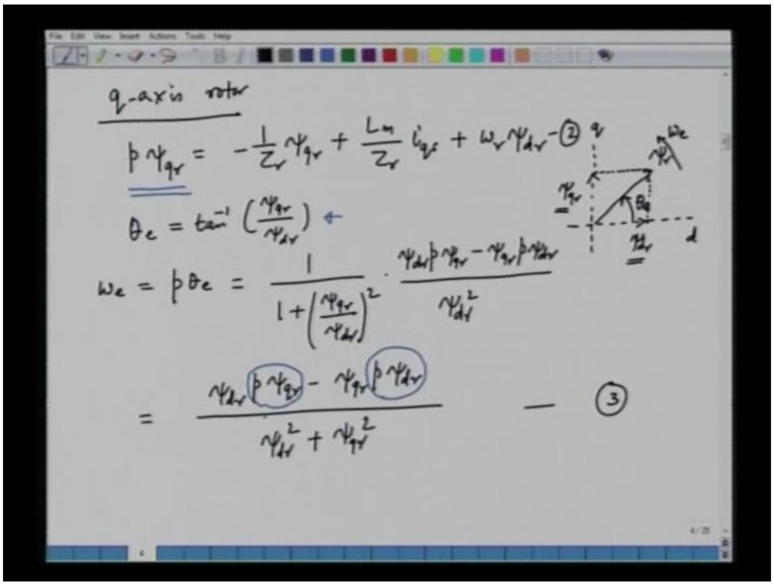

So, in the q axis we can we can in the similar equation; in the q axis is the rooter we can have a similar equation. And the equation will be psi q r equal to minus 1 by tau r into psi q r plus L m by tau r by psi q r plus omega r. So, this equation will help us to estimate the rooter speed that is omega r. Now, this equation is also given us an estimation of the rooter flux. So, the rooter flux are psi d r and psi q r in the 2 axis respectively. So, we find out the rooter flux angle is theta e. So, now what is rooter flux angle; the rooter flax is in psi r and we have stationary d axis and we have stationary q axis; this is our d axis and this is the q axis.

And the rooter plot rotating and the speed of omega e it is rotating in the space with a synchronous speed and the synchronous speed of the rooter flux victory omega e. And this angle obtain with the stationary d axis is theta e. Now, if we want to find out theta e; theta e can found out as follows; if we take the flux components; the component here is psi d r in the d axis and psi q r in the q axis Now, if we project the rooter flux along the d and the q axis respectively; we obtain psi d r and psi q r respectively. So, we have this is our d axis flux and this is our q axis flux.

And we are taking about the angle of rooter flux that is theta e that is given us tan inverse of psi q r by psi d r. So, this is what we can obtain here. And in this case we find out what is omega e; omega e is the speed of the rooter flux vector that is the derivate of this angle. So, omega e is equal to P theta e and if you differentiate theta e with the respect t you get omega e. Now, this is a differentiation in part. So, we have tan inverse of psi q r in psi d r. So, we can differentiate in part. So, we have 1 by 1 plus psi q r and psi d r square. So, we are basically differentiating tan inverse of psi q r and psi d r. And this has been done differentiation in parts. So, we have 1 by 1 up on psi q r by psi d r square in to psi d r P psi q r minus psi q r and P psi d r by i d r square.

So, we are trying to evaluate P theta e that is d theta e by d t and this is given by the following expression. And if you simplified this expression what you obtain is psi d r P psi q r minus psi q r divided by psi q d r square plus psi q r square. So, this is the expression for the synchronous speed that is omega e. Now, we are interested to find out theta e. And we have to find out the ultimately we have to find out omega r; omega is the rooter speed. So, what we can do here we take this equation and we replace for P psi q r and P psi d r form this expression; we know that we have the expression of for P psi q r similarly, we have the expression for P psi d r. So, form these 2 equations we can obtain these values and substitute in the third equation. So, we can in fact name this equation; this equation is equation number 1 and this is equation number 2 and this we called equation number 3.

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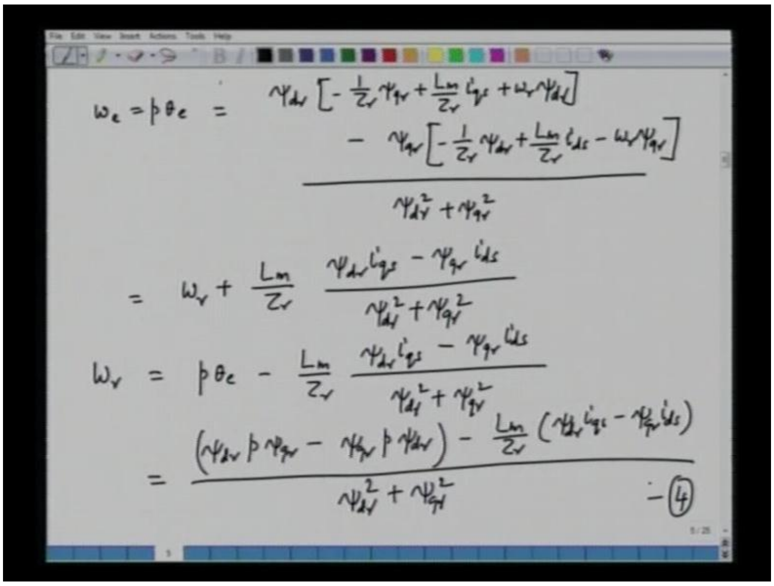

So, we can substitute for P d r and P q r form equation 1 to respectively in equation 3 and then simplify. So, if we do that we get the following expression; we are revaluating the omega e that is theta e that equal to psi d r minus of 1 by tau r psi q r plus L m by tau r into i q s plus omega r in to psi d r minus psi q r 1 by tau r into psi d r plus L m by tau r in to i d s minus omega r psi q r; that divided by psi d r square plus psi q r square this is what we have obtain. Now, if we simplify this equation already this is complex there is scope for some simplification. So, if you simplify this equation we get the following will get omega r plus L m by tau r in the psi i d r psi q s minus psi q r and psi d s divided by psi d r square plus psi q r square.

And, we can further simplify this we have to obtain what is omega r; omega r is equal to P theta e minus L m by tau r into psi d r i q s minus psi q r divided by psi d r square plus psi q r square. So, we have to substitute the expression for the P theta e. So, P theta e value is already known here. So, we see that P teat e is given by the equation number 3. So, we can substitute the value of P theta e form this equations; in the final equation here to find out the expression for omega r. So, if we do that what we obtain here in the following; we get psi r psi d r P psi q r minus psi q r P psi d r minus L m by tau r into psi d r psi q s minus psi q r psi d s divided by psi d s square plus psi q r square.

So, we have able to obtain the estimate of omega r; omega r can be elevated by the following expression that is expression number 4. So, the equation number 4 will give up an estimation of omega r and in this equation we know that psi d r can be evaluated psi d r also can be evaluated and i d s and i q s can be measured. So, we in fact know all the variable in the expression in the right hand of the expression. And when we know the right side we can evaluated what is omega r; the omega r is the rooter speed can be evaluated form the equation that is the equation number 4.

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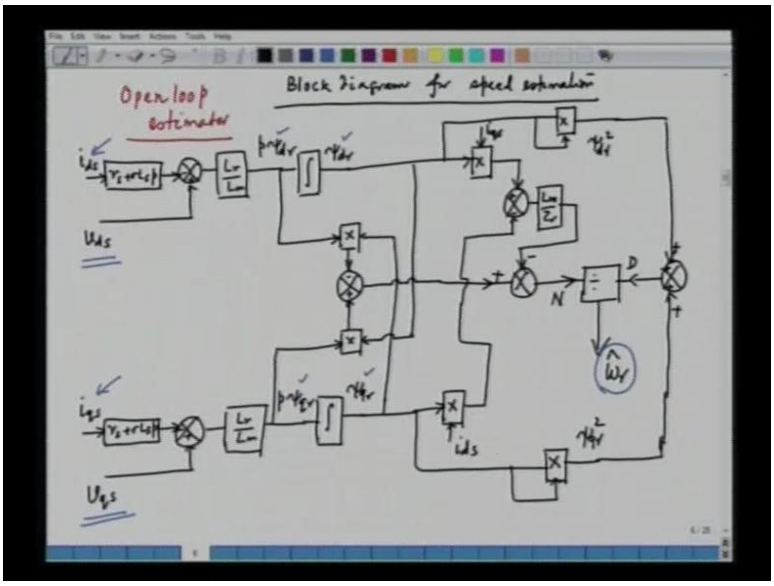

Now, this can be explained by means of block diagram. So, we can show this in the form of the block diagram for the speed estimation. So, here we start with estimate of the fluxes. So, what we have here what we can give the information of the current and the voltages this is r s flux sigma L s P this go here. And input of this is v d s, this is i d s and here we have minus and plus in this case then we have L r by L m and what we obtain here is P psi d r. So, the rooter plots in the d axis can be estimated form the voltage and the current that is v d s and i d s.

Similarly, in the q axis we can have v q s and we can also have i q s. And this negative and positive here are in the multiplied in this case L r by L m. And what we obtain here is psi q r and then we use an integrated; we integrated this we obtain psi d r integrate this quantity we obtain psi q r respectively. And we use the multiplier also here we also use the multiplier in case; the multiplier one of the input speed is P psi d r and all the input is P psi q r. And here in this multiplier we take the signal from this side then we subtract. So, after subtraction we get one part psi d r P psi q r minus psi q r P psi d r.

So, this part can be obtained after sub track similar fashion we will here another multiplier here and we will multiply in this case i q s. Similarly, here we can also the multiplier we can multiply i d s. And we can take this signal we can find the square of the signal we have multiplier and their we can multiply the same thing and what we obtain here is psi d r square. Similarly, we take this signal we use a multiplier and then we multiply the same thing here we obtain psi q s square. And we can use a former in this case we can art i d r square and psi q r square this 2 are positive in this case. And this can be use in a divider and the denominator. And the numerator can be obtain in the following fashion this is what we have positive in this case.

And then form this we can use another subtracted followed by gain block L m tau r. And this goes to the subtracted negative sine here and this gain block other input to this subtraction comes from this multiplier. And finally this is the numerator of the ratio. So, this block diagram shows how we can estimate the rooter speed. So, what we have here basically taking this v d s and v q s form the machine terminal; we have v a, v b and v c form that we can find out what is v d s and v q s. Similarly, we can have current sensor the sense i d s and i q s. So, form this we can evaluate the rooter flux psi d r and psi q r and the derivate of the corresponding fluxes.

And, then we can evaluate the ratio which will finally give us the rooter speed. So, this is our point of interest what we want the is rooter speed and the rooter speed can be obtain in the terminal value. So, in the estimator we called the open loop estimation. Because this does not have any crone machining in fact if there is some error in the measurement their is no way we can correct the estimation. And hence we can call the estimation and loop estimator. So, this estimator is called an open loop estimator because there is no error connection mechanism. So, to have little more error correction mechanism; in fact if there is some error in the measurement there have to be some correction mechanism to correct the speed estimate; so open loop estimation have error correction mechanism.

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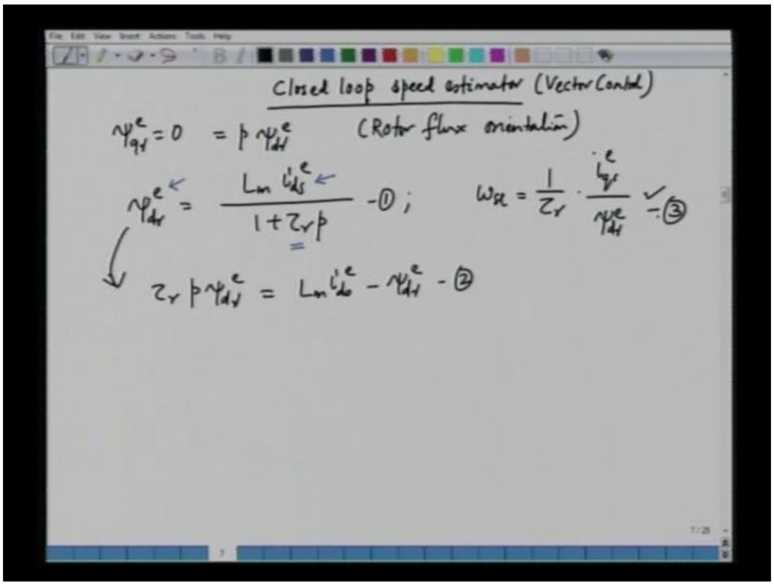

So, we go for what is called a close loop speed estimator. So, we see how we can implement close loop speed estimation. So, here we rely on the principal of the vector control of course we have to understand that this is basically for vector control. And we know that we have this equations psi square equal to 0 and P psi d r square also equal to 0 this is for rooter flux orientation. And we know that psi d r e is equal to L m in to i d a c by 1 plus tau r P. So, this is already evaluated when we talk about for rooter flux oriented vector control we saw that whenever we warring the flux component of the current i d s is the flux component of the current; the flux is delayed and the delayed is the rooter time constant.

So, this is flux component of the current and if you change this the flux response will be deled by the rooter time constant. So, this 2 equations will and also we know that the expression of this feet is equal to 1 by tau r into psi q s by i d r e. So, this respect to the 3 feet which have be evaluated for the rooter vector control then from this equations the equation form the flux; we can simplify this tau r into P psi d r e that equal to L m into i d a c minus psi d r. So, we can call this as the equation number 1, this as equation number 2 and this as equation number 3. So, this 3 equation will help us estimate the rooter flux in the close loop factor.

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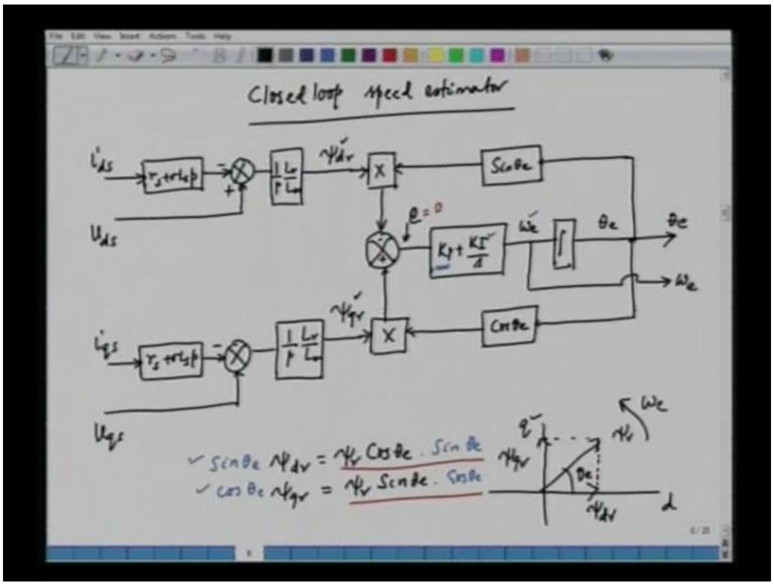

So, we will see the block diagram how we can estimate the rooter flux in a close loop factor. So, we will see close loop speed estimator. So, we will start with original our voltages and current. So, this is my voltage v d s and this is the current to the i d s. And we have r s sigma d s P as we seen earlier; we have subtracted there what we have is 1 by e L r by L m and this is giving us psi d r. And similarly in the q axis we can have current form the voltages r s plus sigma L s P this is i q s minus. And then we have v q s this is 1 upon P L r by L m and this will be giving us psi q r.

So, this flux psi d r and psi q r are estimated in the previous expression. So, this we have also evaluated here from the voltages and current. And from psi d r and psi q r we will try to do some way, some technique to estimate the simian speed. Now, we know that whenever we have a rooter flux with rotating at a speed of omega e; we have 2 different components we have d axis here and q axis and this angle is theta e. And if we project this is i r d and q axis respectively; we can take the projection of this is called psi d r and if we project this on q axis we called this psi q r.

So, psi d r and psi q r of the projection of the rooter flux vector and the d and q axis respectively. So, we can evaluate that is psi d r and psi q r in terms of psi r. So, we will say that psi d r is nothing but psi r in the cos of theta e this we can say here. And similarly we can say that psi q r is equal to psi r into sine into theta e because the d axis is the cost component and the q axis is the sine components. So, we have evaluated here sine here and psi q r from the voltages and the current. And then what we will do here we multiplied; what we multiplied in this case with the psi d r we multiplied sine theta.

So, we multiplied with psi d r sine theta e and we multiplied sine q r is cos theta e. So, if we multiplied sine theta e with psi d r it will be what we have do here; we are multiplying sine theta e here with psi d r. And the sine theta e also available in the right side and i have sine theta e here. And with psi q r we are multiplied cost theta e here. So, I can have this in the left hand side also in the right side. So, we can see in this case that sine theta e into psi d r is equal to psi r in to cost theta e into sine theta e; cost theta e into psi q r is equal to sine theta e into cos theta e.

So, in facts this 2 quantity is same. So, what we can do here; we can have in the case subtractions. And the subtraction is going to give a 0 value the estimate is correct. So, I am subtraction this from that and then we are using a simple the p i controller which is a KP plus K I by F. And then it is integrated this is giving me the synchronous speed this is integrated. And what we obtain out of this is theta e and the theta e is the gives us speed back for cost theta and the sine theta respectively. So, here we have an error correction mechanism; if the estimate is correct we will have 0 value here this is will be 0. And this estimate is not a correct this A controller will be giving me finite output and I will automatically have correct mechanism will be built here.

So, we were discussing about the close loop a speed estimator for an induction motor. And we have an error here; the error is in this case e which is the subtraction of psi q r cos theta e and psi d r sine theta e. And the both have the same we already seen that these 2 quantities are exactly same. So, in the study state we can see that if the estimate is correct; if is the value of theta e is correct this is going to give me that s equal to 0 and we have a controller following the error. And this will have propositional gain and the integral gain; K P and K I by F the integrator will be sufficient to give me study state value; even if the input is equal to 0 the output not be equal to 0 because we have an integrator in this case.

So, this output omega e here. And we can integrate this omega e to obtain theta e and the theta e is feedback and sine theta e and cost theta e for this comparative. So, from this what we obtain; we obtain theta e and we obtain omega e. So, this estimator is going to give us omega e and theta e and we have to use some other technique to evaluate the speed; it means if you can have 6 speeds you can find out the rooter speed by subtracting6 speed form the synchronous speed theta e.

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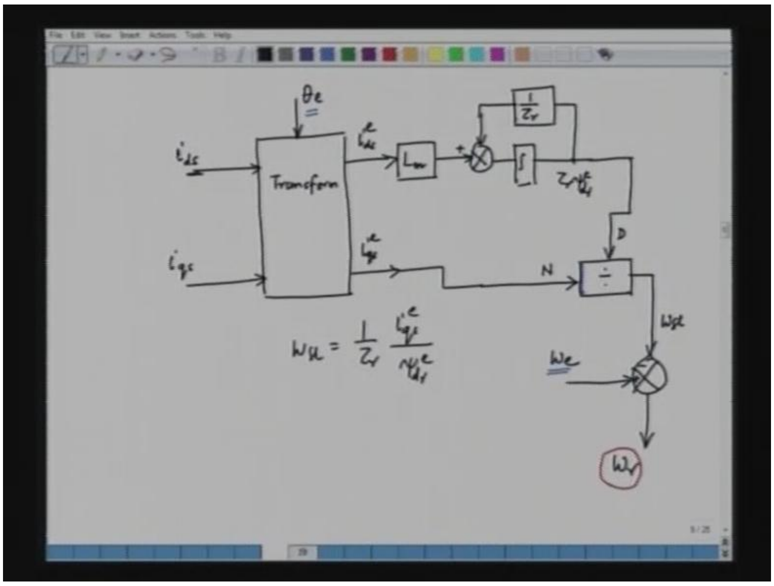

So, we have the transformation block here that we have already used. And in this case we can measure i d s and i q s there the stationary reference current i d s and i q s; we can use the transformation. And the transformation can have theta e has obtain from the previous block diagram. So, theta e that we obtain here can be straight back to this our theta e here. And this transform can transform this i d s and i q s here in to i d s e the rooter flux reference from i d s e and similarly i q s e this i d s and i q s are the variables in the rooter flux reference frame. And from i d s e and i q s e we can do some operation and find out the ((Refer Time: 38:08)).

So, what we do here is that we multiply in this case L m the magnetizing inductions and then we use a sub tractor and here is 1 by tau r; we integrate this. And this output is tau r into psi d r e. So, as per this equation we can see that we can use this equation that tau r into P psi d r equal to L m i d s minus i d r. So, if we take the right hand side we will subtract L m i d s minus psi d r e. And that will be giving us tau r into psi d r and that see in this block diagram. And the finally, the result is tau r into psi d r and that we are using a divider; in the divider we can use in the denominator and this as a numerator. And this going to give up omega s l itself because we know that omega s l is given by 1 by tau r in to i q s e by psi d r. So, we have psi d r in to theta and we also i q s e by the transformation we obtain i q s e and from this 2 we can find it ((Refer Time: 39:56)) that is omega s l.

And, we know that we have already evaluate omega e. So, what we can do here; we can again use the sub tractor this is minus. And we can use the signal omega e that is already available here in the previous block diagram. So, this is already known so this is omegas e can be fed here. And what we finally obtain out of this is omega r. So, this is our estimated rooters speed. So, this actually is the method or estimated the rooter speed loop fashion this is the close loop because we have an error connection mechanism. And the error connection mechanism is the available here using a p i controller following an error is the study state the error is going to be equal to 0; unless the error is 0 the p i controller will be give an action either increase or decrease the value. So, omega you, will be so adjusted that error became equal to 0.

So, the speed of the clock vector is the omega e that is going to adjusted by the mechanism and hence this is called a close loop speed estimate. And this estimator will definitely have better parts than an open loop one in the sense whenever we integrated there is scope of an error. But in this case since we have a p i controller this error will be minimize and the omega e the speed of the rooter flux vector will be very accurate. And if the omega e will be accurate theta e will be accurate and from that we can evaluate what is scrip speed. And from the scrip speed and the omega e we can evaluate the rooters speed. So, this is practically implemented in many application were we do not need any speed sensor.

So, with this background we have already discussed about the rooter flux oriented vector control the ((Refer Time: 42:05)) oriented vector control and the heater flux in the vector control. And we know now understand what is the meaning of the vector control of the induction motor. Now, we will so by mean of a problem how we can talk a problem in the vector control. And especially we already seen that air flux oriented control and the stator flux oriented control are little complex. And they are not very much in use the most popular vector control method is rooter flux oriented victor control.

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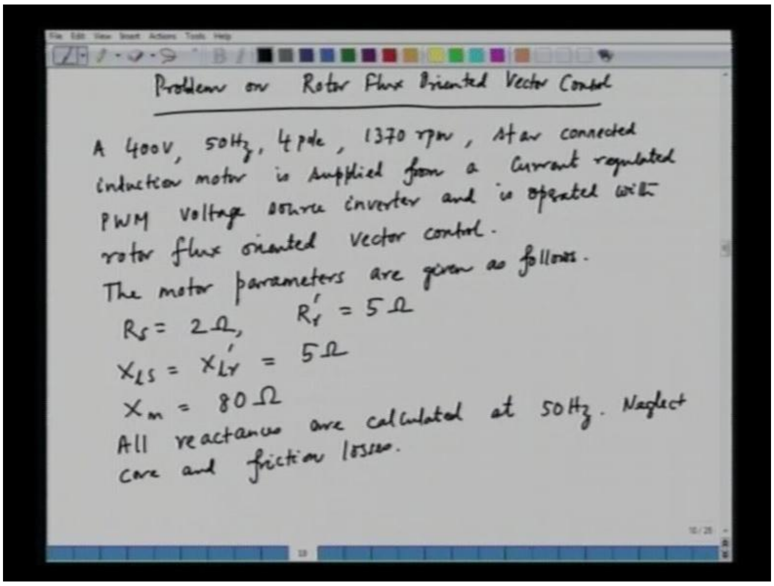

So, today we will solve a problem on rooter flux oriented victor control. So, let me write the down the problem statement this is a numerical and we have to solve this particular problem; the problem as follow a 400volts, 50 H z, 4 pole 1 370 r p m, star connected induction motor separate form a current regulated P W M voltage source inverter and is operated with rooter flux oriented vector control. The motor parameter as given as follows; the parameters are R s equal to 2 ohms, R r prime refer in the primary side 5 ohms the leakage reactor of the stator same as the leakage reaction in the rooter refer in the primary side that is 5 ohms the mintage indexation equal to 80 ohms. All reactions are calculated and 50 H neglect core and frication losses.

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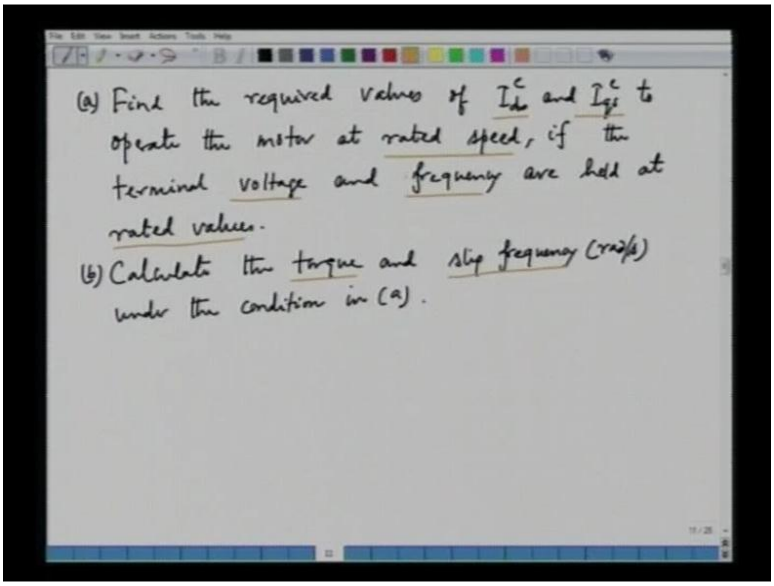

Now, what we have find out is the following; we have to find the required value of I d a c and I q s c to operate the motor at rated speed; if the terminal voltage and frequency are held at rated values calculate torque and slip frequency that is in radiant per second under the condition in (a). So, this is a problem in which you have to solve and this is on rooter flux oriented vector control. So, we have to first understand that this say that machine operated under rooter flux oriented vector control the machine parameter are voltage, the frequency is given, the number of voltage is given, the rooter speed is given, the configuration is star connected.

And, it is states from P W N inverted in the correct control the parameter is also mention here this are basically equivalent parameter of an index machine they were well know. So, they are given here. So, we have to find out i d s and i q s to operate the motor dated speed; the speed is the rotted speed that is 1370 r p m. And the terminal voltage is the rated terminal voltage, the frequency also the rated frequency the terminal voltage and frequency at little rated value. And we also have to calculated the torque and the slip speed frequency as in the conditions (a) so with (a). So, we will make to attempt how to solve this problem in this problem what we have to do is that we have to first draw the equivalent circuit of an induction machine.

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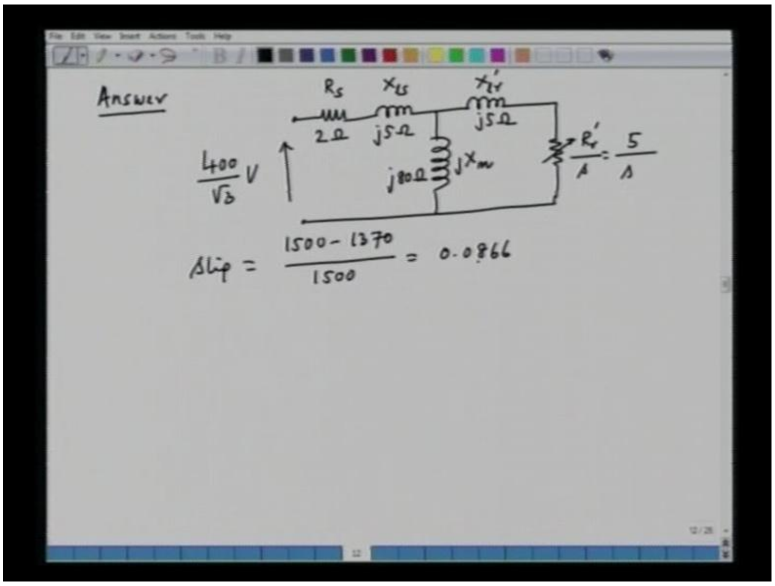

So, the equivalent circuit looks like this. So, we have the steady steady equivalent circuit of an induction machine for phase this is the applied voltage for phase is 400 by 3 root volts. And this is the stator registrant, the stator leakage reactants the rooter leakage reactants. And the rooter registrants and the mitaging reactants and the values are already given 2 ohms and 5 ohms this is 5 ohms this is 80ohms and R r is 5 ohms. So, we have 5 ohms by the slip yes. So, this actually the equivalent circuit and this case we find out the rated slip.

So, the rated slip we given us 1500 minus 1370 by 1500 that equal to 0.0866. So, we have all this parameter of the machine available to us we have the voltage we have the frequency information mechanism is also given to us. So, we can find out the imp rents of the machine. Since form this side and we can divided and find out the stator current i s. So, in the next lecture we will be discussed in the detailed how to find out the stator current how to find out the corresponding torque and flux component current and the slip speed of the induction machine.