Advanced Electric Drives
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Lecture - 9

Welcome to this lecture on Advanced Electric Drives. In the last lecture, we have just started the vector control of induction motor, which is also called the field oriented control or trans vector control. This is a advanced control technique for induction motor, in which we can control the torque with high dynamic response. So, today we will start with the vector control of induction motor.

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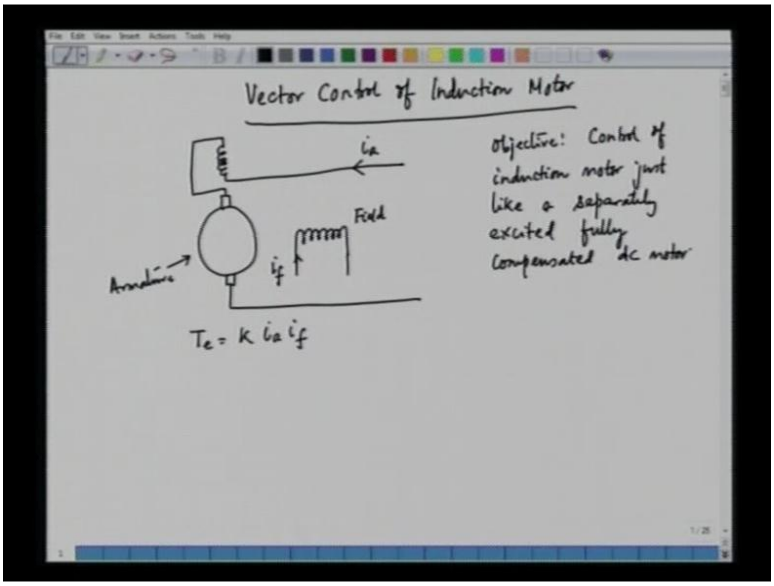

Now, by vector we mean there has to be an amplitude anal phase angle, now when we are controlling an induction motor we are controlling the stator MMF both in amplitude and phase angle. So, when you are controlling the stator MMF with amplitude and phase angle, we call that be vector control, the primary objective of vector control is to control an induction motor, similar to that of a separately excited d c motor. There has to be a control similar to separately excited d c motor, because in d c motor we have separate brush armature and field, so let us see the structure of a d c motor.

So, ((Refer Time: 01:48)) this is d c motor, we have, we have brushes here this is armature and we also have a field winding, this is the armature of the d c motor. And often what we have in case of large d c motor, we also have an compensating winding, the purpose of the compensating winding is to neutralize the effect of armature reaction. And the compensating winding is connected in series with the armature, and the MMF of the compensating winding is in opposition to the armature MMF, so that there is a cancelation of the armature MMF and effect on the field is reduced.

So, we can also have the compensating winding here ((Refer Time: 02:44)), and how do we connect it, we connect it in the following fashion, so we have the armature current. We can say this to be i a and we have the field current, which you can say to be i f and we know that the torque is equal to K in i a into i f ignoring magnetic circulation, so the objective of vector control is to control an induction motor just like a d c motor. So, the objective in this case, control of induction motor just like a separately excited, fully compensated d c motor.

And we have the flexibility in this case, we can control the torque by if the controlling i f and i a, but controlling i f will be accompanied by delay, so we do not control i f we keep i f constant and we control i a to control the torque of the d c motor. Similarly, in case of an induction motor although apparently we do not have any field and armature, we have to identify a field current or a flux component of current, and armature current or a torque component of current. So, that we can control this independently, we can control the flux independently and we can control the torque independently by some other component of current.

So, this concept of field orientation or vector control was given by a scientist call Felix Blaskay, way back in 1969. And that time he introduced a concept of field orientation, but it was difficult to implement the field orientation for some time, because of non availability of flux digital signal processing devices. We have to have faster computer to process the signals is real time to be able to control an induction motor, just like a d c motor; so let us try to see the concept behind the vector control of induction motor.

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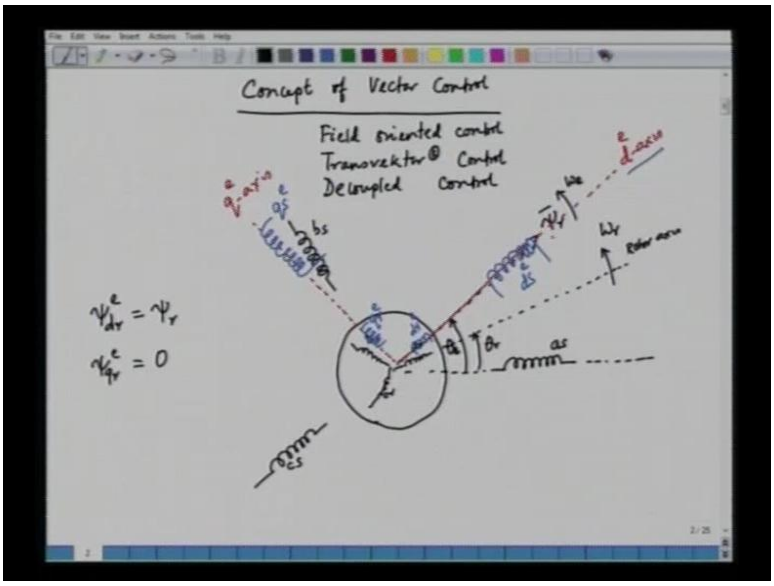

We can call this to be also field oriented control or trans vector control or decoupled control, now if we take a three phase induction machine, we have three phases, phase a, phase b and phase c. We can draw the three phases of the machine, this is the rotor and we can have one phase here, we can have the second phase here and we have the third phase here. And similarly, the rotor can also have three different phases phase a, phase b and phase c, so these are the status phases, and these are the rotor phases.

And rotor is rotating this is rotor axis ((Refer Time: 07:05)), and the rotor is rotating at a speed of omega r radiant per second and the stator is stationery and this angle, is the rotor angle that is theta r. So, what we do here that we are talking about three phase symmetrical induction machine, the rotor is rotating at a speed of omega r, we analyze a machine from a synchronously rotating reference frame. And the reference frame is so chosen that, the reference frame is attach to the rotor flux vector that is extremely imported, that we are talking about the reference frame which is attach with the rotor flux vector.

So, we can say for example, so this is the rotor flux vector and this we can say to be psi r which is also rotating and the rotor flux vector is basically a flux vector, that is rotating in the space with synchronous speed and the synchronous speed is omega e. So, this is the synchronous speed which with the rotor flux vector psi r is rotating, it is a vector have been amplitude phase angle. And when this is rotating the angle between the flux vector and the stationary phase a axis, this angle is theta e.

So, what we do we take a reference frame and the reference frame is attached with the rotor flux vector, so we will choose a d-axis, so this is our d-axis ((Refer Time: 08:59)) and we can also choose a q-axis orthogonal to d-axis, so this is our q-axis. And this d q-axis are rotating with the rotor flux vector at synchronous speed, and synchronous speed is omega e and since, this is very special reference frame. We call this reference frame to be d e and q e, d superscript e and q superscript e symbolizing that, these are the reference frame attached with a rotor flux vector.

And when we are analyzing this from rotating reference frame, we can always have fictitious winding like d e s winding and q e s winding, so we can have the stator windings which are fictitious. So, we can have the windings here in the stator and this you can call to be d s winding, but this is rotating with the rotor flux vectors, so we can call this to be d s superscript e. And similarly, we can have a q s winding and the q s winding is also rotating winding, we can call q s e and similarly, in the rotor we can always have a equivalent rotor winding also, like d r e and q r e.

So, we can have a rotor winding here in the rotor, this is d r e and similarly, we can have q r e as we have seen in case of Crohn's simitive machine model, we can have two windings in the stator and two windings in the rotor. But, these windings are not stationary they rotating at the speed of rotor flux vector, because the reference frame is attach with the rotor flux vector. Now, this is a very special reference frame, now if we are taking this reference frame what is the advantage, the advantage is this, that if we are orienting the d-axis of the reference frame.

This is the reference frame d-axis along with the rotor flux vector that is psi r, we have this following equation, the equation is this that psi d r e is equal to psi r. You can see that if I find out the d-axis component of the rotor flux the total rotor flux in the oriented along the d-axis. So, we can say that the d-axis flux is entirely psi r and if I ask this question what is psi q r e, what is the component of rotor flux vector or the rotor flux along the q-axis rotor, and that will be equal to 0.

Because, the rotor flux is entirely along the d-axis there is no component of the rotor flux along the q-axis, so we can always say that psi q r e equal to 0, so this is very similar to that of a d c machine. Now, if you take a d c machine in this case that we have the flux along d-axis, so this is our d-axis ((Refer Time: 12:32)), so we can call this to be the d-axis here and this is the q-axis. And we can always say that, the total flux is along the field, this is the flux produced by the field winding, what about the q-axis flux, the q-axis flux is 0.

Because, in the q-axis we have the armature winding no doubt, we also having compensating winding and the compensating winding is compensating for the armature flux, it is canceling the armature flux. And we are talking about a fully compensated d c motor and due to this the q-axis flux in the rotor is 0, so we can say that there is no q-axis flux, so in this case the q-axis flux does not exist. So, we are trying to have an analogy between an induction machine and d c machine in a rotating reference frame, and the reference frame rotating at a synchronous speed.

And if the reference frame is rotating at a synchronous speed, all the s c variables will appear as d c variable, actually if you see the phase a, phase b and phase c of a induction machine, the currents are ac current. But, this ac current will appear as dc current, if we view them from a synchronously rotating reference frame. We can take an example suppose two trains are moving at a same speed, if the two vehicles are moving at a same speed both the vehicles are moving, and a person is seated in one of the vehicle, he will observe the other vehicles to be stationary.

Although both the vehicles are moving the relative velocity between the 2 is equal to 0, so if we are having a moving observer, moving at the same speed, the speed of the other vehicle from the moving observer will appear to be equal to 0. Similarly, if we are house in a reference frame rotating synchronously, the variables seen from the reference frame will appear to be d c variable. Because, there is no relative velocity between the reference frame and the a c quantities in the study state.

So, if we try to see that this is our currents, ((Refer Time: 15:02)) this is i d s e in the d-axis and this is i q s e in the q-axis. And similarly, we can have i d r e in the d-axis rotor and we can have i q r e in the q-axis rotor and this current will be d c current in the steady state. So, since the currents are d c currents, we can think of a d c machine we can visualize a d c machine in phase of an induction machine, so to be able to control we have to derive from equation, and the equations will give us the control scheme for vector control.

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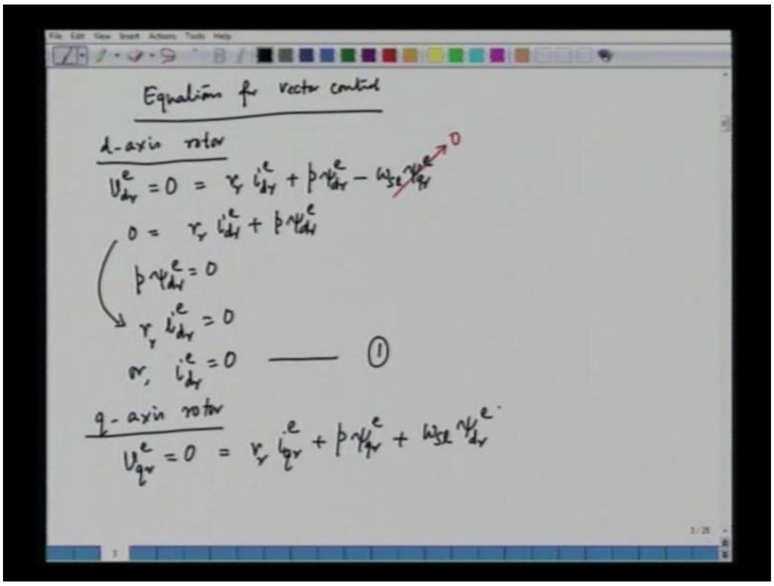

So, what we will be doing in this case, we will be writing down the equation for d-axis rotor, so we are writing down the equation for the d-axis rotor. So, we can say that v d r in the rotating reference frame that is superscript e that is 0, because the rotor is short circuited, that is equal to r r i d r plus p psi d r. And if you see in this case, the relative velocity between the reference frame and the rotor is omega e minus omega r, the reference frame is rotating at a speed of omega e. And the rotor is rotating at a speed of omega r, and the differential speed between them is omega e minus omega r and we call this speed to be the split speed.

So, that is written as omega s l ((Refer Time: 17:10)) and omega s l is call the spilt speed, so when we are writing down the equation of the rotor, the actual winding a rotating at omega r, physical rotor is moving at a speed of omega r. But, the hypothetical winding in the rotating reference frame they are moving at speed of a omega e, the relative velocity between these two is omega e minus omega r. And that is the speed at which the rotationally induced e m f will appear in the rotor equation.

So, we can go back to our equation here ((Refer Time: 17:45)), so we have minus of omega s l into psi q r, so this is the first equation which is in the d-axis. Now, we have already seen the psi q r is equal to 0, so we can cancel this, this is equal to 0, so if psi q r is equal to 0 we will again simplify this, we can say that 0 is equal to r r i d r plus p psi d r e. Now, when we are writing down all these equations, all the variables are referred from the primary side, so although we do not show in terms of prime variable, we assume that all the variables are observe from the stator.

So, the effective number of terms have been multiplied, the parameters are also seen from the primary side, so this equations are all taking from the primary side, so this is what we have here. And if we see in this case ((Refer Time: 18:46)) that psi d r equal to psi r and we would like to keep the flux constant, because if we change the flux, the flux is associated with a inductance, and the flux cannot be change is synchronously, it will take some time for the flux will change.

So, if we change the flux the torque response will be delayed and to change the torque what we do, we keep the flux constant, so what we say here that psi r is kept constant or the rotor flux kept constant. So, if psi r is kept constant or psi d r kept constant, we can say here that p psi d r equal to 0, and from this equation what we obtain here is that r r i d r equal to 0 or i d r e equal to 0, so it means there is no d-axis rotor current. To achieve the d-axis rotor winding is upset or that winding is not having any effect on the machine performance.

So, this is the first equation of the vector control, there is in the d-axis we have i d r equal to 0, so this we can say as number 1 ((Refer Time: 20:10)). So, similarly in the q-axis rotor, we can write down the equation for q-axis rotor v q r e that is short circuited that is equal to 0, that is r r i q r plus p psi q r plus omega s l psi d r. We are again writing down this equation in the rotor flux reference frame and the reference frame is rotating at synchronous speed, and speed of the reference frame is omega e, that is why the speed induced e m f is appearing with a factor of omega s l omega s l is the script speed. Now, in this case this is equal to 0, because we do not have any q-axis flux ((Refer Time: 21:15)) psi q r is 0 here and because of this, this quantity will be vanish. So, we can say in this case 0 is equal to r r i q r plus omega s l psi d r e.

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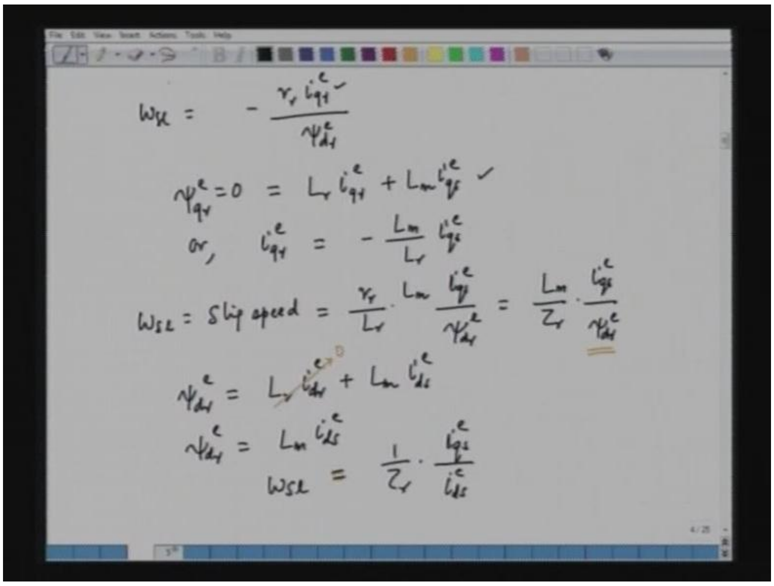

And we can find out the value of omega s l here, omega s l is equal to minus of r r i q r e by psi d r e, so this is the expression for the split speed. Now, this split speed expression is quite interesting, the slip speed is proportional to i q r e and it is inverse proportional to psi d r e. Now, we can substitute for i q r e because i q r e is the rotor current in the q-axis, on the rotor current are not easily acceptable, so we have to replace the rotor current by stator current.

So, we can say here, that psi q r e equal to 0 and that is equal to L r i q r plus L m i q s or we can say here that i q r e is equal to minus of L m by L r i q s e, so what we will do here we will substitute for i q r e in this case. So, we can rewrite this equation for the spilt speed that is equal to r r by L r into L m i q s e by psi d r L r by r r is called the inverse of the time constant. So, we can say in this case it is L m by tau r into i q s e by psi d r e, so the slip speed expression will be useful when we control the induction motor with vector control.

Now, here we can also another simplification, we know that psi d r e is equal to as we row the expression for psi q r e similarly, we can write for psi d r e, psi d r e is L r i d r plus L m into i d s e. And we have already seen that i d r e equal to 0 ((Refer Time: 24:01)), this is what we have already seen. So, we can substitute this i d r e equal to 0 in this expression, so this will be 0, so this vanishes in this case. So, what we have here is that psi d r e is equal to L m into i d s e, now it means the rotor flux can be control only by stator current.

If we vary i d s e we can change the rotor flux and psi d r e is same as the total rotor flux that is psi r, so when we change i d s e we can change the rotor flux. And the expression for the slip speed, we can replace psi d r e by L m into i d s e, so we can write the expression for the slip speed and the slip speed here is 1 by tau r into i q s e by i d r e. So, this expression for the slip speed will be useful for us, when we control the induction motor with vector control, now let us see how it will be useful. So, we have been able to find out the slip speed and the other equations.

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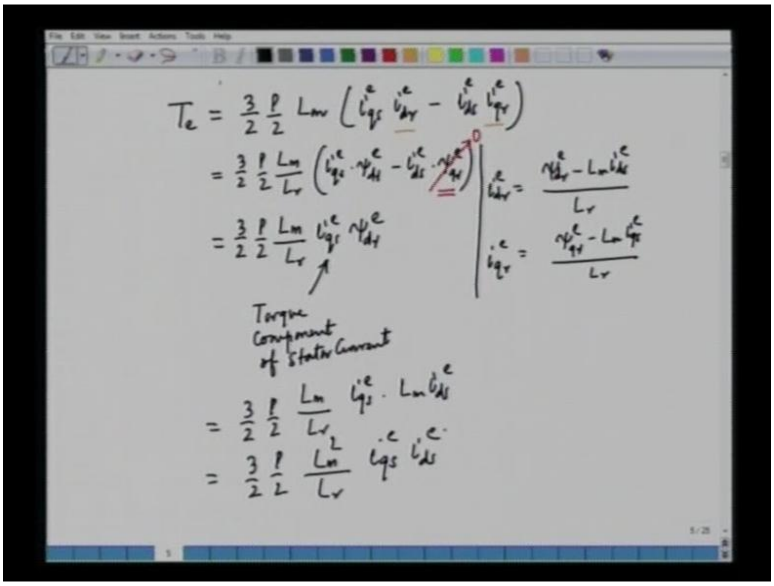

Now, what about the torque, torque equation is given as for an induction motor, we know it is 3 by 2 into P by 2 into L m into i q s i d r minus i d s i q r. And since, we are talking about the rotor flux reference frame will have to put a subscript here, so this is the torque equation of an induction motor. And we can further simplify this and this if we simplify this what will do here, we will replace this i d r by psi d r minus, we can say here L m into i d s by L r.

And similarly, we can we can substitute for i q r, i q r is psi q r minus L m i q s by L r, so if we substitute for this i d r and i q r we can get back the torque expression in a different form. So, we can rewrite the expression for the torque, 3 by 2 into P by 2 and after simplification we will get L m by L r into i q s into psi d r minus i d s into psi q r. So, ((Refer Time: 27:23)) this is the expression for the torque of an induction motor, as a function of the stator current and the rotor flux.

And this equation will give us the equation of the torque as we have seen in case of d c machine, so what we have here is the following that we have psi q r equal to 0. Now, if psi q r equal to 0 we can make this equal to 0,and if psi q r equal to 0 we can rewrite the expression for the torque of 3 by 2 into P by 2 in L m by L r into i q s into psi d r. And this is a simple expression compare to a very complex equation of an induction motor and the torque can be produce by the product of two variable, and one is the flux and other is the component of stator current.

So, this is call the torque component of current and this is the flux, so we can rewrite this expression for the torque as 3 by 2 into P by 2 L m by L r i q s e. And we can substitute for psi d r and psi d r is L m into i d s e, so that will give us the following expression 3 by 2 P by 2 L m square by L r into i q s e into i d s e. So, we see that the equation of the torque current induction machine it just like a d c machine.

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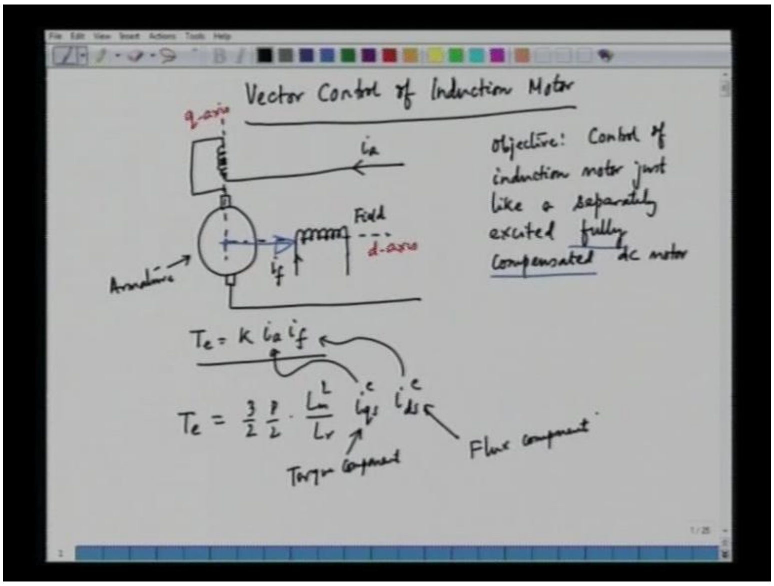

If you see the d c machine toque equation, what you have is that T e equal to K into i a into i f and what we have here is something very similar, we have in case of an induction machine that we have just seen, it is 3 by 2 into P by 2 into L m square by L r into i q s e into i d s e. So, this i q s e is compare able to i a, so we can say that this is something similar to i a and i d s e is something similar to the field winding current, so we have two types of currents here, two component of current that is i q s e and i d s e; i q s e is call as we have already seen this call the torque component of current and i d s e is call the flux component of current.

So, we have two, that is i q s e, the flux component of current that is i d s e, so if we control these two currents, we can control the torque of an induction machine just like a d c machine. So, usually what we do here is the following, we keep i d s e constant, so ((Refer Time: 30:49)) this we can keep constant, because if we change i d s e the flux will change and in the flux changes there will be delayed. So, we keep i d s e constant and we change i q s e for the torque control, so the torque is control not by i d a e primarily by controlling i q s e. Because, when we control i q s e there is no delay involve, so i q s e can be control quickly and the torque will response linearly to i q s e.

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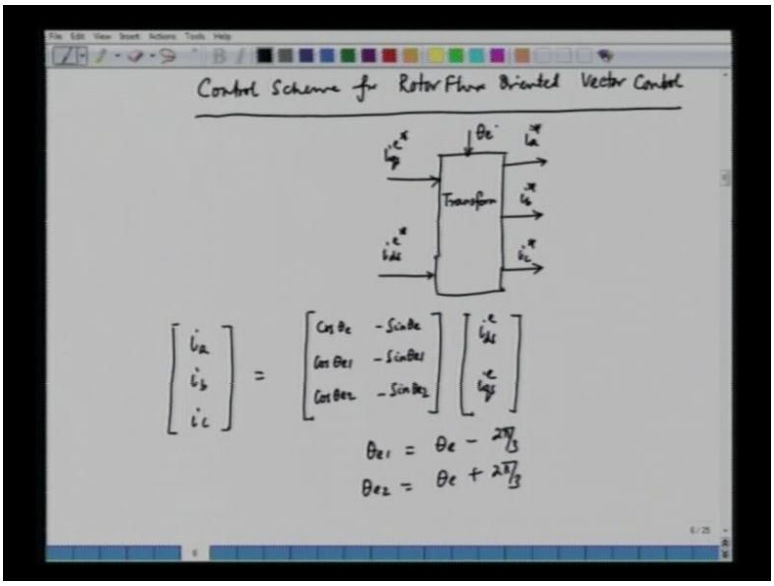

Now, let us see the control scheme, control scheme for this is call rotor flux oriented, vector control, this is call rotor flux oriented vector control, because the reference frame is oriented along the rotor flux; and hence, it is call rotor flux oriented vector control. Now, we have two currents in this case i d s e and i q s e, but this i d s e and i q s e are hypothetical current, they are the current in the rotating reference frame which is non existing and this is only in our mind this is only in the concept. Now, when we are actually controlling the machine we have to translate or we have to transform, this i d s e and i q s e into the actual current of the machine and the actual currents are i a, i b and i c.

So, we have to transform this i d s and i q s into i a, i b, i c, so what we have to have here is the following we have to have a transformation. So, this is our i q s e and this is i d s e and we have to transform these two current components into the actual current of the machine and that is i a, i b, i c. ((Refer Time: 33:13)) Let us see our original diagram here actual currents in the machines are i a and this is phase b, i b and this is phase c and i c. And we have been able to evaluate what is i d s e and what is i q s e these currents we know, but these currents are hypothetical current, although we can do the control in the i d s e and i q s e, we have to actually inject i a, i b, i c into the machine winding.

So, we have to transform this i d s e and i q s e into i a, i b and i c and that involves the transformation, and if we see the this reference frame is having an angle of theta e with a phase a. So, the transformation will involves theta e, so the transformation that is applicable here is a transformation that is involve theta e, so we can say here that if you want to get back i a, i b, i c we have to use a transformation as follows. So, the transformation in this case is, i a, i b and i c, this we have to obtain from i d s and i q s.

And what is the transformation here, ((Refer Time: 34:46)) this transformation we have to find out, the transformation will involves theta e, now the transformation will be as follows, this will be cos theta e, this is cos theta e 1, this is cos theta e 2, this is minus of sin theta e minus of sin theta e 1 minus of sin theta 2. And where theta e 1 is equal to theta e minus of 2 pi by 3 and theta e 2 is equal to theta e plus 2 pi by 3, so this is the transformation that will transform i d s and i q s into i a, i b, i c.

And when we obtain this i a, i b, i c we can use a inverter to inject this current to the winding of the actual machine, so in fact these currents are the reference current. So, we can say here i a star i b star and i c star, they are not the actual current, they are the reference current, so they have to impress on to the machine winding. Similarly, these currents are also i q s star and i d s star, so we can have a inverter to inject this current on to the machine winding. And this transformation as we have seeing ((Refer Time: 36:15)) this will involve theta e and what is this theta e, theta e is the angle of the rotor flux vector, if we see as we have already drawn here this angle is theta e.

Now, as we have already seen that we need theta e for the transformation from i d s, i q s to i a i b i c, now there are ways to evaluate theta e, theta e can be evaluated indirectly, it can also be evaluated directly. And accordingly we can have an indirect vector control or a direct vector control, evaluate now rotor flux vector angle theta e.

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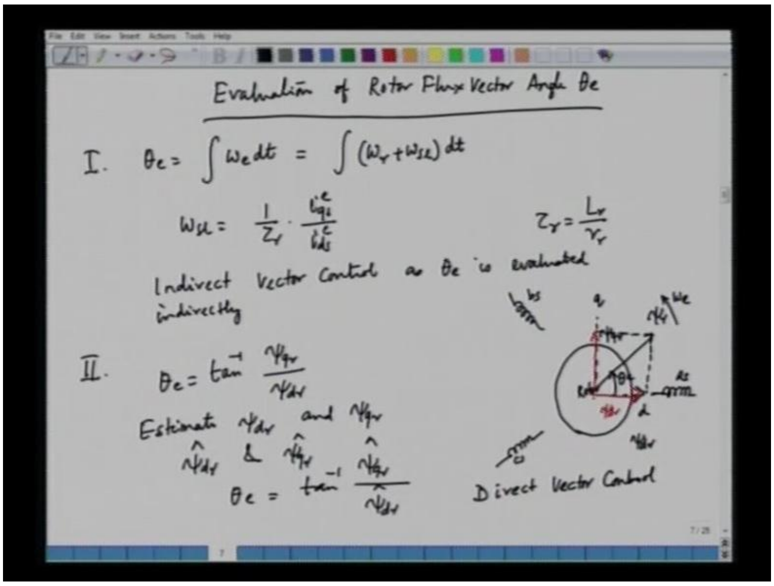

So, we know that theta e is obtained by integration of omega e, omega e is the speed of the reference frame, and this is also the speed of the rotor flux vector. Now, if we integrate this omega e, we get the angle that is theta e that is one way and how do you find out this omega e, omega e can be evaluated as omega r plus omega s l. So, if we add the rotor speed and slip speed we get the synchronous speed that is omega e, now slip speed can be calculated we already seen that slip speed is given by 1 by tau r into i q s by i d s.

So, if we know i d s and i d s and if we know tau r and tau r is the rotor time constant that is equal to L r by r r, we can evaluate what is the slip speed there is omega s l, so slip speed can be easily calculated. And the rotor speed that is omega r can be measured by using a deep sensor or an encoder, so we can measure the rotor speed we can calculate the shift speed and then the summation on these two will give us the speed of the rotor flux vector that is omega e, integration of that will give us theta e and theta can be use to transform i d s and i q s into i a i b i c.

Now, this is call indirect vector control as theta e is evaluated indirectly, this is one of the ways evaluate theta e, now the second method of evaluating theta e is to change the rotor flux. If we can change the rotor flux in the d-axis and in the q-axis, stationary d-axis and q-axis, suppose we are having a machine, ((Refer Time: 39:34)) these are the machine windings the stator a f, b f and c f and this is the rotor, and we want the rotor flux vector. So, we can have some sensor in the rotor and this is our stationary d-axis and this is the stationary q-axis, so we can find out what is psi d r and we can find out what is psi q r in the stationary.

So, psi d r and psi q r can give us theta e, so we can say that theta e is obtain by taking the tan inverse of psi q r and psi d r, these are the stationary flux component psi d r and psi q r are the stationary flux component. Now, if we have a rotating flux, actual flux is rotating at omega e and this flux with a two component, one is psi d r this we can call to be psi d r, and this can also have component in the q-axis that psi q r. And the angle in this case is theta e, now if we want to evaluate the angle we have right angle triangle and the perpendicular is psi q r.

And the base is psi d r, we can evaluate the angle theta e a tan inverse of psi q r psi d r this is pretty straight forward, but the difficulty in this case is that how to sense the rotor flux. The sensing of the rotor flux is not very easy, because rotor is a moving member and housing a sensor inside the rotor is very difficult, and this cannot be use for retrofit application and hence, we cannot have rotor flux sensor inside the rotor. So, if we do not have rotor flux sensor, how to change the rotor flux, how to how to evaluate the rotor flux, that can be evaluated by using flux estimator.

So, what we can do is that we can estimate ((Refer Time: 41:54)) psi d r and psi q r and estimation of psi d r and psi q r can give us psi d r hat and psi q r hat. And then we can evaluate what is theta e from the estimate these are the estimates, and from the estimate we can calculate or we can evaluate what is rotor flux angle that is theta e, so this is call direct vector control. Because, in this case we are able to find out theta e directly without taking a help of slip speed, so we will now see a control block diagram of a vector control drive.

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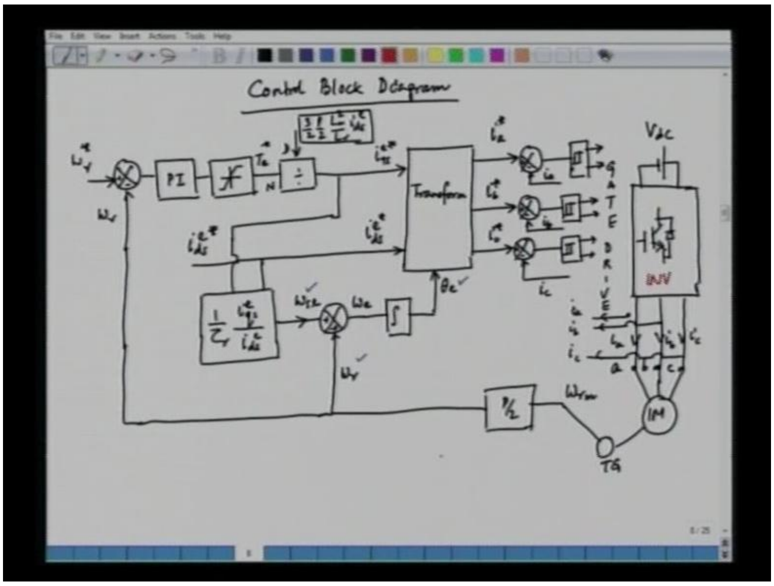

So, we have here the transformation block and this angle is theta e which use for the transformation, we have reference speed in this case omega star, then we are subtracting the actual speed. We are feeding into a P I controller and we can as well have a limiter in this case, and the limiter is use to limit the output of the P I controller, in case we do not have any limiter, some time the P I controller output can reach a very large value. So, to limit to the practical value we have to have a limiter after the P I controller.

And the output of the limiter is the reference torque T e star and this we can divide by 3 by 2 P by 2 L m square by L r into i d s e, so what we obtain here is i q s e, this is what we can divide here, this is the numerator, this one is the denominator. And this is i q s e star because this is the reference torque component of current and i d s e is given directly, what we have here is i d s e star, because we want to keep the flux constant and we are keeping i d s e constant. So, this i d s e star is fed directly we are not changing i d s e and from i d s e and i q s e we can evaluate the slip speed, the slip speed is 1 upon tau r into i q s e by i d s e omega s l. And we have the feedback from the two currents and then to the slip speed we are adding the rotor speed.

So, what we obtain here is omega e, omega s l plus omega r is equal to omega e and that when we integrate this get theta, so the integration of omega e theta e and this theta e will conform i d s e star and i q s e star into the 3 stator current i a star i b star and i c star. And then we have the comparators here, we can have the current comparator and this we can have some sort of controller for three independent phases, this is phase a, this is phase b, phase c. Here is a inverter we have d c input of the inverter and this is an inverter may be having ((Refer Time: 48:00)), and then we have the induction motor here, the inverter will have the three phase output.

And outputs are stay to the induction motor, and we have a speed sensor or a tachogenerator here, the tachogenerator will be giving the output and then this is omega r this will be giving us a mechanical output. So, what we can do here is that, we can multiply this by P by 2 or 3 by 2 this is P by 2, this will be omega r m the mechanical speed then we can multiply by P by 2 to get the electrical speed. And the electrical speed is fed back here, and this what we are controlling is the electrical speed which can always the scale.

So, this omega r here is the electrical speed, omega r m is the mechanical speed and hence we have to multiply the mechanical speed by pole pair to obtain the electrical speed. So, this is the close loop control and this will be giving the gate drive signal for the inverter, so these are the gate drive signal, and this feedback will be i a, this is the actual current that is fed back. Here we have i b and here we have i c, and in this case we have three different phases ((Refer Time: 49:59)) this is a, this is b and this is c, and the currents here are i a, this is i b and this one is i c.

So, we can have the current sensors, we can have the current sensors in three phases to give us i a, i b and also for phase c we can have a another current sensor to give us these three signals. And these three signals can be fed back as the feedback signal for phase a, phase b and phase c inverter control. So, this actually is a close loop control block diagram for indirect vector control, it is call indirect vector control, because the slip speed is calculated. And we are adding the slip speed with the rotor speed to evaluate the transformation angle that is theta e, now we will focus on the control of the inverter this is the inverter. This inverter is a voltage source inverter, so let us try to see what is the structure of this inverter? So, if you see the structure of the inverter, this inverter would be a three phase inverter something like this.

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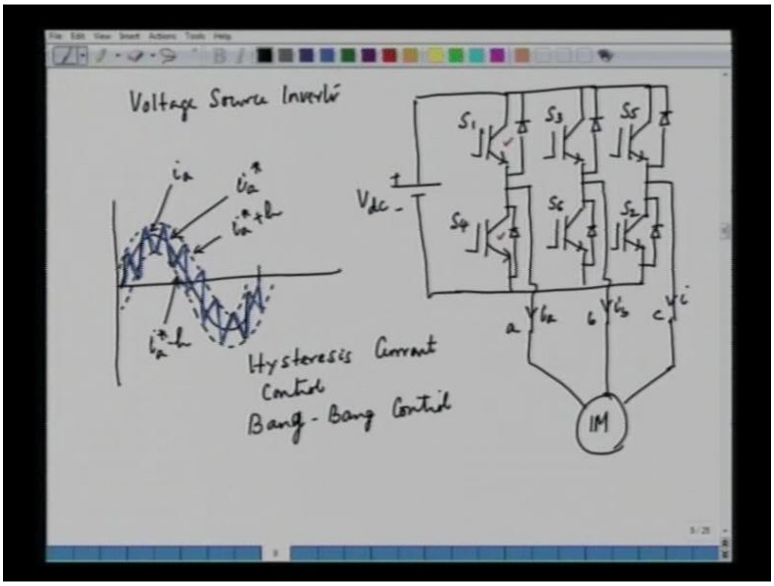

And this is the d c voltage, and these are the three phases of the inverter, we have say for example phase a, phase b and phase c, and since this is a V f i the transistor will have anti parallel diode, so we have the diodes here to facilitate by directional flow of current. So, this is the voltage source inverter and the currents are in this case i a, i b and i c and this will be feeding to the motor, so we have phase a, phase b and phase c of the machine, so the inverter fits to the induction motor.

And we have the inverter switches, we can call this to be S 1, this to be S 3, this to be S 5, this to be S 4, this to be S 6 and this to be S 2. So, we have 6 switches and when we have 6 switches we have 6 gate drive, so the 6 gate drives can be fed to the transistor 1, S 1, S 2, S 3, S 4, S 5 and S 6. The objective is this that whenever we have the phase a current the actual current should follow the phase a reference current as faithfully as possible. So, in this case what we have here is the following, we have phase a current this is i a star and the actual current will follow the reference current within a bang.

So, this is how the actual current will look like this is i a, so what we do we have a reference current that is i a star we define a bang around the reference current, we have upper bang and lower bang. So, this is the upper bang call i a star plus h, star means the reference current similarly, we have a lower bang which is shown as a dotted line, so we can call this to be i a star minus h. So, what we are trying to do here the actual current is made to follow the reference current, within a upper bang and a lower bang and this is call hysteresis current control.

So, we can call this to be hysteresis current control, so if you talk about a particular phase say for example, phase a if you want to increase the phase a current, we switch on the upper switch. And if you want to decrease the phase a current we switch on the lower switch and go on doing like that and hence, the current will rise and fall, rise and fall, so it basically follow the actual current I mean the reference current within the band. So, this has got other name also we call this as bang-bang control, so we have to control the inverter in such a way at actual current with follow the reference current within hysteresis bang.

So, this is for phase a and similarly we can control phase b and phase c current and phase b is shifted from phase a by 120, phase c is shifted from phase b by 120. And the inverter is control in such a way that, the inverter with inject the actual current within a hysteresis bang of the reference current on to the three phases of the machine that is phase a, phase b and phase c.

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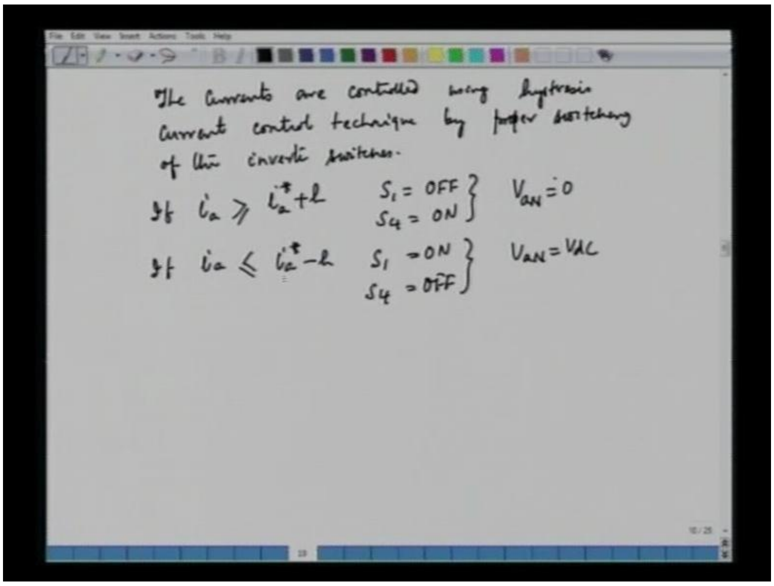

The currents are controlled using hysteresis current control technique by proper switching of the inverter switches. So, we can just have a logic, that if i a is higher than i a star plus h S 1 is turn off and S 4 turn on, and if i a is less than i a star minus h S 1 is turn on and S 4 is turned off. So, this means V d c is equal to 0 or the voltage here will be equal to 0, so it means we have V a N is equal to 0, and this means V a N equal to V d c. And if we see this inverter structure we can define a is P, and we can define N here and these are our three phases a, b and c, so we are concentrating on phase a.

Now, if we concentrate on phase a, we can define V a N, V a capital N, now if the current is hitting the upper bang it means it is increasing, so we have to bring it down, now we have to bring it down by switching the lower switch, the lower switch is S 4. So, in this case, if it is hitting the upper bang greater or equal to this, we can switch off the upper switch and switch on the lower switch, it means we can make V a N equal to 0 And if i a is less or equal to i a star minus h, it means the current is hitting the lower bang, we have to switch on the upper switch, may have increase the current.

The current can be increased by switching on the upper switch and switching off the lower switch, so that is what we can do here, that if i a is less than i a star minus h, we can switch on the upper switch and switch off the switch. And S 1 and S square complimentary, we can see this inverter structure, ((Refer Time: 59:52)) that these two switches are complimentary. The gate drive to S 1 is the inverse of gate drive to S 4, similarly the gate drive of S 3 is the inverse of gate drive of S 6, and gate drive of S 5 is the compliment of gate drive to S 2.

So, these are complimentary switches and this is basically the structure for one phase there is phase a, and we can similarly half for phase b and phase c. And hence, we can control the three phases as per the reference current requirement, and when we control the three phase current, the machine is automatically controlled on the vector control. So, in this particular lecture we have discussed the vector control of induction motor, we have seen how the vector control is similar to that of a d c motor control, we derived expression for the slip speed.

We have see what is the difference between direct vector control and indirect vector control, we have also seen a control block diagram of close loop speed control of induction motor with vector control. So, in the next lecture, we will try to see that instead of keeping the flux constant, if we vary the flux how does the response change; so we will see the vector control operation under variable rotor flux.