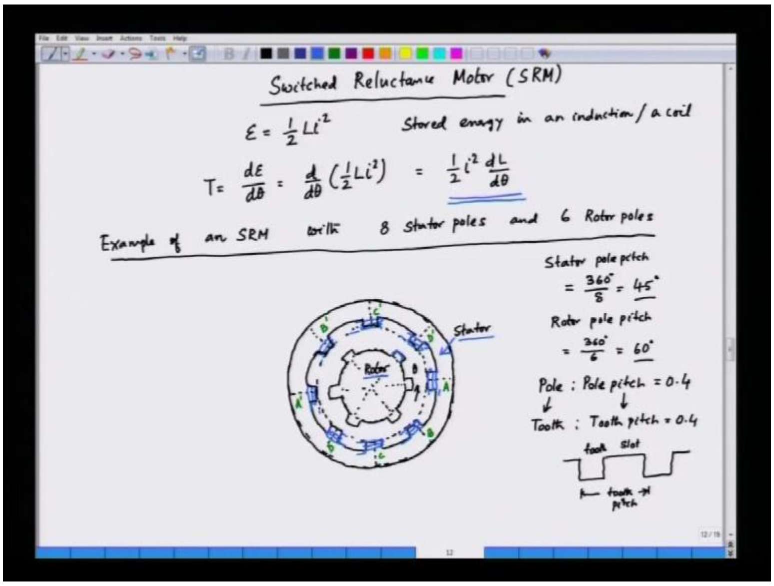
Advanced Electric Drives
Prof. S. P. Das
Department of Electrical Engineering
Indian Institute of Technology, Kanpur

Lecture - 28

Hello, and welcome to this lecture on advanced electric drives. In the last lecture, we are discussing about the sieves reluctance motor drives, how to control this motor. And we have seen that we are seen sieves reluctance motors the torque is produce by the variation of inductions T is equal to half i square L d L by d theta. So, this is the principle of torque production.

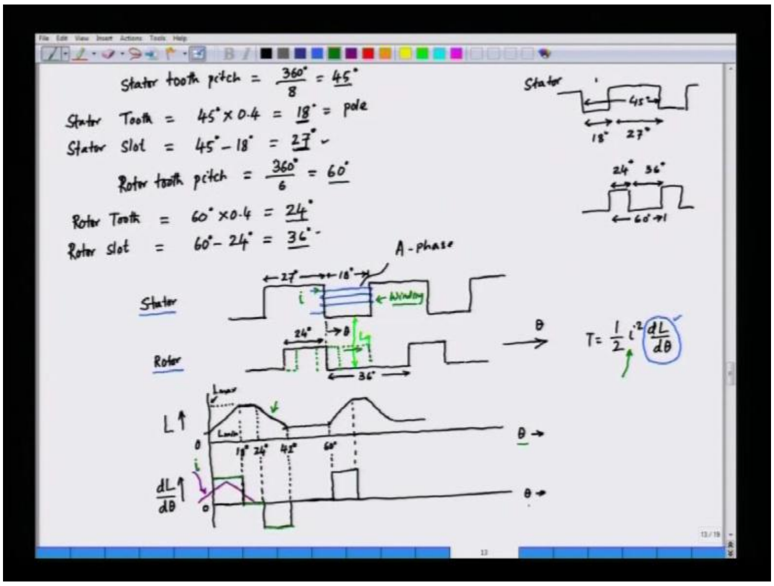
(Refer Slide Time: 00:44)



The torque is produced by this expression that is d L by d theta into i square half of this is the expression for the torque. And hence the torque will produce only when where is the position dependent on inductance on the inductance should be a function of time. So, if we see the cross sectional view of a seize reluctance motor of a farin, we can take a motor and take a cross section of that. And see that both the stator and the rotor are salient in a nature. So, we see here we have the stator pole in the step which is laminated is the laminated curve.

The rotor pole is also laminated these are the rotor here and the stator we have saliently these are the stator poles or tooth here. And we have the slades in the step, in the stator, in the rotor also we have the rotor tooth, this is the rotor tooth and we have the rotor slade also. So, the stator and the rotor both are slant end and the stator can windings consult with windings And this motor becomes a light weight motor, because the rotor does not have any winding the rotor have only the slated structure lamination. Which are slated because of the winding and hence the rotor inertia becomes very very low and speed response of the rotor can be fast. So, if we analyze the inductance variation.

(Refer Slide Time: 02:27)



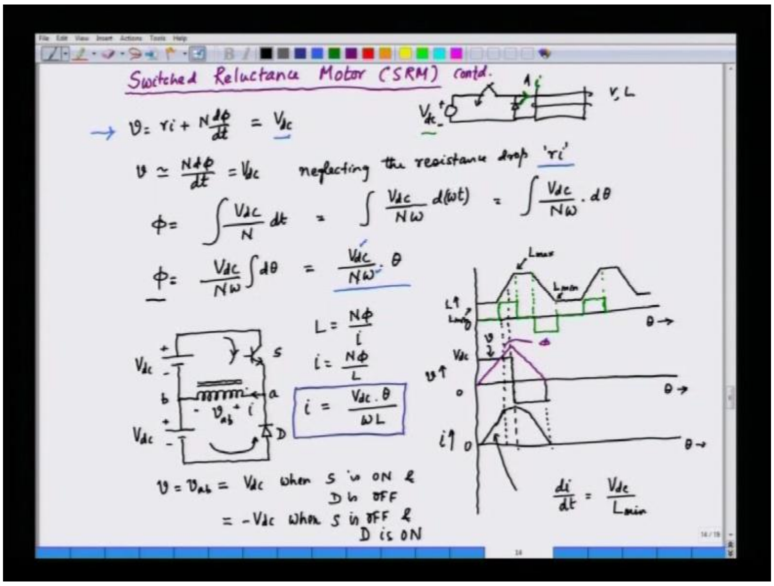
You see that is the rotor moves; you have the rotor here and we have stator in this case. The stator carries consulted winding we have the windings of the stator. This is for example, of particular phase let us A phase A here the stator phase A, and the rotor pole are the rotor tooth is coming under the stator pole. Now, under this situation if you see the inductance of the stator winding these are the stator winding this inductance will graduate raising linearly. Because trans the rotor pole moments under the stator pole the air gap in this case will be gradually reducing and hence the inductance will be increasing.

So, the inductance of this winding of phase A is the function of the position that is theta. And after some time the rotor pole fully under the state to the pole and hence the inductance will be a constant, this is the constant inductance that is the max we started with L changes linearly. And then romance constant when the rotor pole come to the under the state pole then after the rotor poles goes away from the stator pole. The inductance reduces this region basically the region for which d L by d theta negative. So, we have we can plot this d L by d theta for the raising condition from L minimum to maximum d L by d theta is positive. And when the inductance remains constant d L by d theta is 0 and when the inductance decreases d L by d theta is negative.

So, since we have the variation of inductance with position we have finite d L by d theta it would be positive. Or it would be negative again the expression have the torque if you see it is half i square d L by d theta. And hence for positive torque i square is always positive irrespective of fact that I is positive or negative. So, if you want positive torque I should be concentrative during the positive of d by d theta it means the current the phase current here it this is the phase. And if with this current carries i and i should be predominately in the positive d L by d theta not in the negative d L by d theta.

Because with the current exist by during the negative d L by d theta torque will be negative i square is always positive. So, if you want positive torque i square is only exist during the positive d L by d theta. That the principle of torque production will be the inductance motors. The current in the winding first we show seized optimally based in such a way the current only exist during in the positive d L by d theta. And if you ensure that the torque of index is maximized and we can have motor with good trapper and pear. So, if we plot d L by d theta, this is the ultimately becoming positive then 0. Then this region form 42 degree into 602 degree 18 we have inductance region then we have further vise the next pole is coming under the stator. So, this is the radian form and d L by d theta is all so, period with theta with the rotor angle.

(Refer Slide Time: 06:38)



Now, how we control? We can control the current in such a way the current only exist during positive d L by d theta and that is achieve by switching a voltage on to the winding. So, if we seize a voltage V d c on to the windings we have a power switch is by using a switch; we can a switch is voltage on to the winding will have a current that is psi. So, we can write down this equation v is equal to r i plus N d phi additive is equal to V d c that is the v c voltage. In fact, we can have a alternative torque vilogy also for injecting this current we can have winding like this; this is the phase winding. And we can switch the voltage in the following passion, we can have a transistor here is the electronic switch. And with this electronic switch, we can seize the current and to the winding this is one phase of the switched reluctance motor.

So, we can seize the current and to this winding and this is psi and this is V d c and will have a power supply with V d c like this we have V d c and another V d c. In fact, we have the voltage V d c having a center point. And here what we do the connect to the diode and diode is D and switch we can study s. So, when we switch the transistor S the voltage and could be the winding is V d c. So, if we have this is A and this is V terminal. So, we can say that this is the voltage that is applied here is V V a d in this case is positive. So, we say that v is equal to v a h that is the voltage v a b that is plus V d c when S is on and d is off. So, naturally when S c is on the diode is reword diode and hence the diode is off.

So, the voltage across the a b that the upper voltage is V d c now when we switch off this wave is f the current choose winding is plane from a to b. And that would be required to when we switch off this f this current winding would be the maintain, because it is the inductive current. So, the current through the winding has to be contentious or as to be maintained when the switch is off. So, the current will try to find out alternative part and the arithmetic diode is volt. So, if the force in diode and there is to the transistor now, you felt into diode and the diode terms on and S terms off. And as a result we can see that g a b will be in this case minus V d c that is equal to minus V d c when S is off and d is on so. In fact, when we switch on S I increases and when we switch on or switch off S I would decrease we are applying manage this is to be this particular winding and the current fall will try quickly. So, apply can both V d c or minus V d c to the winding to control the current.

So, may controlling this current you can control the torque because you know that the torque is proportional to i square it. In fact, half d L by d theta to I square. So, if you can control I we can control the torque now how to control I in a proper way because I has exist only using d L by d theta so. In fact, if we see the diode here that be in the 3 pare what we have in this case is the following we have the inductions variation. This is a L is some time minimum some time a L is raising reaches L maximum then this decreases becomes again minimum again raises which is maximum value. And again terms down and this is replaced the x axis is theta with the rotor position.

Now, if we plot d L by d theta this is L the d L by d theta is the same graph is like this during this time d L by d theta is 0. The L is constant because this is the L minimum this is L minimum. And this field L is maximum d L by d theta it is 0 theta is positive the L is constant at maximum again 0 And then L decreases to a L minimum this is again L minimum at this point. So, d L by d theta is negative here and here is again 0 and this periodic this continuous like this. So, our objective is to seize the current is the such a way only exist periodic is d L by d theta.

So, we seize the current in following passion now, we have already seen that we have the equation about this equation. We look like this v is equal to r i plus N d phi by d theta rate of change of flux linkage and that is equal to applied voltage plus V d c. And we ignore the resistance torque here the resistance torque is r i. So, we can ignore the resistance torque r i in this case with respect to the induce c m f in d psi by d t. So, if you say that r i is neglected you can say that v is equal to L d psi dt. And that is the applied voltage and the flux can be find out by simple integration omega is the speed. If we do by speed and multiply by speed we get the expression integration of V d c by N omega d theta and that simply V d c by N omega into theta.

So, in fact what we have to observe here if the speed is constant, the flux is linearly proportional to theta then we apply V d c. So, theta will increase and the flux is also increase linearly with theta as per the situation. V d c is applied which is constant voltage we are assuming the steady state that is omega is constant a with the number of terms of the phase of the stator that is also constant. So, if you applied voltage now, how to apply the voltage? The voltage is applied in the following fashion the voltage is applied in such a way that the current raises and remains for d N by d theta positive. So, we apply the voltage here this is v in this case we turn on this phase S and the voltage become V d c. So, if the voltage is V d c the flux will rise linearly. So, what is the flux? The flux will rise like this.

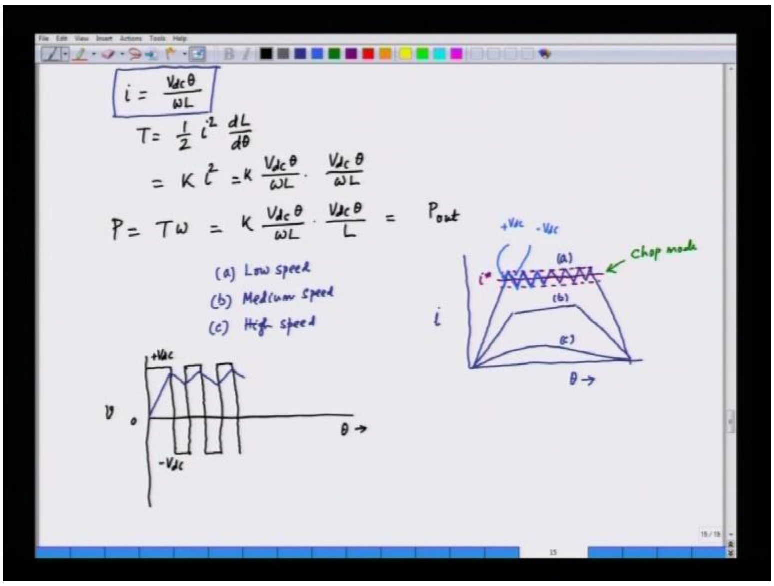
So, this is the flux waveform psi and here we have a voltage that is v. And then if we are obtain flux how do you obtain the current? Ultimately the current is something that decide the torque; current can be obtain from the flax. And we know that inductions is flux linkage per ampere N psi by i is the, is inductance. And we can say that current is nothing but N psi by L and we know what is N psi. So, N psi is saturated psi here. So, if we saturated psi here i e is given as V d c in to theta divided by omega L. This is an important equation this equation is extremely important, because this gives the value of current when we apply the voltage that is V d c I equal to V d c into theta divided by omega l. So, what is omega? Omega is the speed of the rotor what is L l is the inductions which is not constant. Inductance can be very small value it can be large value it increases linearly from L minimum to L maximum speed can also be a variable.

So, i is not only function of theta, but also function of the speed and the inductions also the applied voltage. So, under this situation we can say that I y proportional to V d c see it will it is basically proportional to V d c, but it increases with theta also. So, if you flat i in this case i will starts in 0 and here the inductance is N minimum. So, i will i will varies almost linearly and this instant inductions is increasing now this is the initial rate of rise i. So, what is this rate of rise? The intial rate of rise is giving by d i by d T is equal to V d c by L minimum. We are applied a voltage and V d c among that instant when we are applying the voltage the inductance is minimum value. So, when the inductance is minimum current can change quickly the inductance is large current inner change that quickly inductance opposite the change of current. So, when the inductance is minimum we apply the voltage current can change quickly and reach a high value.

So, the current rises and reach a high value here and then the inductions is trying to increase. Now, when the inductance increase current growth will be arrested because inductance is oppose a change of current. And there after the current rise in the still they are will be arrested this L will be rising in that particular slope it will be reduced. And then we have to make the current 0, because we do not want the current to stay long enough for the theta this is basically the positive advantage theta. And if the current is allow to flow it can also flow during the negative d L by d c theta. So, we apply negative voltage there is minus V d c. So, what we do here the voltage is reset. And we apply negative voltage in this case and when we apply negative voltage here. The flux is going to fall the flux will be falling like this because flux is proportional to V d c.

So, V d c is positive the flux will increase in the positive direction in V d c is negative flux reduce. And it will become 0 after some time and then the current will be reduce because we are applying negative voltage. So, this coil will also become 0 after some time, but initially the inductance is quite large inductance c a d quit large it is increasing. So, the current rate will be less here it is reduce by low rate and then it hence constant. So, it is somewhat decrease and become to 0. So, this is current has to be save that it in be stage during d r by d theta is positive. So, this is how the current pulse look like this is the face current the current is only present during d r by d theta positive. Now when the inductance rate will be negative the current should have die down the 0. And if you can insure that the torque is optimize the torque it means positive. So, this is done by proper switching of the current. So, that it is only present during positive d L by d theta.

(Refer Slide Time: 22:39)



Now, if you see this current expression that we have already derived is a following I S equal to V d c theta by omega L. Now, this is the current what about the torque? Torque is equal to half i square d L by d theta and d L by d theta is a constant quality that is positive I make a replace this d L by d theta by some arbitrary constant. So, we can we can say that is equal to k in to i square half is a constant d L by d theta is a constant. So, T is equal to i square and that is equal to V d c theta by omega L in to the same thing V d c theta by omega L in to k. Now, you can also find out the mechanical power this is the torque and the power is equal to torque in the speed.

So, we can calculate the power by the following equation P is equal to T into omega and that is equal to K V d c theta by omega L in to V d c theta by l. So, this is the mechanical power i k this is same as P out. So, this is what we have here now, when we operate fuse electron motors. It is operate in various modes when the speed is very low current will rise quickly, because we have already seen the expression for the current. And we see that is omega is small close T 0 I will rise very quickly. And this omega is medium the rate of rise of current will not be that fast if omega is large the rate of rise is still low. So, i depends upon speed. So, we can plot I for various speed so, for example, if speed is very low.

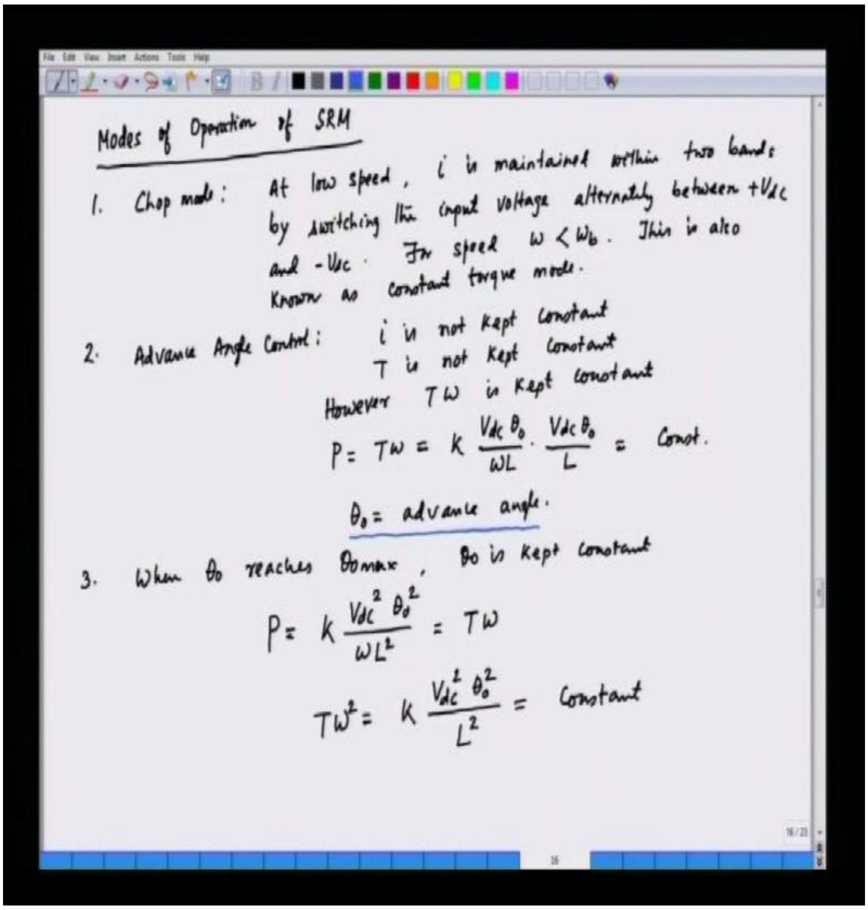
So, if the speed is very low we can plot i, i will raise like this is let from a the current varies is quickly what you have plotting here this I and this is against may be theta here.

So, this like this is very quickly and if the speed is V d m to raises, but not as fast as a by to raise like this straight. And then falls down this is v let us say and if i is if the speed is low as speed is high it change like this. So, we have 3 different situations this is for a this is for low speed b is for medium speed and c is for high speed, because the current is impossible proportional speed. And hence are low speed the current will be the very quickly and how do you control the current the current is controlled what is calling a chop mode. So, at low speed we employ a chop mode this is basically called the chop mode; the chop mode we need we apply plus V d c and minus V d c in such a way the current is limited to a band.

So, we want the current will be constant to positive d L by d theta to switch V d c and minus V d c in such a way the current will be 2 bands, the bands will be design around the reply value of current. So, this is reference current let us say i star. So, we can defined a upper band and we are define a lower band and we can seize the voltage in such a way that the current is to be the band. So, this is how the current base control and for the current raise to positive we apply plus V d c. And when we apply minus V d c the voltage is negative and the current decreases. So, we alternative switch on v d c and minus V d c.

So, the current will be the stage band and this is call chop mode because they chopping the apply voltage high and low high and low. And if you see the inner voltage from V d c it look like this initially we apply voltage are plus V d c. And then the current raises to certain value. And then they apply manage will be see it decreases then we again apply plus V d c then minus V d c then again plus V d c and again minus v d c. So, the current will raise very fast and also fall very fast because the speed is low. So, it can raise and fall very fast. So, raises and falls to the raises and falls raises and falls. So, this voltage is plus V d c and this voltage is minus V d c this theta. So, this is how the current changes and since we are changing the voltage this is called the chop mode.

(Refer Slide Time: 29:37)



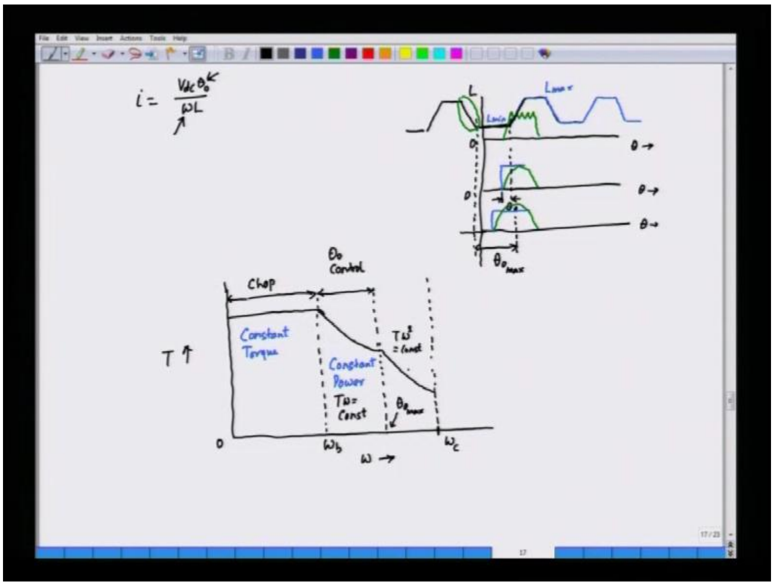
So, we have various mode of operation modes of operation of sieves reluctance motor now first mode is called the chop mode. So, this is basically of low speed is maintain constant maintain within 2 bands by switching the input voltage alternately between plus V d c and minus V d c. So, this is absolute power converter. So, we can have a power converter by means of which we can apply plus V d c for to buy the current drives and minus V d c to buy the current come back to again the original value. So, it is maintain within a band and this is for the speed omega less than omega b omega b is the base speed. So, up to the base speed we can go for chop mode now, beyond base speed what we do here is this that the rotor drive is not very fast.

So, current does not rise quickly. So, what we do in this case if you see this expansion that the torque has to move maintain constant. So, we can keep the current constant up to the base speed. So, this i is kept constant by controlling this current within 2 bands. And hence delay base speed into the chop mode and that is also called constant current mode, constant torque mode. So, we say this also to be this is also known has constant torque mode. Now, what happens after the base speed? After the base speed, we have to maintain the current and the current does not increase. So, quickly because the speed has become large. So, what we do? We do not keep the current constant, because we keep the power constant so. In fact, after the base speed we go for constant power mode and that is controlled by controlling theta. So, we call that to be the advance angle control.

So, we do that by i is controlled i is not kept constant T is also not kept constant; however, T w or T omega is kept constant, what is T omega. Let us go back and see the expressions for T omega; T omega is given by this expression; this is T omega in this case we do not keep T constant that we keep T into omega constant. And speed is increasing gradually the speed is increasing. So, V d c is constant inductions is almost less to constant here inductance may be variable that are objective this to keep the power constant. So, for this we adjust this theta with omega and that is called advance angle control. So, we can adjust this theta to control the power and power is kept constant to constant to change theta. So, in this case we can p is given has T into omega. And that is equal to we have the expression for this power K V d c into theta by omega into L into V d c theta by L so.

In fact, we can say this is theta naught here and theta naught here is called the advance angle. So, with the increase of speed we increase theta naught. So, that the power L is constant and that is called the advance angle control. And this goes up to some speed and once we increase this theta naught, theta naught reaches its maximum value. So, at theta naught equal to theta naught max we cannot further increase theta naught. So, when theta naught reaches theta naught max theta naught is kept constant. So, we have expression for the power in this case P is equal to K V d c square torque mode constant power mode and and a constant T omega square mode. Now, when you talk about this advance angle control that we have just discussing what is this advance angle theta. So, this theta is called the advance angle and the advance angle is controlled in such a way that the power remains constant.

(Refer Slide Time: 37:23)



Now, this will be clear if we say this inductance variation with theta. Now, this is the variations of inductions with theta the inductance raises in the sketch from L minimum to L maximum. And then from L maximum to again L minimum and again it remains at L minimum and this continuous when the speed is very low the current builds up quickly. So, we have to operate that in the chop mode. So, the chop mode means current has to be control in such a way it remains within a band. So, this is how current is controlled And then before the following of the inductions the current is brought by 0. So, it is confined within the power T d L by d theta now when the speed becomes large beyond the base speed this mode is not preferable. So, but still we have to maintain the power current has to build up. So, what we do instead of switching at this voltage we switch it little earlier. So, this is L minimum this value is L minimum this is L maximum. So, we see some voltage the positive voltage little ahead that angle is called the advance angle, angle by which the voltage application is advanced is called the advance angle.

So, instead of applying the voltage here, what we do in this case? We apply the voltage in the earlier and when we apply the voltage little earlier current remain time to rise. So, in this case here in the boarding we apply the inductance is L minimum current can rise quickly. So, this will raise and then this will go into regime where there is plateau and we apply a negative less current. Then again come down and it increases speed we already seen that the current is is given by V d c into theta by omega l. So, i is equal to V d c into theta by omega L and here we can say that the approximately the theta mark below the upper the inductance rises.

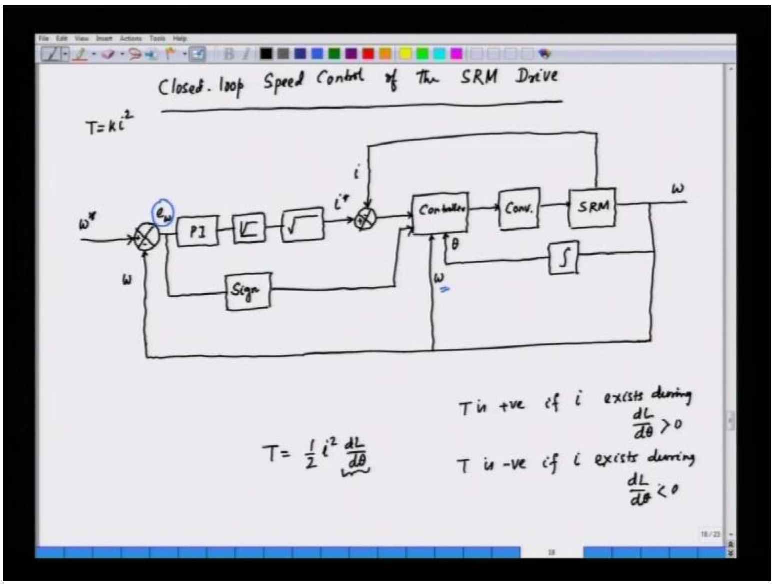
Then new scope for the current will build current can only build up during L minimum, because this L minimum is a line of a inductions during the current builds up and when the inductions rises the current build up is arrested. So, we can control this advance angle. So, this theta naught is increased in such a way that the current raises quickly during this L minimum. And with the increase of speed when the speed increases we increase theta naught in such a way that the current is still maintained. So, what we can do here that we can have another situation this is our advance angle here theta naught within the voltage earlier to this also. So, we can apply earlier to this and the current can rise still quickly here.

And then we can apply a negative voltage from the current to is by 0. And then we can still increase this by torque we cannot increase infinitely so, up to this region. So, this advance angle has a limitation because this inductance value is a periodic. So, if you go into the advance angle it may heat again the negative d L by the theta region this is the region in which d L by theta is negative. So, we should admire the current existence available in this region. So, this is our maximum advance angle. So, we can say that the advance angle as a limit and this advance angle is theta naught maximum. So, after theta naught theta naught becomes maximum we cannot increase the advance angle.

So, we have to go for T omega square constant now, we can divide this various operating region into 3 region. As we already discussed the first one is the constant torque region let us see what we are plotting here is as follows we are plotting here the torque verses speed. The first line up to the base speed, this is our base speed omega b is called the chop mode these also called the constant chop mode. Then we go for advance angle control where theta naught is increased. And we enter into constant power mode and this mode is called advance angle control and theta naught control and this is known has constant power mode. Here we reach maximum theta naught or this instant theta naught is maximum we cannot go near the maximum theta naught. So, we enter into T omega square constant T omega square is kept constant after theta naught reaches theta constant.

So, constant power is T omega is constant and this region is called T omega square constant And here we stop it at the speed called the critical speed beyond the speed. The machine will not run, because the bearing extra we begin to fail this is limited by the mechanical constant of the machine. The machine has been dissolved for the maximum mechanical speed beyond this the machine will not operate. So, this is the critical speed. So, we have 3 different modes here the constant torque mode the constant power mode and T omega square is constant mode. Now, let us now see a closed loop speed control block diagram of a speed reluctance motor.

(Refer Slide Time: 45:17)



Closed loop speed control of the speed reluctance motor drive. Now, here we will start with the reference speed our objective is to have a variable speed operation we take a reference speed. And we control the machine with the closed loop speed feedback to have a variable speed operation. So, we start with a reference speed here than the omega star and we control with actual speed of the motor. Then we speed this to a p I controller and P I regulator you have a speed error that is P of omega, the P I regulator to give us something to the torque. We can have a limiter as well and limiter only the positive value here. So, it is the torque and then we have the value block in this case because T is equal to k i square approximately.

So, we can have a square root block here and you take the reference phase current i square. This phase current has to be injected into the motor windings for a brief phase.

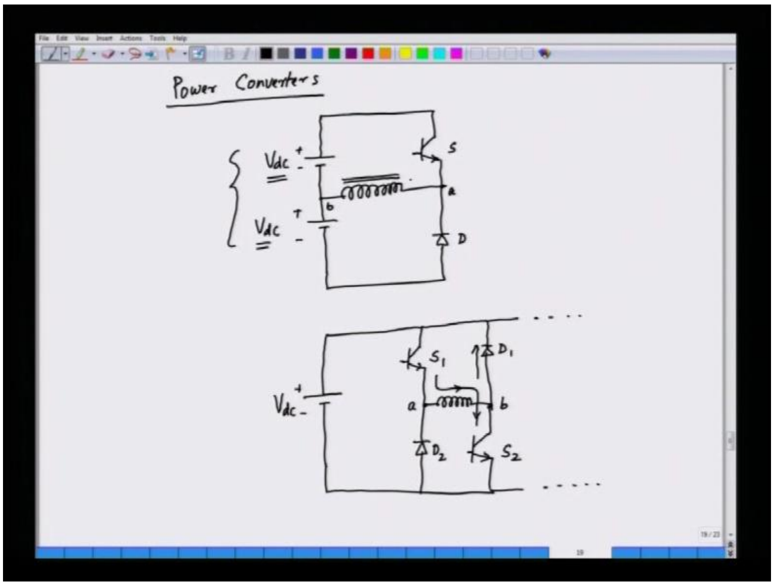
And then we have a compare to here the reference compared with actual current and actual current is i. And this is set to a control of block controller you can say it is basically current controller. And then we have the converter and then we have the motor seize inductance motor and doubtful here is speed the speed is fed back from the tool control. So, we can have this fed back from to this speed is fed back here and this i obtain from the motor here we can have the current sensor. This is the phase current to the speed is fed back from the control now. Also we have the position the position information is obtain by integrating the speed we can have a position encoder. Or we have a integrate speed to find out the position because theta information is quite in Borden.

So, the motor have to be phased in accordance with theta it basically position depend switch in, the phase has to be applied with voltage we synchronize rotor position. And hence we need the information about theta. And theta can be obtain integration of the rotor speed or by a speed encoder also by absolute slade encoder. So, this is theta in this case and we also have information about speed here, because we have a various more operation. So, we have a omega information here and for the negative torque when it to absolute the position. So, this area it to a sign block this sign block will be either positive or negative sign And depending upon that we can have a positive torque or a negative torque to this absolute to the controller.

So, this is this is the phase look block diagram of few reductions motor drive a reach go for a value of reductions. You know the base speed you can have a chop mode, we have the speed information which is available here or the controller will be the chop mode for the speed. You know the diode speed up of the base speed, we can go for the and hence are control and theta not control and about theta is not maximum, we go for T omega square equal constant T is the maximum speediest list. So, this gives complete operation range for a 0 is the maximum speed. And when we need negative torque for the speed reversion the speed error is T omega is usually negative now, we understand that T is usually is equal to half i square d L by d theta.

So, if you want positive torque you have seize the current d L by d theta. But if you want negative torque the torque can be reversed not can reversing i not by making are reaching i d L by d theta is negative. So, T is positive if i exist during d L by d theta is positive T is negative if i exist during d L by d theta less negative. So, we can have proper switch in. So, that we can let torque positive by switching the current is positive d L by d theta. Or if you want the torque negative for this waves or breaking or first we speed reversal we need to are negative torque. And that can be ensured by switching the current during negative d L by d theta. Now, let us try to see is the various tabulated used for converters. You understand the converter is input for a fees elective motor drives now always use converter not used the current. Now, we will see a few examples of converter we used in SRM prime.

(Refer Slide Time: 52:39)



So, the power component opulence will be as follows a simple topology we have already this curve. These are 2 motor sources and we have transistor like this in have the diode this is V d c plus minus. And we have a phase inductions in this phase this terminal is a this terminal is b. So, if you want positive voltage if future S if you want negative voltage a b c slade and the fusion d you have a different category in this case we have a need both 2 supplied V d c here applied V d c here V d c here. So, if the variation can be see if we match this same thing by simulation supplied. So, we can have a seen this supply here V d c.

And then we have positive transistor and we have a transistor here and we have 2 diodes here 1 diode here, and another diode here now here this is a and this is b. So, we have a full though voltage. So, if we have positive voltage and switch on transistor S 1 and S 2 so, the voltage plus will V d c if you want to reverse the voltage what we do in switch on

S 1 and S 2. If you switch off S 1 and S 2 the diode will be conductive this is the variation of the current it through the winding. And if you switch off S 1 and S 2 this current has maintain to diodes this is diode d 1 and d 2.

And hence the voltage applied across a b is all negative. So, this is the torque will be main popular this is for phase A and similarly we can extend this for phase b and c. And this is one of the converters that is used for speed reluctance motor. And in the next lecture, we will be discussing about few more conduct terminology which are use for speed reluctance motor drive. And also we have introduction to the stepper motor, the stepper motors are used for position control. They are also based on the principle of reduction variation that we will see in the next lecture.