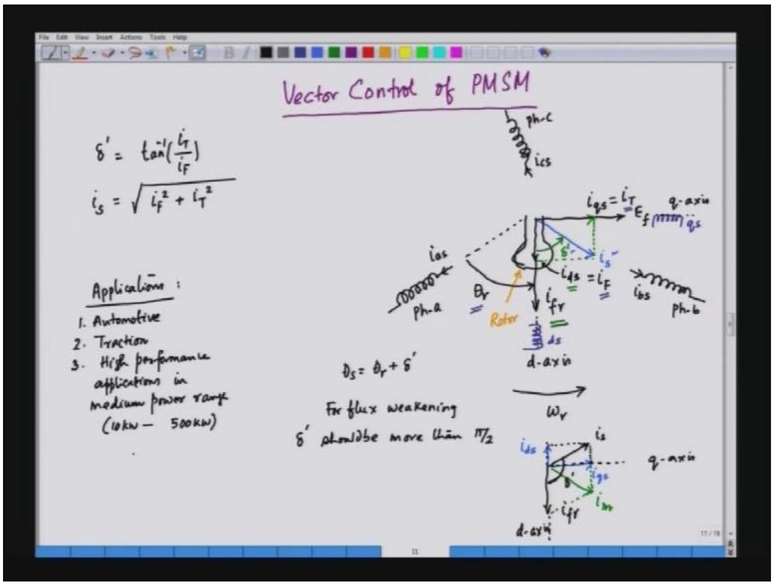
Advanced Electric Drives

Prof. S. P. Das
Department of Electrical Engineering
Indian Institute of Technology Kanpur

Lecture - 27

Hello, and welcome to this lecture on advance electric drives. In the last lecture, we are discussing about the vector control of permanent magnet synchronous motor or PMSM drive. By vector control, we mean we should be able to control a permanent magnet just like a DC motor. In other words, we should be able to control the torque component of current and a flux component of current independently. Let us took again a look at the feather diagram of permanent magnet synchronous motor.

(Refer Slide Time: 00:55)



So, we have the permanent magnet rotor which is shown by field winding and this is a corresponding current, the current is i f r the rotor field current. And then we have the induced t m a, because of the field winding flux that is i f r and this is E f, the stator current can be in any ((Refer Time: 01:31)) direction. So, we can bought the stator current like this; this is i S and we can say this is a d axis. This axis is called the d axis and the beret axis and this axis with the key axis or the cubature axis the stator current i a s can be decomposed into 2 components. One along the b axis and the other one is along the q axis. The component along the b axis will be in line with the flux the rotor flux, the component in q axis will be cubature with the flux.

Now, we can resolve this into 2 different components like this if we present on the key axis. This component will be known as i q s the q axis stator current and if you present this i a s along the d axis. We call this current to be i d s. So, we have 2 currents i d s and i q s we can end them in a big different way we can call i d s as i a f the flux component of current because we can see that i d s even shown with i f r, i f r is the rotor equivalent current. Rotor is actually a permanent magnet do not have any field winding in the rotor, but; however, i f r represents the effective rotor current due to the permanent magnet if you have a typical current i f r. So, i d s is along i f r and we will call that current to be i F. So, this is the flux component of current, we can call this to be i F. And similarly i q s is along the q axis, we will call this component of current to be i T the torque component of current.

So, in permanent magnet synchronous machine we have no freedom to value the rotor flux the rotor flux is constant. Because rotor is excited by a permanent magnet; however, we can control the flux from the stator side by controlling i d s. So, we are seeing a block diagram of this control. In the last lecture this block diagram is as follows; this is the close loop block diagram of a vector control permanent magnet synchronous motor drive. And we have 2 components of current that I was discussing that the flux component of current is i S. It is produced from the stator side, the torque component of the stator current is i T and this i F and i T and in the rotor reference frame. Now, what do we mean by rotor reference frame? We are taking a reference frame attached to the rotor; the rotor is rotating at rotors speed.

Now, if we see here this is the rotor and rotor is moving away. This is the physical phase a axis here the actual linings of the of the motors are like this; this could be phase a and phase b could be shifted from this by 120 and phase c is shifted from this by again by 120. So, this is phase a this winding is phase b and this winding is phase c. And this rotor is rotating at the speed that is equal to omega r; omega r is a rotor electrical speed. Now, if we see the angle between phase a and the b axis this angle is theta r, the rotor angle. And again we have already defined the angle between i F and i S; this angle is delta prime which is something like torque angle.

And we have already shown that the torque is the function of delta prime. So, in this situation the reference frame is attached to the rotor. So, we have already derived the equations for the d axis and q axis the d axis stator winding is housed here. So, this we can call to be d s the stator winding in the d axis and this winding is the q s the stator winding in the q axis. So, this reference frame the d 2 reference frame is attached to the rotor and this i T and i F are the currents in the rotor reference frame. So, we need to transform i T and i F into physical i a i b and i c and physical i a i b and i c are the currents in the 3 three phase tetro windings. So, in this case we have phase a we can call this current to be i a s phase b this current is i b s and phase c, this current is i c s.

So, what we need to do? We need to transform i T and i F this 2 currents; this is i T is a torque component of current and I F is flux component of current into i a s i b s and i c s. And for this we need a transformation, the transformation is involved theta r, because this frame the reference frame is rotating at omega r theta r is a angle here. So, when we transform this i F and i T into i a i b and i c we need the angle theta r. So, theta r will be will be fed here this is this will require theta r; theta r is already here. So, in this case, we need this theta r; this theta r will transform this into the stator currents. And the stator currents are i a s i b s and i c s. In fact, we do this in 2 stages, first of all we have 2 orthogonal components i T and i i F are mutually orthogonal to each other i T is in the q axis i F is in the d axis. So, we convert these orthogonal components in the rectangular coordinate into polar coordinate. So, this i F and i T are transforming to i S and delta prime.

So, we will be transforming this i F and i T into i S i S is this current the stator current and then delta prime is angle between the d axis and the current vector that is i S. So, how do we calculate delta prime? Delta prime is calculated once you know what is i T and what is i F, we can calculate delta prime as tan inverse of i T by i F that is of delta prime. And we also need a magnitude of i S; i S is a stator current which as the 2 components and the components are i F and i T and they are orthogonal component. So, as for the Pythagoras theorem, we can say that i S equal to i S square plus i T square under root. So, this i S is known and delta prime is known that we need to transform this i S into i a i b and i c. So, what we need with the rotors angle theta r. So, this theta r is added here. So, the total angle is theta s and theta s is this angle theta r is a rotor angle plus delta prime.

So, if the current vector i S is shifted from phase o by an angle theta r plus delta prime only this angle. What we do here? We transform this into i a s i b s and i c s. And then we can have inverter with current control, we compare the reference current this stars are actually reference current i a s star, i b s star and i c s star. And the 3 reference currents of the respective phases they are compared with the actual currents and the actual currents are obtained by hard senses. So, these are the actual currents i a s i b s and i c s they are obtained by having hard senses in the 3 phases of the stator of the PMSM drive. So, in sense i a s, i b s and i c s and these are used for feedback purpose. So, we feedback this actual currents i a s, i b s and i c s and we get a error there is comparator. And we have the error in the output and this error is fed to a hysteresis controller. So, we have we have a hysteresis controller here this is a hysteresis current control.

So, we have hysteresis controller here which will trigger or generate the great signals for the inverters, inverter here is a 3 phase inverter having 6 identity or 6 transistor. And this inverter is feeding the 3 phases of the PMSM drive. And the hysteresis controller will be generating the gate drive signals of this inverter. And the inverter will be driving the current into the stator of the permanent magnet synchronous motor from the control. Now, we also need the position information that is theta r is left ten by a position encoder. We have a position encoder here which is mounted on the rotor soft, we have rotor soft in this case the encoder is mounted in the rotor soft. And this gives us the mechanical position of the rotor that is theta r n. The mechanical position is multiplied by the pole payer that is p by 2 to generate the electrical rotor position that is theta r in the mode. We have the electrical rotor angle theta r and the theta r is used for transformation into i a s i b s and i c s.

And hence for transforming this into 3 phase current, we need the electrical angle theta r. And this is added with delta prime to give us theta s for the reference current generation as we already seen that the flux controller flux remain constant up to the base speed. And after the base speed we go for the flux weakening. So, this function generator generates constant field current like a vowed field synchronous machine. But in this case the flux is reduced by injecting a negative i d s how is a negative i d s injected we can we can say that in this phase diagram. So, here we can see that i d s is helping the rotor flux that is i f r, i d s and i f r are in same direction.

Now, if we take a situation where we have the fields here the field current here i f r and unit to go for flux wakening for flux weakening the result and flux has to be reduced. So, what we do here? This is d axis; this is the q axis v inject i S in such a phase angle; this angle is delta prime that i d s is negative i d s is in phase a opposition with i f r. Again here i S can be b compose in to 2 components; one is i q s; this is i q s the q axis component of the stator current. And then this component is i d s the d axis component of the stator current now we can see here the i d is apposing i f r. So, in i d s is opposing i f r the flux is reduce and the resultant of i F and i S is going to be low.

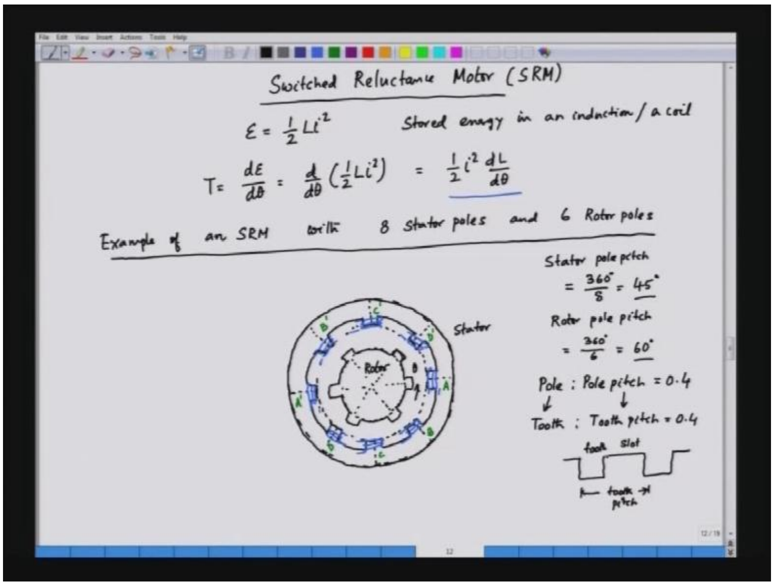
So, if we find out the resulted and c r also we can do that by comporting this par aglow low gram this is the resultant of i S and i f r. And we call that to be I m is the magnetizing current i m that will be reduce because of negative i d s and that what happens in flux weakening. In fact, will flux weakening delta prim will be higher the 90. So, if this angle delta prime is higher than 90 we can go for flux weakening. So, we can say that for flux weakening delta prim should be more then phi by 2.

So, we operate at constant flux up to the base speed and beyond the base speed be go for the flux weakening and that is achieved by having a negative i d s. So, this is the close lop control black diagram of the vector control permanent magnets synchronies model drive and this dive is quite popular and the application of this drive r in automotives also in high performance of applications. So, variable we need to have is high performance of application with compact size we go for.

So, the applications here automatic applications and that case we go for PMS in drive where the size of the motor is small it is compact. But the power is coats substantial sum times, this also use for traction application traction is also auto motif. But at live a higher power it means beyond 100 kilo watt 21 mega watt, we can go for this kind of motor. And then in high performance of application in medium power range in medium power range this means we can we can go form something like ten kilo watt to about 500 kilo watt the much problem. So, this is the application of permanent magnate synchronies motor drives when which the m m f is distributed in the space the induce t m f is seine. So, dial and the torque cripple is also reduced because the induce t m f is seine. So, dial we inject the motor based seine.

So, dial current and voltages average of the current and voltages at seine. So, dial and hangs this drive is suited for high performance applications. We will see and new class of motor we have all ready torque they about the permanent magnet synchronies motors which are use for those applications where the space is we can strait something like space applications; the wait is a constant. So, the permanent magnet synchronies motors are used for those application where the torque to wait ratio leads to behave we need high torque. But the wait should be minimal we have another class of motors which can also be use for light weight applications and those motors are cold the switched reluctance motors. So, now, we will be discussing and switched reluctance motor.

(Refer Slide Time: 20:37)



In switched reluctance motor the torque is produced by the variation of reluctance or permeance of air gap. And general we see that whenever we have in inductor the stored energy is half in to realize square. So, we can say that e is equal to the stored energy is half L i Square this is a stored energy in an inductor stored energy in an inductor or in a curve. So, if we want to find out the torque the torque is the derivative of this energy with a respect to the position. So, if there is a variation of the energy which position will get a torque? So, if we differences this d e by d theta we get the torque and that is equal to d by d theta of half L i square. Now, usually the current is an independent variable it is injected by i inverter or a convertor.

So, i in this case is not depend upon theta, theta is a position position of the rotor. So, I that case I can be taken out of the derivative because it is not a function of theta r. So, we can take it out. So, we can say that it is half i square in to d l by d theta. So, what we understand that the torque in a séance reluctance motor is proportional to i square and also it is proportional to d L by d theta. So, it means there has to be inductance variation with a respect to the position that is theta and is the principle of séance reluctance motor.

Now, let us take an example of 8 poles stator and 6 poles rotor séance reluctance motor this is also known as SRM the sort form of séance reluctance motor is cold SRM. So, we will be take in and example, example of an SRM with 8 stator poles and 6 rotor poles. Now, if we want to see the constructional feature, we will have an idea how this flux. So, let us draw this motor this is the stator we have 8 poles.

So, let us try to drag the poles here. So, it poles means they are receipted by 360 by 8 that is 45 degree. So, 8 pole. So, the stator pole peach is equal to 360 by 8 that is equal to 45 degrees. So, we get that the stator poles here the poles of the stator 1 pole, second pole, third fourth fifth pole sixth seventh and 8 poles. So, the stator has got 8 poles structure. So, we can now complete the stator structure here the poles at basically projecting in nature there will project out the stator pay vestry. We can now let us curve the rotor the rotor has got 6 poles, the rotor has got 6 poles, 6 pole means the pole peak which 360 by 6 the rotor pole pitch here is equal to 360 by 6 is equal to 60 degrees. So, let talk to the rotor poles the rotor will have structure here and here we have you have to have 6 pole structure.

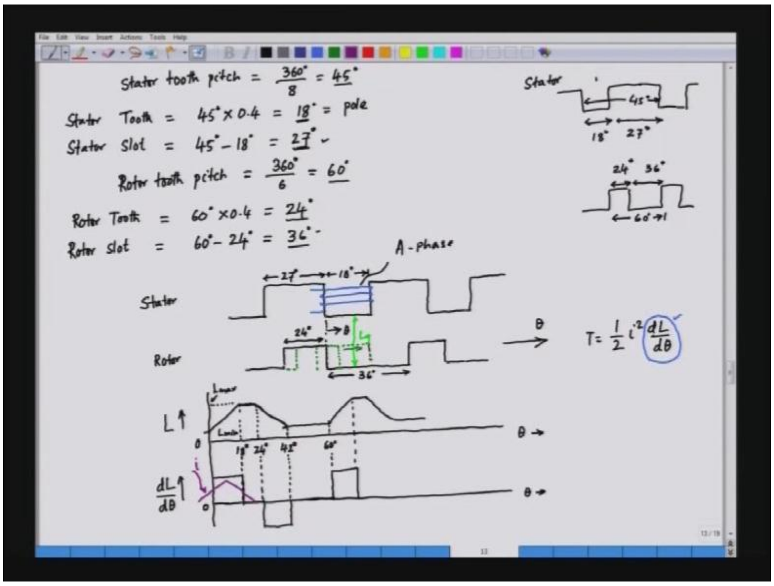
So, we can have the rotor poles like this is 1 pole, second pole, third pole fourth pole, fifth pole, sixth pole. So, these are the rotor poles. So, we can now complete the structure of the rotor. Rotor does not have any winding; rotor has got only slatted structure by pole and slate that to a die here. Now, this is the pole you have the slate here then again we have pole and then slate pole and slate. So, this is the structure of the rotor the stator have salience go to how the salience the stator is slatted rotor is also slatted. But difference between rotor and stator is the, if the stator will carry consultant windings rotor does not carry any winding. So, in the stator we will have winding. So, we can have the windings these are the stator windings. This is also another winding here we have windings in this case this stators poles they have consulting windings the stator carries windings.

So, we can call this suppose this is a, we can call this to be a prime v is diagonally opposite. Similarly, if we say this is b, the diagonally opposite is this b prime and if you say this is c this could be c prime; this is d and this could be d prime. So, in this case, we can say that if we have 4 phases and the phases are a b and c. Although we have 8 poles structure we have 4 phases and this phase has the 2 windings a, and a prime b and b prime c and c prime and d and d prime. So, this is the structure be the stator; the rotor has does not have any winding. This is slated structure and that is why it is light weight, the rotor has any winding does not carry any dos on the slight induction machine does not have any tabular bar here the rotor does not have any bars. So, the rotor weight small. So, the total weight of the machine is small, small is compare to equivalent induction machine and that is why this is specifically main for those application where we need light weight motors.

However, the control is little difficult here now as we already seen that the torque is produced by the variation of induction i Square d L by d theta is positive. Then only we will have positive to production. So, here we see that the rotor rotates as the rotor rotates. So, we will be say for example, if the rotor rotates like this in the anti clock wise direction. The induction of every phase will be changing if we concentration phase a north phase a pole is facing the tooth of the rotor we have the rotor here and this is the stator. So, the inductions are every phase in the function of theta as it as it moves it basically moves than angle theta. So, we can we can draw the variation of inductions of every winding with the respect to theta. In fact, we have 4 phase here phase a phase b phase c and phase d if we flat for any 1 phase of phase a, the same thing will happening to phase b after some delay.

So, what we do? We will be plotting the induction variation of any giving phase of the rotor rotates. So, we have another specification stator pole pitch is 45 degree and rotor pole pitch is 60 degree. And we have being also be in given that the pole is to pole pitch is equal to 0.4. In fact, we can say pole is something similar to tooth is to tooth pitch is equal to 0.4 same thing. Because the poles are something similar to tooth; the rotor will have some tooth the stator will also have some tooth. So, we can use tooth for pole a pole is something similar to a tooth and pole pitch is equivalent to or similar to a tooth pitch it means this is a pole the stator will have this pole structure. So, if this is the pole, we have the tooth here and this is the slot. So, this is the tooth pitch. So, tooth by tooth pitch is equal to 0.4. So, let see in this case then let us try to see.

(Refer Slide Time: 33:01)



The stator tooth pitch stator will have 8 tooth or 8 poles that is 360 degree by 8 that is 45 degree what is the rotor tooth size. So, tooth is 45 in to point 4 is equal to 18 degree and this is also same as pole. So, the rotor pole will occupy an angle of 18 degrees. So, it means this is the rotor pole and if we linearly develop this angle is 18 degrees and the stator tooth the stator tooth pitch is here 45 degree which includes the tooth and the slot. So, this is 18 the tooth is 18 and tooth plus slot is 45 degrees. So, what is the slot here stator tooth this is the stator tooth similarly we can have stator slot stator slot the stator slot is 45 is the tooth pitch minus the stator tooth is 18 degrees. So, what remains is the stator slot angle and this angle is 45 minus 18 and that concept to the 27 degree. So, this is 18s and what remains here is 27; this is the stator.

Similarly for rotor rotor has got 8 tooth rotor has got 6 teeth. So, the rotor tooth pitch is 360 by 6. So, we can say that the rotor tooth pitch is 360 by 6 that is equal to 60 degree and the rotor is like this phasing the stator. So, this is the complete 60 degree which includes the tooth just locked now what is the rotor tooth pitch we can say that the rotor tooth pitch rotor tooth here is 60 into 0.4. That is equal to 24 degrees that is the rotor tooth what about the rotor slot the rotor slot is 60 minus 24 that is equal to 36 so. In fact, this is the rotor tooth and the rotor tooth is 24 degree and the rotor slot is here this is 36 degree. So, the 36 is the rotor slot, 24 is the rotor tooth, 36 plus 24 is 60 that the rotor tooth pitch. We had been discussing about the shift electing motor the rotor and the stator configuration rotor tooth pitch is 60 degree.

And out of 60 degree 24 is the rotor tooth and the 36 is the rotor slot. Similarly the stator tooth pitch is 45 degree and outer that 18 degree is the stator tooth and 27 degree is the stator slot. Now, let us develop the actually the motor is a cylindrical structure. So, if we take cross section the cross section will be a circle and the cross section we are already seen here that we had the stator. And we have the rotor the stator carries winding and the rotor does not carry any winding. And the when the rotor moves every stage of the stator we will see alternately the pole, the rotor tooth and the rotor flat the rotor tooth and the rotor flat thus the induction of every phase will undergo variation. So, with the inductions of every face will undergo the variation. To find out the torque, we should be able to find out the torque, we should be able to find out the variation of induction with the rotor position although it is a circle structure as we are seeing here we can develop this linearly.

So, what we will do? We will cut it and develop this linearly. And we have the information about the various angles, the stator tooth pitch; the stator tooth and the slot individually the rotor tooth pitch; the rotor tooth and the slot individually. So, we will be developing this in a linear fashion, we will cut it and open it and this would look like this. So, we have the stator and the stator slot is 27 and then tooth is 24. Again we have this slot and then the tooth. So, this is the stator we are concentrating on 1 phase, we have the windings here we are interested to find out the inductions of this winding. What about the rotor? The rotor is below the stator and here the stator this angle is slowly 7 degrees. The slot angle and the pole angle of the tooth angle is 18 degrees, the rotor will start our reference from. This position the rotor is just waiting to go under the stator pole the rotor tooth is here and tooth here is 24 degrees.

So, this will occupy up to this position is 24; this angle is 24 degrees and then the rotor slots is 36 degrees. So, we will have here the rotor slot, this is 18 and then we have another 18 here and this makes 36. And then again we have slot in this case a slot is 24 and this will continue. So, this is the rotor structure. So, the stator is stationary, rotor is moving and the rotor is moving in this direction towards the right with our speed on angle is theta. Theta is basically measures of this particular position; we can say this position is theta now at the starting theta is 0. And the rotor is just rotating to come under the stator now we can float the inductions the inductions of the winding and the stator. So, for example, we can call this winding is the phase a winding a phase.

So, let us try to see how the phase a induction vary as the rotor comes under the stator and moves away. So, we are not floating the inductions of phase a we have theta here in the x axis. And at this position we can see that the stator is seeing a larger air gap. So, this air gap is quiet large, this air gap this is the air gap that is L g. So, gradually the rotor will moves under the stator. So, after some time the rotor will go under the stator. So, this will be somewhere here and this particular course will be go somewhere here because this is moving in the right side. So, the stator will see at decrease inductions. So, the induction decrease a air gap the inductions of phase a is gradually increase, so initially theta by equal to 0.

So, this is l minimum we have some minimum inductions that is l mean an as the rotor moves the inductions of phase A will increase. Because the rotor tooth will be coming gradually under stator pole and the induction of particular phase is increase. How far it will increase? It will increase after the rotor completely comes under the stator. So, it will take 18 degrees for this to increase from 0 to sum 1 maximum. Here we have l maximum initially it was l minimum and then we have some l maximum here. So, it will take 18 degrees to go from l minimum to l maximum. So, this is 18 degrees and then this rotor has already come under the stator it will stay. And it will again move away and for some time there will be over lap the air gap will have change. The air gap between the stator and the rotor will not change, that will remain constant.

And then that is called the overlap region and the overlap will be for again for 6 degrees. So, the overlap will be here the induction will be constant for 60 degree for 6 degrees because this is moving away and this comes fully under the rotor. So, it is something like this and then this is still moving away. So, this overlap will be for 6 degrees and 6 degrees plus 18 degrees will be 24 degrees.

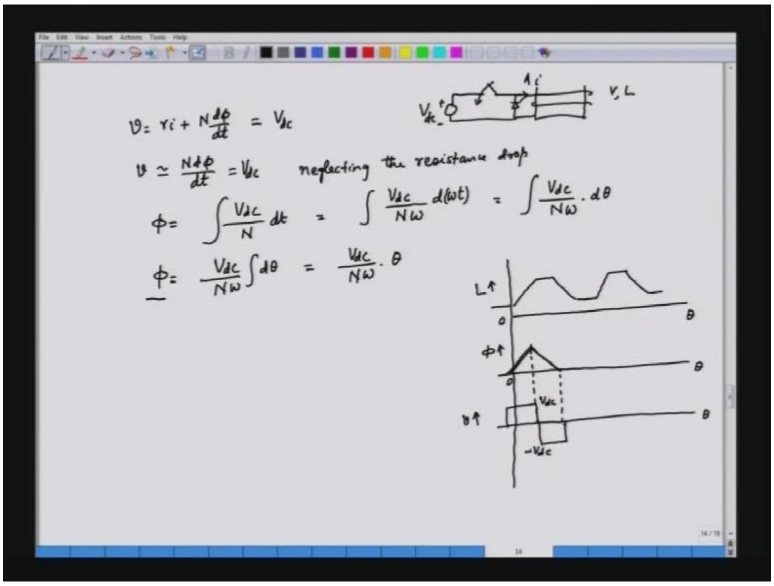
So, up to 24 from 18 to 24 the inductions of that particular phase will. In fact, be constant and after that the rotor will be moving away for the and again the induction of phase l will be decrease. So, if further moves away these inductions will follow decrease will be the same way like this linearly it decrease. In fact, and this again take 18 degrees to comp l minimum; this is 18 degrees 28 plus 18 is 48 degrees. So, this is how the induction values, it goes from minimum value it maximum value variable. We are in fact, neglecting the fielding effects it goes from minimum to maximum.

Then step of compact the maximum value again it goes a minimum value and are the minimum value to again step for some time. So, are the minimum value it will step of this angle is impact 36 degrees it stain in the minimum value and it again for 18 degrees. So, this is 36 and for 2 plus 18 is 60 and the same thing again repeat induction raising. Then remaining constant and then decreases and then remain constant again. So, this is how induction of particular phase changes. So, if we plot d l by d theta this induction variation again theta is in the x axis and this is how the induction full change and this is happens phase b and also after some time. So, d l by d theta which is important for the term production, because we know that torque is equal to i square d l by d theta. So, this is expression for the torque.

So, this d l by d theta is a extremely important. So, we evaluate what is d l by d theta. So, this d l by d theta is a derivative of inductions respect to expression that is theta. So, we can differentiate that and find out what is d l by d theta. So, here what we do this is inductions and here we can calculate what is d l by d theta. So, here it is raising. So, we can say that the derivative is constant. So, it is positive the derivative is positive here then come 18 to 24. It is again constant induction values constant and then derivative will be 0 and from 24 to 42 the induction is decreasing and hence the derivative is negative. So, we will have minus d l by d theta. So, this is positive 0 and negative and from 42 to 60 induction again constant. So, d l by d theta will be 0 the derivative of induction will be 0 to the induction variation. It respect to theta and d l by d theta we look in the following passion. So, this is d l by d theta and this is respective for the torque production, because induction is not a function of theta or it is almost constant then torque is 0.

So, if d l by d theta is 0 torque is 0. So, it is because d l by d theta is finite that is why inject the current that the torque production. So, how in the current injected we have both d l by d theta is positive d l by d theta negative current is injected such a passion. It exist only during the positive d l by d theta, because we have positive plot. So, in fact, the current is exist if you switching the current; the current is be along to exist in the positive d l by d theta. And it is will be 0 for the negative this is what is the current for the positive torque. So, the current will be confine to the positive d l by d theta regiment to produce the positive torque. Now, this is achieve the applying voltage and apply the suitable time. Now, we will see how about this applying. So, we have this phase here.

(Refer Slide Time: 49:21)



This is say for example, the stator phase A and this induction is N and the register is r. So, we have the switch in this case, we can have a switch here. And let us we apply the voltage to this particular phase in have a filling in diode in this case. So, if you have arrangement like this we can apply voltage that is V d c. So, if we apply both the voltage call V d c then we apply this particular voltage what happens here is that the current shows the winding i we can write down this equation that v is equal to there are r i plus N d phi additive phi is the flux linkage in the winding. So, v is equal to r i plus N d phi divided by d additive and here we want to find out what is phi. So, phi can be evaluate like this on that is say is equal to V d c that is the constant voltage.

So, if you want to find out what is phi, we can say that v is approximately equal to N d phi additive neglecting. You make some simplification neglecting the resistance drop the resistance drop is small compared to the induce c m f. So, winding is melt up of the copper the resistance is very small. So, we can ignore the resistance drop compare to the induce c m f the d phi will be additive. So, we can do that you can say that approximately equal to N d phi additive and that is equal to V d c and you to find out what is phi? So, phi here is equal to V d c by N into d t into gamma that and that is equal to into along V d c by N into omega; omega is rotor speed. So, we can add or multiply this omega in positive is numerator. So, we have d omega t and that is equal to into aleph V d c by n omega into d theta now usually for a steady state condition to speed is constant.

So, if the speed is constant and V d c also constant, we can have a simple integration the phi is equal to V d c by n omega integral of d theta and that is equal to V d c by n omega into theta. So in fact, we have to find that apply the voltage, the flux will raise linearly with theta the flux will proportionally theta. So, what you do here? We have this inductions and the induction is a function of theta. And it varies like this raising the remaining constant and it will be falling. Then remaining constant raising and the remaining constant in particular way and before that also with constant this is 0 position. And what we do here we apply the voltage and in particular passion. So, that the flux linkage is follows will change the following passion is the flux linkage phi this is applied voltage v, v is in this case we apply here plus V d c.

And then for this pole we apply negative voltage, so the flux which will be 0. So, this is the hyper voltage where in the flux linkage and this is inductions. So, are we apply the voltage the flux which is linear they are applied a voltage to earlier that. So, when we apply the voltage some adverse angle, the flux linearly raise are we seen already flux equal to V d c by N phi into theta, so in fact phi proportional to theta. So, it can linearly and after some time we apply negative voltage. So, if we apply negative voltage if we brought down here. So, this is plus V d c and this is minus V d c. So, in the next lecture discuss can it linearly in happening how to control this switch induction motor and how we can have variable torque and variable speed operation with switch induction motor.