Industrial Automation & Control
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Lecture - 34
Induction Motor Drives

Welcome to lesson 34 of the course on Industrial Automation. Today we are mainly going to talk on not mainly solely going to talk on Induction Motor Drives.

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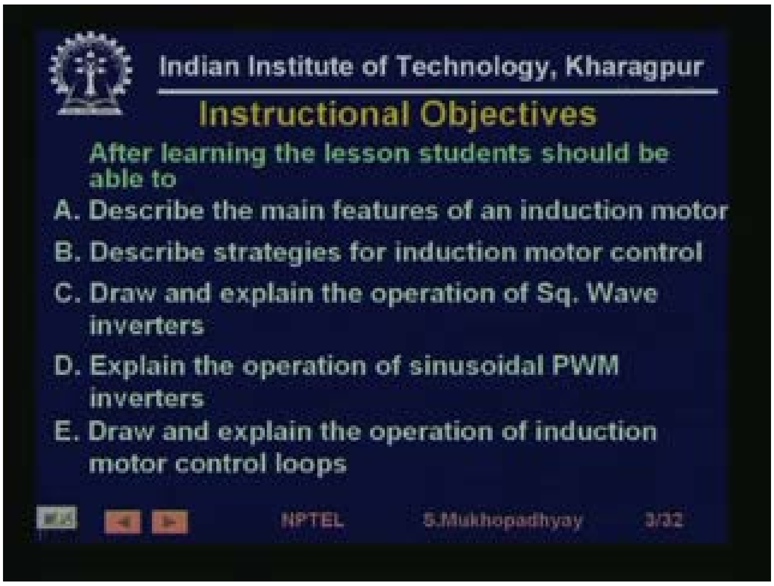

So, we are going to talk on induction motor drives, the instructional objectives are the following, first we will briefly see how an induction motor works and we will try to see the principle of operation and the basic equivalent circuit etcetera. So, the student will be able to explain how an induction motor works then we will see that if once we know what the induction motor is, we will see what are the basic strategies of induction motor control that is how we can speed it up, how we can break it, etcetera.

Having done that we will see, how we will go to the technology side and see how, there are two kinds of induction motor is an ac machine, so it uses inverters. So, we will see actually it can be, it can use various other things, but we will look at inverter driven induction motor drives and we will first look at the square wave inverter, which is a simple inverter and then we will look at the PWM inverters, which are more complicated devices, but have advantages and finally, we will see how an induction motor, what are induction motor control loops looks like.

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So, to this end, first let us see what are the advantages of an induction motor, see these advantages we are considering against what, we are considering visa V typically visa V DC motors. So, what did we see in the DC motor that DC motors have higher weight, their armature cost weighs more and cost more, basically because of the brush commutator arrangement.

And, so the induction motor has lower cost and lower weight for a given rating, see the DC motor also suffers from the fact that its rating that is current densities especially on the commutator and across the brush needs to be restricted because otherwise there will be flashing and there will be other kinds of maintenance problems. So, for a given size it has less rating, So, for a given rating, it has more size, more cost and as we have mentioned before that the DC motor suffers from maintenance problems.

So, the induction motor does not have the commutator and the brush, so it is easy to maintain, it is actually workers of the industry and used everywhere and so from the maintenance point of view it is much more advantageous. The main advantages of adjustable speed drives, induction motor drives is the fact that it requires more complicated electronics, so the inverter and its control circuitry are more complicated and therefore, more expensive, but these are, you know cost is a very changing factor, so as time is passing, the drive cost is coming down. So, the induction motor drives are really have become a viable alternative for DC motor drives and are replacing DC motor drives in various industrial situations, especially at highly rated ones, where the power rating is high.

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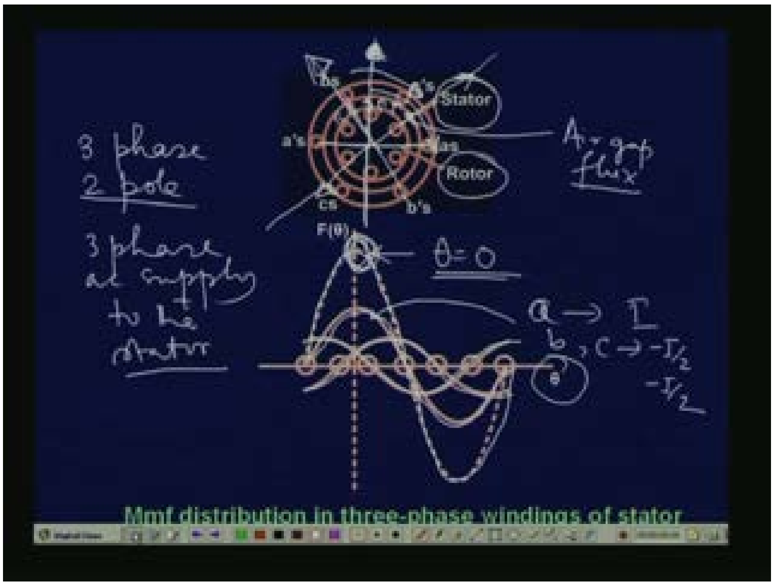

So, having said that let us look at what the induction motor is… So, in an induction motor, we again have, we have a stator, so we have this is the stator and we have a rotor. Now, the stator have some distributed windings in this case typically induction motors are three-phase devices, so in this case we have, we assume that it is a three-phase and two pole machine. So, you see that one coil is for simplicity for each phase we have drawn one set, one coil, so this is one set of coils a and a dashed, whose axis is like this.

So, the even you pass current through this it produces flux and the flux you know passes through all sides, this is called the, so the flux this is the air gap flux, so the net flux will have an axis and this is the axis for the a a dashed coil. Similarly, this the b b dashed coil we have another axis and the c c dashed coil will have, so the b b dashed coil will be having this kind of an axis and now the c c dashed coil will have this axis this sort of an axis.

So, we have three coiled axis specially separated, in this case by 120 degree, so when you, so what are you going to do this is an ac machine, so you give three-phase ac supply to the stator. So, each of this stator coils, the current is pulsating it is a sinusoidal current, so what happens is that, so for example, so for the a phase this is the case, where the a phase contains let us say the full current I is a scenario, snap shot of the Mmf distribution across the motor that is plotted across mechanical angle.

Similarly, b and c phase, provide the return path of the current, so it is minus I by 2 and minus I by 2, so you have, this is the Mmf for the a phase,this is the Mmf for the b phase and this is the Mmf for the c phase. So, these are the three Mmf, pulsating Mmf, so what is the net Mmf, the net Mmf in this case is this one which is nothing, but the resultant of this at this point of time. Now, what happens with respect to time is that right now this Mmf has a peak at theta equal to 0, but as time will pass this peak will actually change.

So, actually what will have is that the result of driving three sinusoidal currents into these three-phases of the stator is that you have an Mmf which is rotating on the stator, in other words this peak that is now occurring at theta equal to 0 what time it will sweep and it will again come back. So, the peak of the Mmf wave is rotating at around the stator, so that is called the rotating Mmf, this is the main point, so if you have these three currents Ia Ib and Ic.

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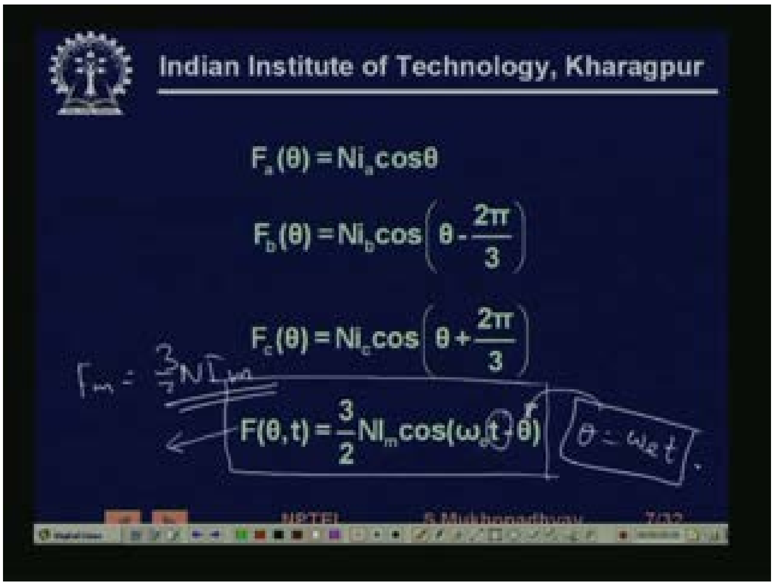

You know which are rotating, which are distributed in time in phase by time phase by 2 pi by 3, so and the Mmf if a current Ia flows, the Mmf due to the current in the a coil with theta if a constant current Ia flows is given by this while for Fb it is displaced in space by 2 pi by 3 and in Fc it is displaced by plus 2 pi by 3. So, now it is very easy to see that if you substitute this Ia Ib Ic values from the three-phase supply currents then you will get the net Mmf variation with respect to space and time, jointly is given by this expression.

So, you can easily understand that at any time t at which angle this F theta by t will maximize, the maximum value, the peak value is equal to 3 by 2 NIm at what, at any given time t it will occur at a given angle theta given by theta is equal to omega et. So, as t varies this theta will rotate, so that is why I said that it gives rise to a rotating Mmf, so now.

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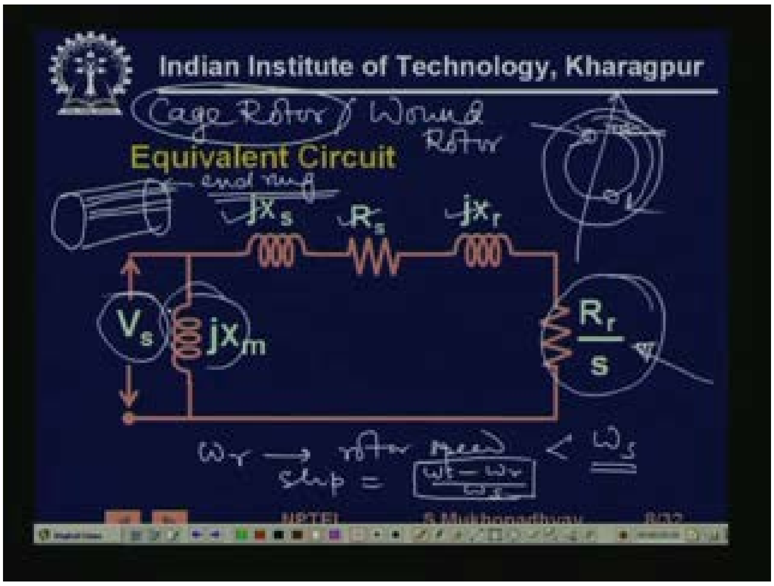

So, what happens before we see the equivalent circuit, so what happens is that there is a rotor, so there is this stator and there is this rotor, so rotor also has this coils and there is a there is an Mmf which keeps rotating in this with this angle. So, continuously fast rotating at some frequency at some speed, which we call the synchronous speed, so naturally that will do what, it will induce emf's in the rotor coil, so once it induces emf's in the rotor coil, the rotor coils are nothing, but you know bars.

They are on the rotor, there are various types of induction motors we are talking about cage there are cage rotor and wound rotor machines. Typically we are talking about cage rotor machines, but whether cage rotor or wound rotor in the cage rotor there are some bars embedded on the rotor, which are connected by what is known as an end ring. In the case of wound rotor machine, the rotor also has slots and there is a coil wound, whatever it is there are some coils.

And these coil in now current will start flowing in this coils because there is an emf induced and the coils are closes circuits, so now these currents the currents in the rotor circuit will now interact with this flux and will produce torque. And the machine will start rotating in which direction, in the direction that this flux that the stator Mmf is rotating because by Lenz's law.

It will, if it exactly catches up if the rotor exactly aligns with the synchronously rotating with the flux rotating at synchronous speed, if it can exactly move in synchronism with that flux then there is no net rate of change of flux around the rotor coils and therefore, now emf. So, by Lenz's law the rotor will try to eliminate the calls that is causing the current to flow, so therefore, it will try to catch up with the stator flux and it will start rotating in the same direction.

But it will not be able to catch up with the stator flux quite be quite because the moment, so it will rotate, but it will rotate at a slightly different frequency such that there is a current flowing because if it had actually caught up with the synchronous flux, then there would be any current flowing. So, there would not be any torque, so the rotor will slow down because it has load on it, so the rotor will rotate at a speed which is close to synchronous speed which is called omega r or rotor speed, which is less than omega s typically.

If you keep the supply constant, so there is a concept of a slip, which is defined as omega s minus omega r by omega s, so this is called the slip or the slip frequency sometimes. So, now so; that means, the as when the rotor rotates the frequency of emf pulsation that the rotor coil c is actually omega s minus omega r because the flux is rotating at omega s, but the rotor itself is rotating at omega r. So, with respect to the rotor coils the flux is rotating at omega s minus omega r.

So, the current that are flowing and the emf induced in the rotor coil are actually at slip frequency, so actually you see that it is like, it is just like electromagnetic induction which occurs in a transformer. So, we can derive, what is known as an equivalent circuit to be able to compute you know what are the kind of current flowing in the rotor what kind of torque will be developed And that that equivalent circuit looks somewhat like this, we are not going into how it is developed, but it is very simple any standard electrical machines book can be referred for that.

So, this is the induction motor circuit, so this is the supply Vs, these are the leakage inductances of the stator, this is the inductance of the rotor and this is the actually the representation of the rotor equivalent resistance. Some of it represents copper law the heat produced in the rotor coil and the rest of it actually indicates, what amount of mechanical power from electrical to mechanical power conversion is going to take place, this is the magnetizing impedance, so now.

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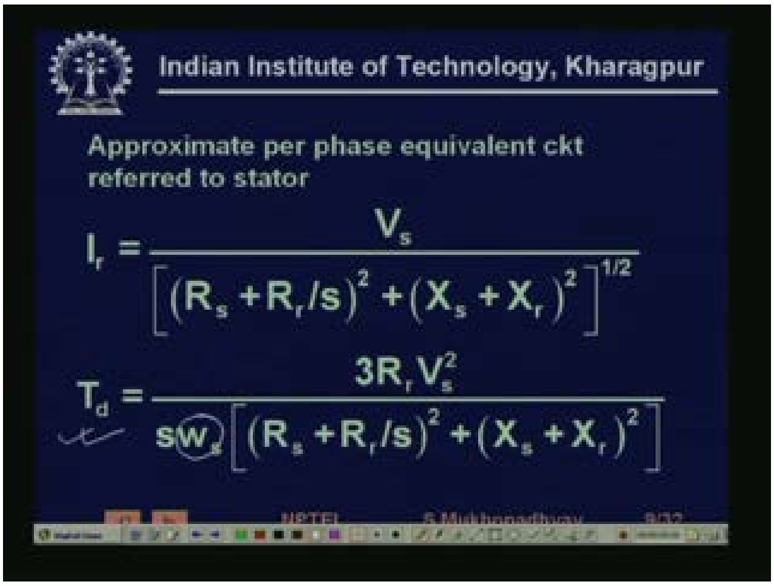

So obviously, if you look at that circuit which is, so the current is simply given as Vs by total impedance, total impedance is Rs plus Rr by S whole square plus Xs plus Xr whole square and it is very simple, just voltage by impedance and the torque is actually given this is omega S this is not W, this is omega S. So, the torque is given by what the power divided by the speed and it turns out that the torque is given as, if you take out the copper laws, the torque will be given by this expression. Now, these are you know just for completeness.

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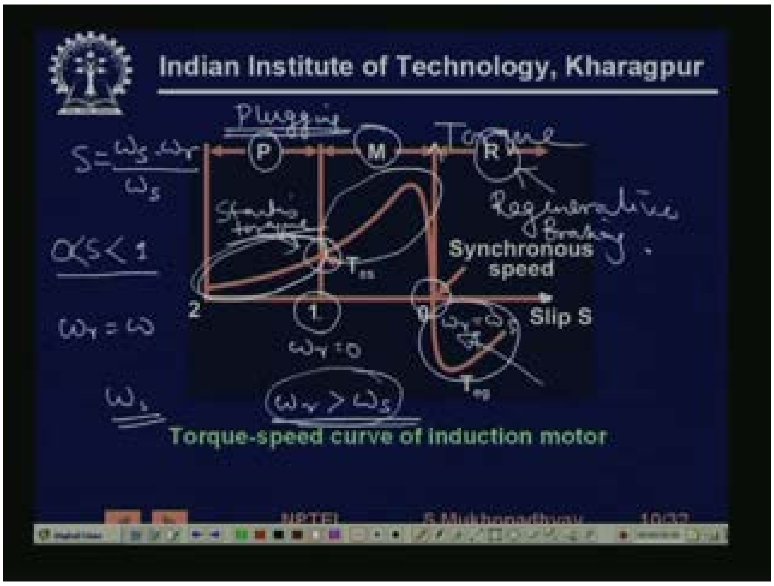

We are more concerned we are in this lecture, we are not understanding things very quantitatively, but rather qualitatively as to how the induction motor is operated, so if you plot that function, you will get at what is known as a torque speed characteristics. So, you know on this side you have torque, electromechanical torque generated and this side is slip, so you see that when we have slip is equal to 0 omega r is equal to omega S, remember the slip is equal to omega s minus omega r by omega s.

So, when S is 0 omega s equal to omega r, so at that point we have no torque as we expected because there is no induced, there is no induced emf. So, there is no current flowing in the rotor circuit, on the other hand when we have slip is equal to 1; that means, that omega r is 0. So, here omega r is 0 here omega r is equal to omega s, so this actually the starting torque, so when the motor is starting, during this phase slip is less than 1 and greater than 0.

So, here there is some positive torque generated and the motor is motoring, so that is why this M for motoring this is a zone of operation. Similarly, when you can see that when slip is more than 1 then actually omega s is in opposite direction to omega r that is the for more, this can happen momentarily especially you know this direction of rotation of omega s depends on the phase sequence of the supply you are giving three-phase supply to the stator, there is a phase sequence and it depends on the phase sequence.

If you reverse the phase sequence omega s will start rotating in the other direction, so if you suddenly reverse the phase sequence then omega r is rotating, so that is a mechanical phenomenon it cannot suddenly change its direction because of its inertia and all. So, omega r will still be rotating in the same direction for some time, but omega s will you can electronically reverse its direction in which case you will be operating in this zone and then will be a large, very large current flowing because now the relative rate of change of in induced emf is very high and high.

So, high current will be flowing and lot of heat will be dissipated this generate this is called plugging mode and generally not used for braking, there is another braking mode and apart from rheostatic braking, which we are not considering here where you just connect the rotor circuit to a set of resistances, typically done in wound rotor machines. On the other hand here what we are doing is here the slip is negative, so slip negative means omega r is greater than omega s.

So, when can that happen, that can happen again if you suddenly reduce the frequency of omega s, so if you have an electronic supply you can this voltage that you are applying to the stator you can both control its amplitude and frequency and if you suddenly reduce the frequency again electronically, naturally omega r will not fall, so much. So, for some time omega r will remain greater than omega s, so during that time you will be operating in this zone, which is called the regenerative braking zone.

During this phase, if you allow current to reverse then the motor mechanical energy will be fed back to the electrical source and will be converted to electrical energy, so while in plugging the mechanical energy will be dissipated as heat and may will result in high temperature of the rotor. In this case, that will not happen, but the power will be fed back and the power will be saved, so this is the regenerative braking mode. So, these are the main modes of interest and especially regenerative braking and motoring at the zones of interest.

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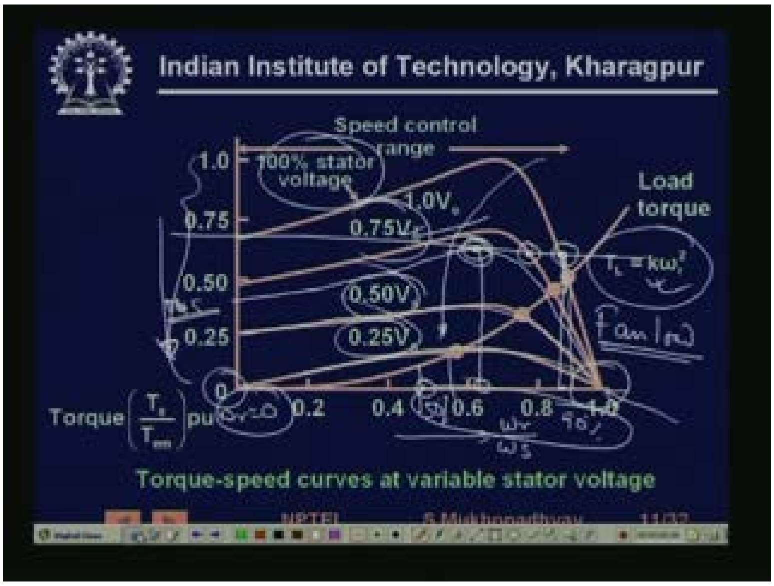

So, now let us see that as we that is how can we vary that is control the torque and the speed of the rotor that is the main purpose of the drive to be able to control motion. So, we know that what is in our hand, the rotor current that is flowing is not in our hand, what is in our hand is the stator supply, so we can, so we have to give a three phase ac supply there and three-phase ac supply we can control two things, either we can control the voltage amplitude or we can control the frequency in during steady state operation phase is of no consequence, so as long as we give balanced supply.

So, let us see the impact of varying the stator voltage and the stator voltage amplitude and frequency on the torque speed current because that will decide, what kind of motions we can create. So, this is a typical curve, which shows that as this side is again slip this side is rather this side is you know this side is omega r by omega s because this is not slip this is omega r by omega s and this is when omega r equal to 0, so you see I want to mention two things that.

Firstly, from that equation also, you can determine that if this Vs there is a rated stator voltage for which the motor has been designed you know motor is designed for a particular voltage, its insulation is designed for a particular kind of voltage level, if it can with stand a particular kind voltage levels plus its flux its magnetic design is based on a certain level of flux flowing, which is decided by the supply voltage. So, this is the rated voltage 100 percent.

Now, if we, so typically we are not going to increase its voltage beyond its rated voltage, typically when we do control, we can reduce it below, but we cannot increase it more. So, we have to, so these are the family of curves obtained as you reduce the supply voltage 0.75, these are just typical values they have not much implication, but what is being shown is that, firstly that the you see whatever, what is the impact.

If you want to vary the speed of a load, suppose the load is of this type, this is the typical you know fan load kind of thing, where the load torque depends on the speed. Then we can see that by doing this, these are these are very simple kind of control you know, it is rather easy to control the amplitude of an ac wave and therefore, it is very simply achieved, frequency is left unchanged.

And we are seeing that for a this kind of load, you can get pretty good speed range for example, at least you can make it vary, perhaps between 50 percent to nearly 100 percent 90 percent variation of speed is possible, for this kind of load. On the other hand, imagine that suppose the load is a constant, imagine a different type of load, so if you have a different type of load then for this supply voltage this is the operating point, for this supply voltage this is the operating point.

And beyond that may be, so the maximum you can have is probably you will have another, you can probably reduce it to some you know point may be this is 0.65, this is 0.50, so therefore, may be this is 0.45 or something. So, you can have a variation of here about 0.65 to may be 0.88 or something, but below that if you reduce the stator voltage below that then; obviously, the machine is not going to start because the torque developed by the machine at lower voltage is will simply not meet that load torque, so it will not start.

So, we see that this kind of drive is actually very simple, but they are only suitable for certain kinds of load, if you use other kinds of load you are going to have starting problem, because the one thing we see is that as the voltage is reduced the starting torque falls. So, at a reduced voltage we cannot have maintain a starting torque, so therefore for constant torque kind of loads and we have seen previously that for various kinds of you know machining loads, they often tend to be of a constant torque kind, stator voltage control alone is not a good, it may not be the best choice right.

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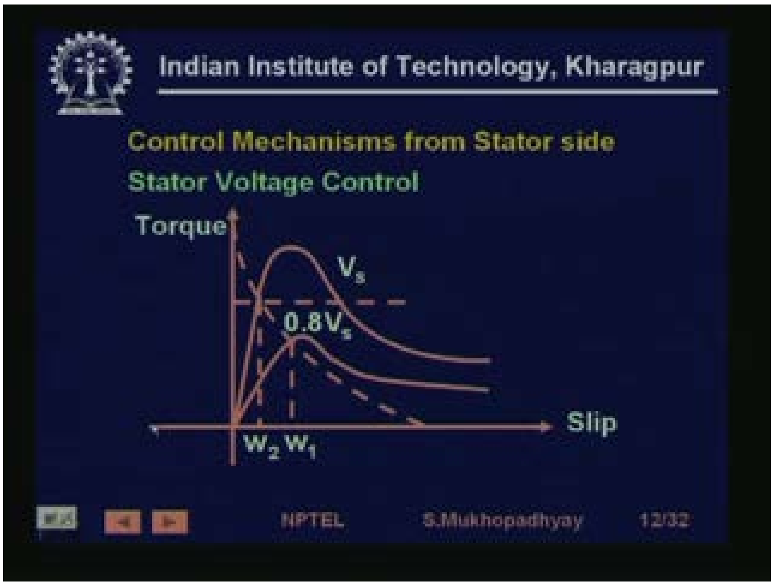

So, this is the same thing saying that if you have a constant load then if you reduce it, it will not start.

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So, in summary stator voltage control, it may be simple control for example, if you are having an inverter, just these if you control the dc input supply voltage of the inverter that will give you stator voltage control. You can have even simpler, you can have series ac controllers things like you know triax using which you can do stator voltage control, but they are used for low power and low starting torque operations like you know typically fans and pumps whose torque varies with the load.

So, initially have a low starting torque and stator voltage control can be achieved in many ways, but PWM inverters are used for not used for stator can be used for stator voltage control, but they are used not just for voltage control also for frequency as we will see right now in this lecture. Or you can change or you can have a variable dc link voltage this is not dee, this is dce or we can have a series AC controller as I said like triax, we are not talking about them right now.

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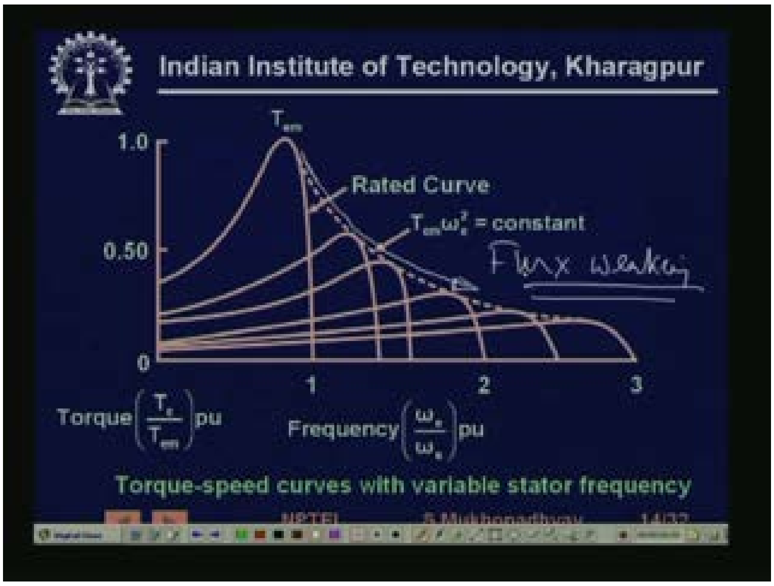

On the other hand, what else the second thing that we could do is that we could change the frequency keeping the voltage constant, so if we changes the frequency again now this time you will notice that just like voltage cannot be increased. So, if you increase then there is going to be magnetic flux saturation, the machine has not been designed for higher voltages. Similarly, when you are talking about frequency there is a rated frequency and frequency cannot be decreased below that, if you decrease keeping the voltage constant then again you are going to have flux saturation.

So, typically frequency is reduced above the rated value and this figure shows what will happen if you reduce it about, if we reduce it higher, so if we reduce it higher then what will happen keeping the voltage constant these are the flux level is going to fall. So, this is you now flux weakening kind of, see that perhaps you can recall the similarities which you found in the DC motor characteristic there also we had a flux weakening zone. So, in that zone the torque will fall basically because of the fact that there is a maximum torque achievable with a certain stator current.

These are also envelopes of operation will fall because of the fact that the air gap flux level has come down, so on the other hand.

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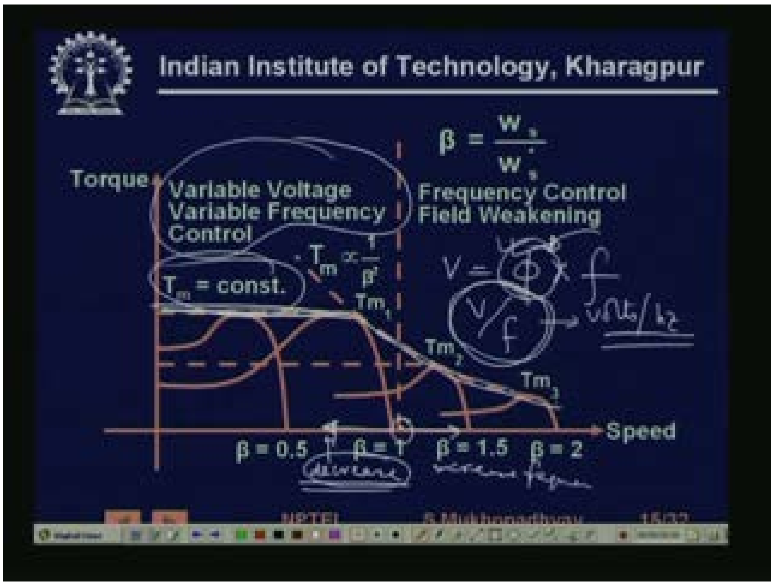

So, what you can do is, so you see that what is the situation, now the situation is that you cannot, you can this is your rated condition, so if you increase voltage then from here you cannot increase voltage, you can only decrease voltage in this region you can decrease voltage. But if you decrease voltage, we have found that there are some problems as we found in the stator just simple stator voltage control.

In this zone we can increase frequency, so when you decrease voltage decrease frequency, when you decrease voltage again what is happening and keeping the frequency constant these are the flux level is falling. So, again the torque is falling, but if, but here because you can you can keep the flux level, how by as you are decreasing the voltage you can also decrease the frequency, if you decrease the frequency then the flux level will remain.

So, you can have a constant you know normally voltage is flux into frequency typically because the back emf if you consider, if you neglect the stator drop, stator resistance and leakage inductance drop. So, you can maintain the flux level by maintaining a constant ratio of V by f, so this is called sometimes called a V by f control or a constant or volts per hertz control. So, if we do that the flux level is going to remain constant and therefore, for a maximum stator current that you can drive through the machine the torque will remain constant, so this is your constant torque zone.

If you use a variable voltage, variable frequency control to keep the flux level constant or a constant V by f. You can have a constant torque zone, just like you had for the dc machine, where in the dc machine the flux automatically remains constant because it is in quadrature, if you neglect armature reaction. That is why the DC motor control is simple because you do not have to bother about the flux level, but here you have to, on the other hand if you want to go for.

So, for lower speeds you can maintain torque by having this V by f control for higher speeds you cannot because you are trying to increase frequency and you cannot increase voltage. So, you have to reduce you have to, so the air gap flux will fall and the maximum torque achievable will also fall. So, this is the operating region exactly it is like the DC motor case.

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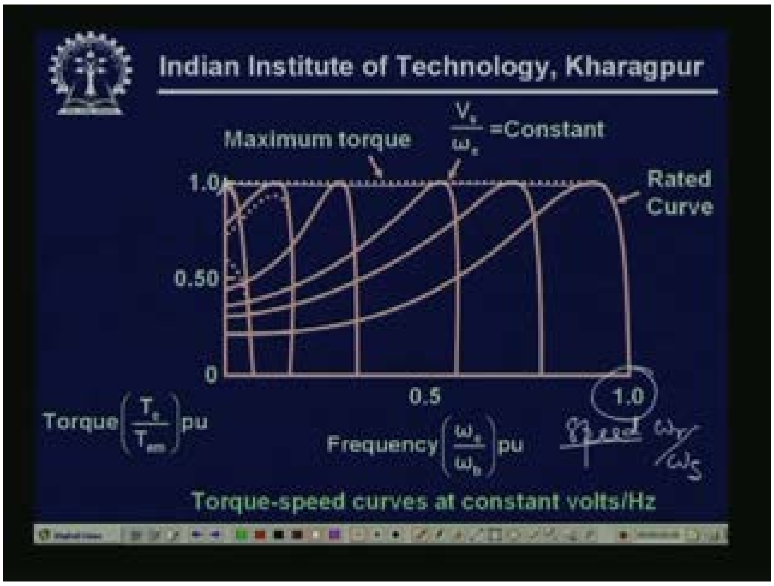

So, these are the you know torque speed characteristic at various this is again this is speed omega r by omega s and this is torque. One thing is interesting, first the maximum torque level can be maintained, so you have, you can achieve a very high starting torque with this control. They are almost like the maximum torque, so these kind of drives are going to be useful for machine which start on load.

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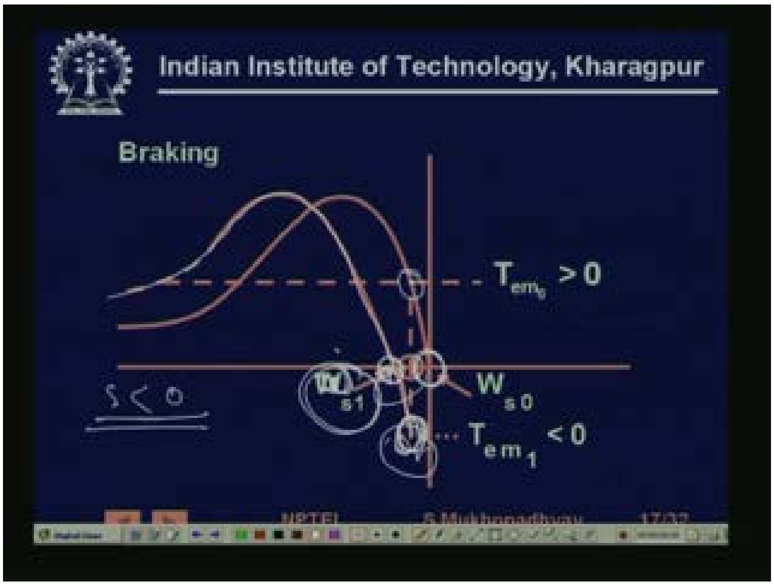

Now, for braking, so you know, you can do this torque speed control by varying the stator voltage and the frequency and you can, you see that you can also use it for braking. So, let us take the case of generative braking, so in this case what we can do is suppose that this we were operating at this synchronous speed or at we were giving this sort of supply frequency and this was the rotor speed, this was the rotor speed.

So, suddenly if you, now reduce the synchronous speed to a new synchronous speed omega s 1 this is omega then what will happen is that now this is omega r and this is omega s, so omega r is greater than omega s therefore, slip is negative. So, immediately what will happen is that it that now the machine will operate according to this curve because now this is the new synchronous speed, so you actually the torque that it will have is now negative. So, you see that the electromechanical torque developed has reversed.

So, the machine is going to slow down and it will try to feed back power to the source, so you see that by doing changing this frequency we can also achieve braking. So, coming to the essence of it, there are two ways that we typically are going to control the machine.

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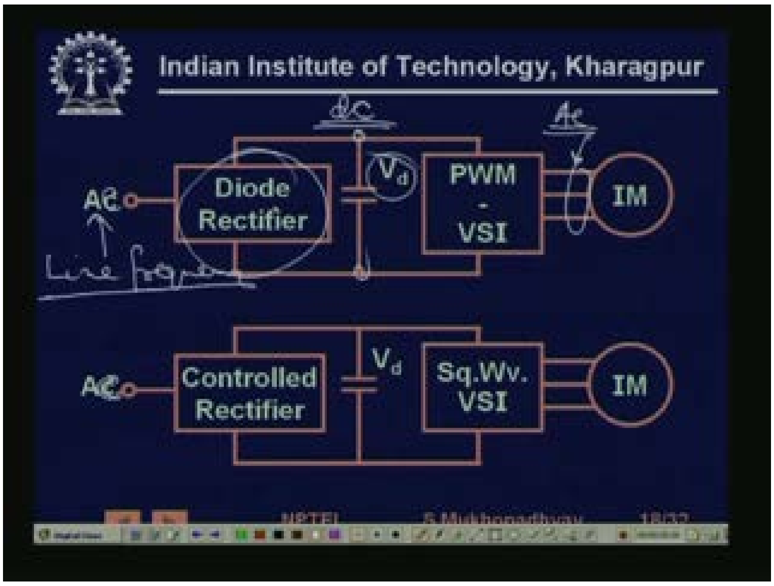

We need to have, so as far as the power electronics is concerned, we are trying to make a voltage source, supply source which will generate three-phase balanced ac supply to the stator, but whose voltage and frequency can be changed. So, how are we going to change, so that it can be achieved in two ways one is that so; obviously, we have this is line frequencies and this is also ac, but this is at a different this is at a controllable frequency and usually quite it may be high frequency.

So, we have to first convert this ac to a dc, so here it is dc, now if we have a diode rectifier, uncontrol rectifier then this dc, this Vd value is going to be constant we have no way of changing it because it is made of diode. So, it is a simple rectifier no controls, but then we must have an inverter. In this case a PWM voltage source inverter, where in the inverter both the voltage and the frequency can be changed or otherwise what we could do is, we could have a square wave inverter, where we cannot change, in the inverter we cannot change the amplitude.

But we can change the frequency and the amplitude can be changed by changing the dc link voltage, so to be able to change that we have to use a control rectifier, so now we have these two possible arrangements. So, we to be able to create this variable voltage, variable frequency ac power source which will feed the stator of the machine for good speed control, we can either have a uncontrolled dc source with a PWM VSI or we can have a control dc source with a square wave VSI. So, we are going to look at these two options.

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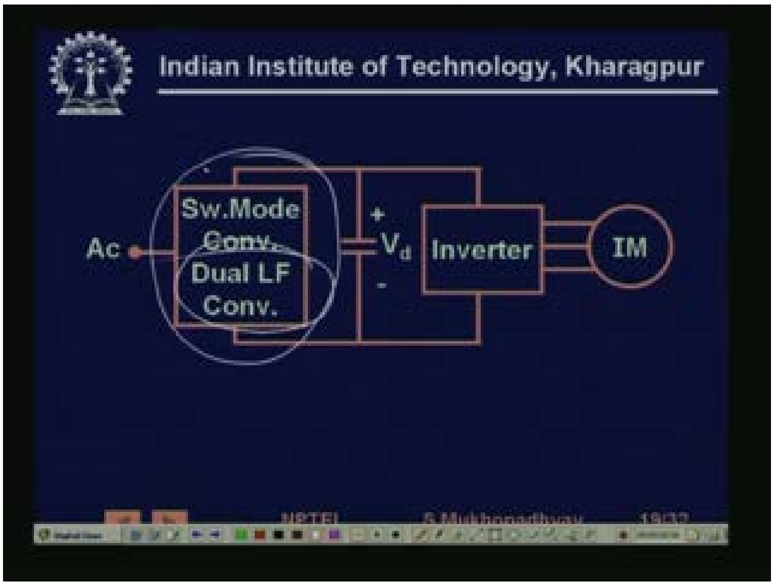

This is a case, where you know as I said that regeneration would be possible, only if you provide a mechanism such that the current can be reversed. Now, you see that in normal converter as we have seen phase control converters, even if you use control rectifiers current cannot be reversed, but voltage can be reversed. So, therefore, if you want to have a current reversal mechanism, you need you need to have dual line frequency converter or you can have switch mode converter, where current can be reversed. So, one of the two, so if you want to have regenerative braking along with that then we need this kind of a device on the dc side.

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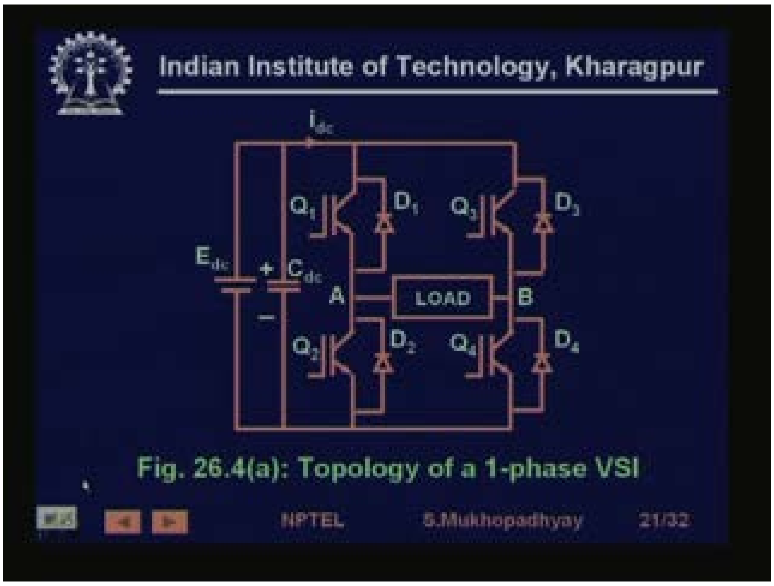

We will look at this one later, this has come out of arrangement, so you see, we can have two kinds of inverters one is, so this is an inverter, simple inverter single phase is that you have a dc source. This dc actually comes from the control rectifier, but we are not we are at the point just simply modeling it as a simple battery and then you have these switches and diodes in anti parallel and this is the load. So, this could be the a, a in the, in the single case it may be a motor winding of a of let us say some single phase motor, but we are typically we use a three-phase case.

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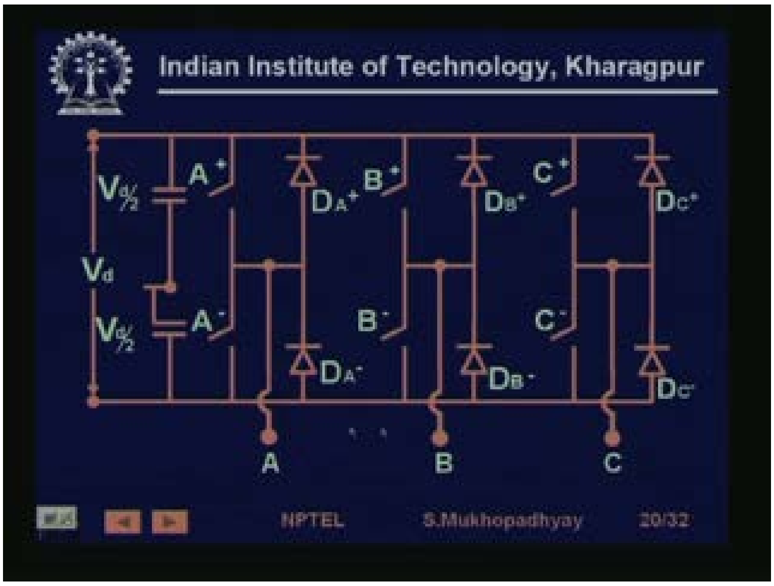

So, this is the three-phase, case which is the same thing. So, you have a dc supply, you have two capacitors in this case and you have just like, the previous we have already seen a switch mode converter which is almost which is very similar to a PWM inverter. So, you have this A plus A minus switches B plus B minus switches and C plus C minus switches this is three-phases and these three points A B C are actually connected to the stator of the motor as we will see, very soon. So, this is what a three-phase inverter looks like.

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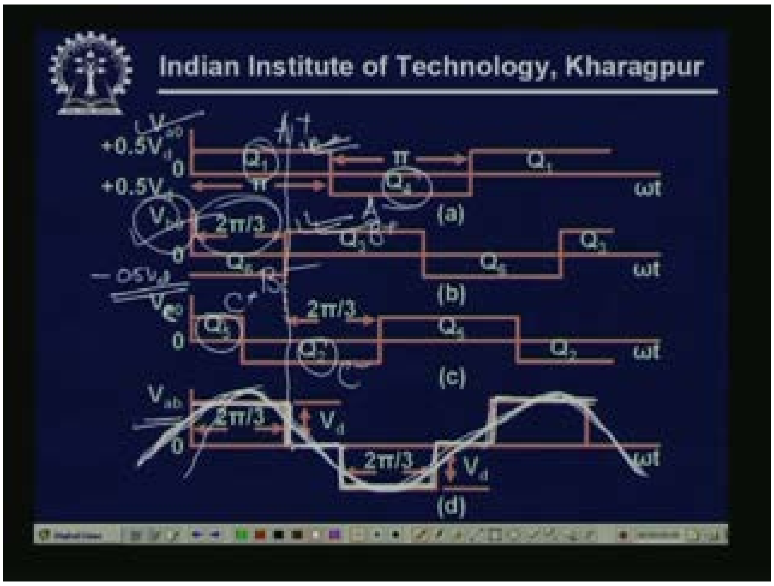

So, now you see the previously we have seen that if we switch on, so look at this, so here if we switch on this immediately this goes to plus V, so suppose this is a plus Vd this is supposed this 0. So, immediately it will go to plus V if we switch on this immediately this terminal will go to 0 or may be if we can call it plus V by 2 minus V by 2 in which case anyway it will go to the negative terminal, this is going to the positive terminal.

So, depending on the switches we can vary the voltages having understood that, let us now go back, so now consider any one phase say Va, so if we switch on the corresponding switch Va can be made to. So, we are switching on, so Q 1 Q 4 Q 1 Q 4 we are switching, Q 1 is A plus this is A plus this is A minus and so on. So, by switching A plus and A minus we can make it vary, now you see if we keep varying the B phase which is Q 3 and so this is B plus and this is B minus, if you switch them, in the similar fashion, but now it is you see phase shifted by 2 pi by 3.

Similarly, this is Vc 0 which is again this is C plus and this is C minus, so again these are also switched then how will the line voltage look like, the line voltage is is Vab which is applied across the motor is nothing, but Vab is Va 0 minus Vb 0. So, now look at Va 0 minus Vb 0. So, this is 0.5 Vd suppose we are switching between plus and minus, so minus 0.5 Vd, so this is full Vd. On the other hand, what happens at this point, at this point they are same this is 0.5 this is 0.5, so therefore, this goes to 0.

And therefore, next time again this goes to negative, so now this line voltage actually looks like this, so can you see first of all that it is alternating. So, if you see it to the

Fourier analysis you could say that the fundamental component of this Fourier wave will look something like this. So, if you only see the fundamental then you can think that you are applying a sinusoid of this type, but you are also applying other harmonics and harmonics create problems in the sense that they create heating and because of you know the magnetic losses increase and they also create spurious harmonic torques on the machine, high frequency torques.

So, harmonics are to be avoided and this is the, in fact, one of the drawbacks of this inverter is that it you get more harmonics, so but what I am trying to say is that, so by switching these, switching a dc voltage through this inverter you have created a voltage source an ac voltage source, whose frequency can be changed by simply by changing this frequencies. So, but the amplitude cannot be changed because the amplitude is always switching between plus and minus 0.5 Vd. So, as such in the inverter the amplitude cannot be changed, but the frequency can be changed, so this is the principle of this square wave inverter.

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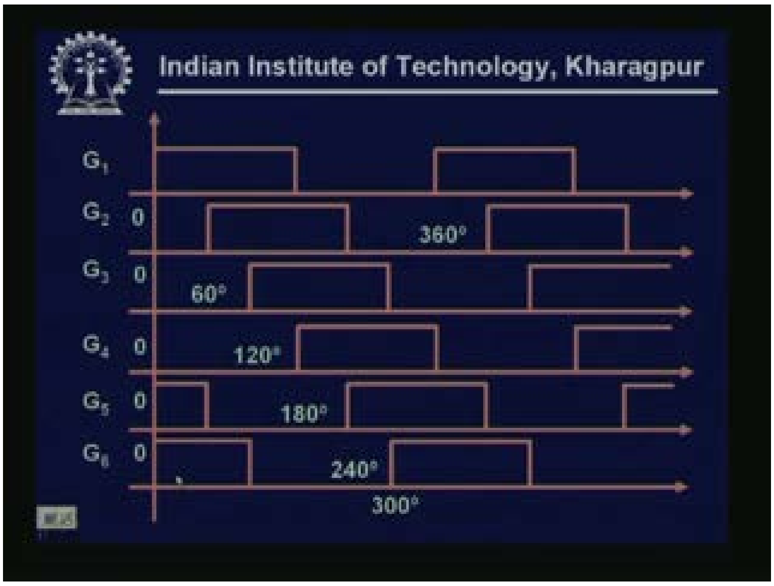

So, these are the switching the six devices G 1 to G 6, if you switch them in this order, so it will find that at one point you will get.

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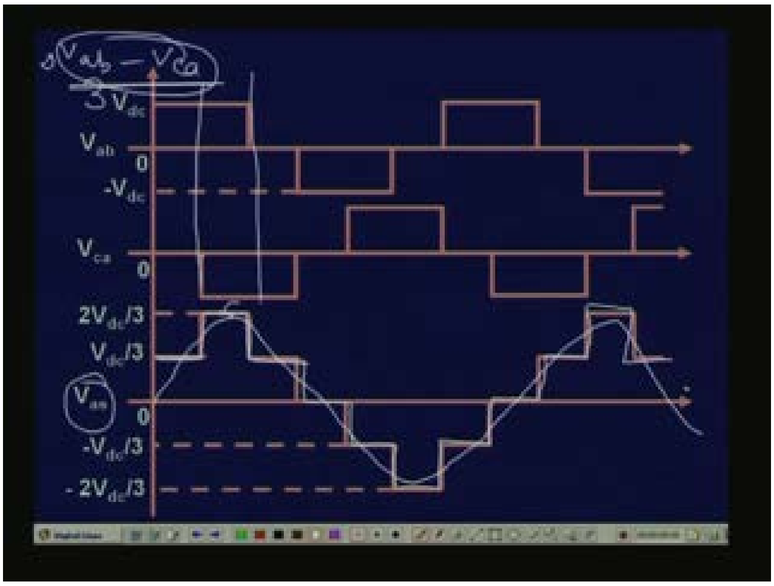

These are your line voltages and if you see the phase voltages across the machine then you will find for example, Vas is you know something like, it is some Vsab minus Vca by it is proportional to that Vab minus Vca. So, if you do Vab minus Vca you will find that here it is divided by 3 I think, so this is Vdc, so this is going to be Vdc by 3 here it is negative, so during this interval it will be 2 Vdc by 3 and again this will be, so you see the phase voltage across the machine is going to be like this six step, wave form. So, again it can be approximated by a sinusoid.

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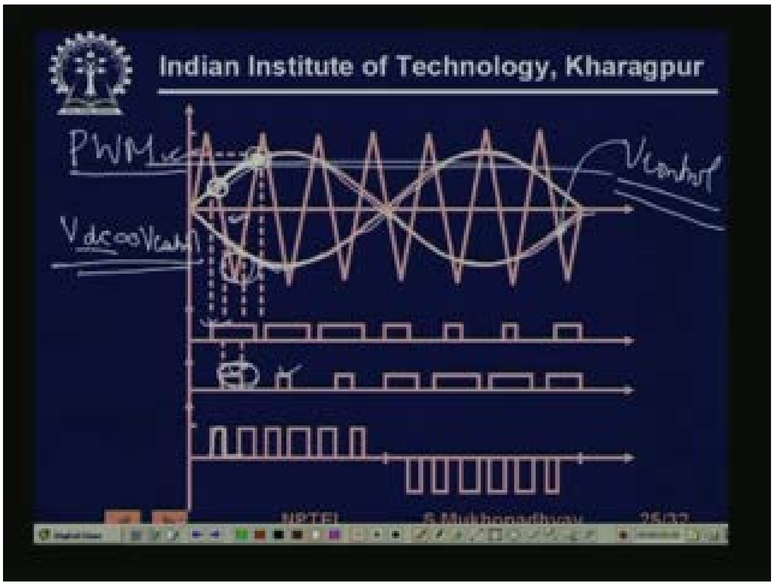

Now, this is the, that was square wave VSI where we just you simply we had a constant dc voltage and we just switch them at some continuous phase difference and at some frequency. Now, we are having this, we are contrasting it with a PWM scheme. In fact, the PWM scheme or pulse width modulation scheme, we have already seen in the case of the switch mode dc dc converter.

So, there we had seen, there what did we do if you recall and there we had a, we had we used a control voltage which went which was constant, why it was kept constant at that time because we wanted to generate a control dc voltage. Here and we found that with this kind of switching the dc voltage, the actual effective Vdc was proportional to this V control value we also found that in our dc motor control, if you recall, so now here we want to generate a variable amplitude s.

So, what is the obvious strategy, the obvious strategy is to is rather than having a constant voltage here which we needed for creating a dc, let us vary this control voltage like a sinusoid. So, now we have a sinusoidal V control and we again have the same strategy that is for example, we say that say this wave, we are saying that when this falls below this then we are going to switch on this device. So, now what we have is that suppose, so in one phase, so we are having, now two sets of devices.

So, suppose this is for a single phase PWM, so we are saying that top halves we are going to switch on, so you see this is one phase, so whenever this point to this point and this point to this point. So, whenever my control voltage this wave, this control is greater than this triangular, I am opening this switch on and on the other hand this switch is being operated with respect to the other triangular wave, so whenever this voltage falls below this triangular wave, I am going to operate this switch on, this is my strategy.

So, now what is going to the happen to the, if you take, if you subtract we will find that sometime this will be on then this will be actually this is not properly drawn in the sense that this initially actually you will get a set of, let me draw it here.

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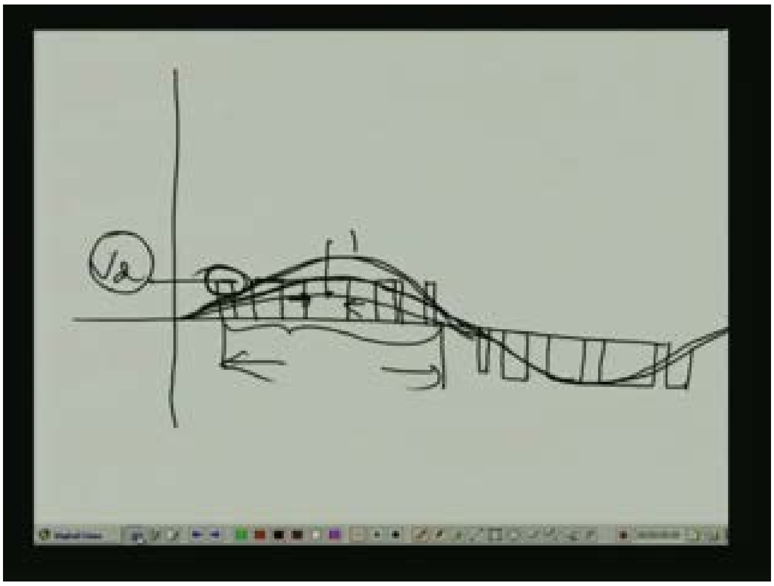

So, actually what you will get, let me change the pen, so actually what you will get is you will get a set of wave, which are voltages may be here and then narrower and then you will get a similar thing then for a sometime there will be a break and then you will again get a narrow pulse. So, this pulses will get consecutively wider then it becomes narrow here, so if you take this sort of a wave and do Fourier analysis then again you will find that you will get a sinusoidal wave.

So, because these amplitudes keep varying, so therefore, this is called pulse width, so this pulse width keep changing and this pulse widths can be changed in, so what will happen see the in the switched wave the heights remain the same, this is again Vd. But if the pulse width can be varied then it can be shown that the effect on the fundamental, you can actually see this the what will happen to the fundamental the amplitude of the fundamental will actually depend on these pulse width.

So, this fundamental amplitude can be changed, so by having this pulse width you can make the amplitude like this or you can make the amplitude like this, by just varying this pulse widths. Although the height here does not vary, but the effective amplitude of the fundamental will change, but and the frequency can; obviously be changed because the frequency is going to be simply the frequency of the wave.

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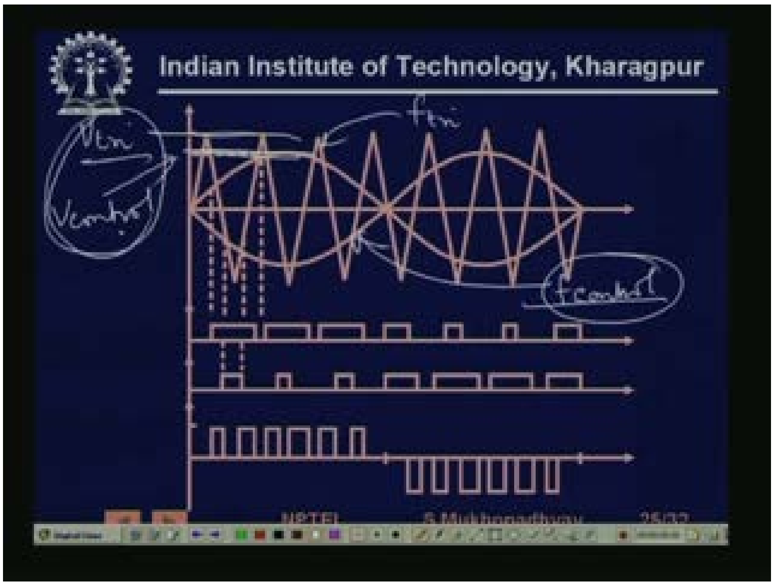

So, going back you see that we have two kinds of modulation, firstly, this is V triangular, go back to the white pen, so this the V triangular and this the amplitude of the V control. Similarly, this V triangular has some frequency f triangular and this has some frequency f controller, so we can see that by varying, we can change the frequency by simply changing f control of course, we have to assume that f control f triangular is much, much higher than f control.

Significantly, higher and the amplitude ratios we can change by this we V triangular by V controller, so we can change both amplitude and frequency, so this is the idea of PWM, where in the inverter itself you can change both amplitude and frequency this is what I was talking about.

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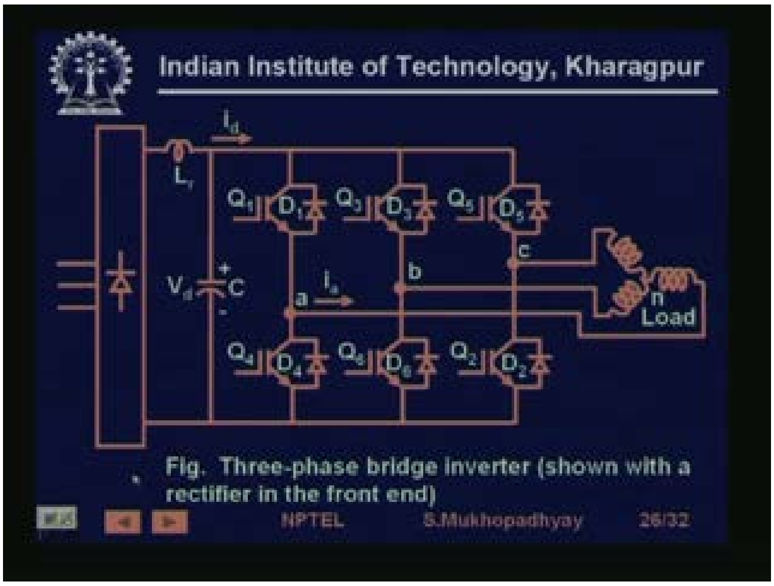

So, this is what you do, so you have a, this is again a PWM three-phase with a motor connected, so there is nothing new in it. So, if want to generate three-phase supply then you use three waves, Va Vb Vc and then with respect to these three waves you actually generate the PWM waves, so that is the way it is done.

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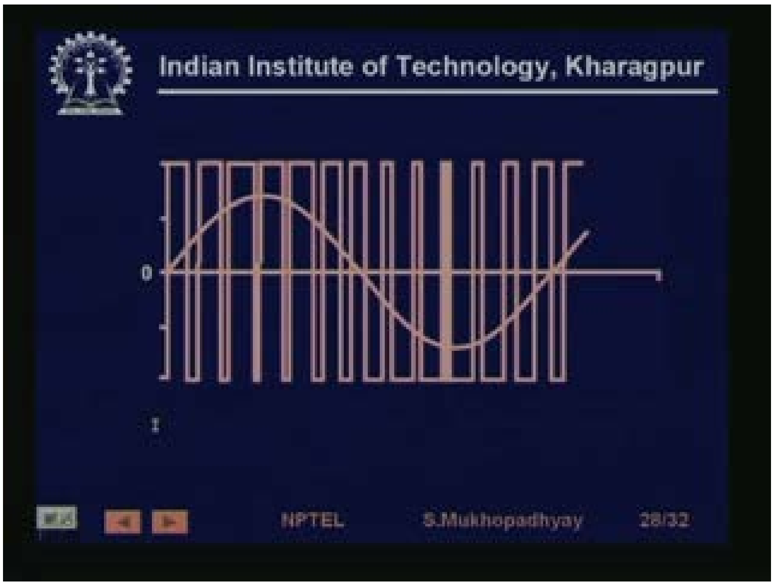

We are not going into this, so this shows that if you have a PWM switched wave like this then it its Fourier transform will generate an ac wave, it will generate fundamental like this and its harmonic content will also be improved over the square wave VSI in the sense that lower frequency harmonic will not be present.

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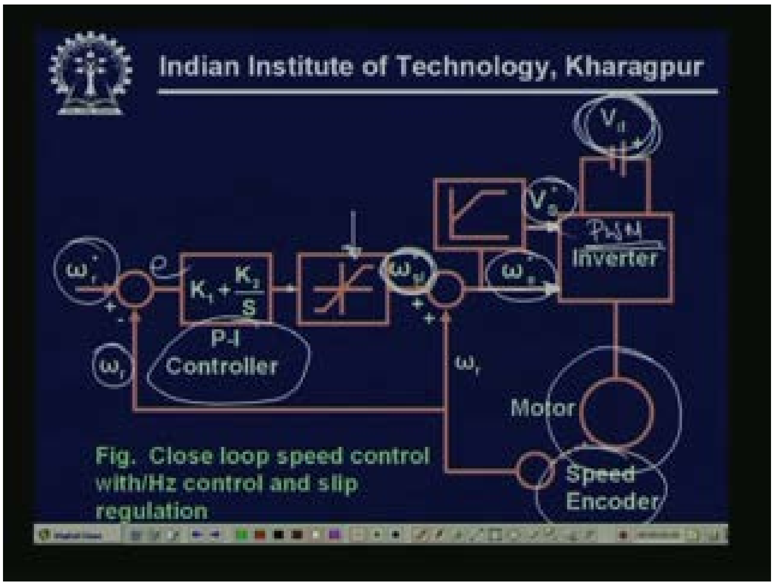

So, now, so you see that using we have seen that we can how we can vary voltages and frequencies, so now if you want to implement a variable voltage, variable frequency control loops, so what happens is that this is the motor. So, we are sensing the speed, this is a speed sensor, speed encoder you are feeding it back to the controller omega r. So, the controller is see this is the reference speed, this is the speed error and this is the PI controller, typically a PI controller is used.

So, the PI this is the saturation function which is applied, so that you do not apply too much voltage and frequency, so I assuming that the saturation does not take place, this is, so the PI controller now generates a set point basically a control input. Now, so with respect to in proportion to this, now you have to provide a frequency set point to the inverter as well as a voltage set point to the inverter, if it is a PWM inverter then you can set to the inverter itself you can set Va star and omega e star and have a constant dc source.

On the other hand if it is a square wave converter then this voltage command will actually go to the control rectifier which will generate the, which will control this Vd. So, a different, slightly different control scheme will be applied, so this brings us to the end before closing, we will quickly look at the lesson summary.

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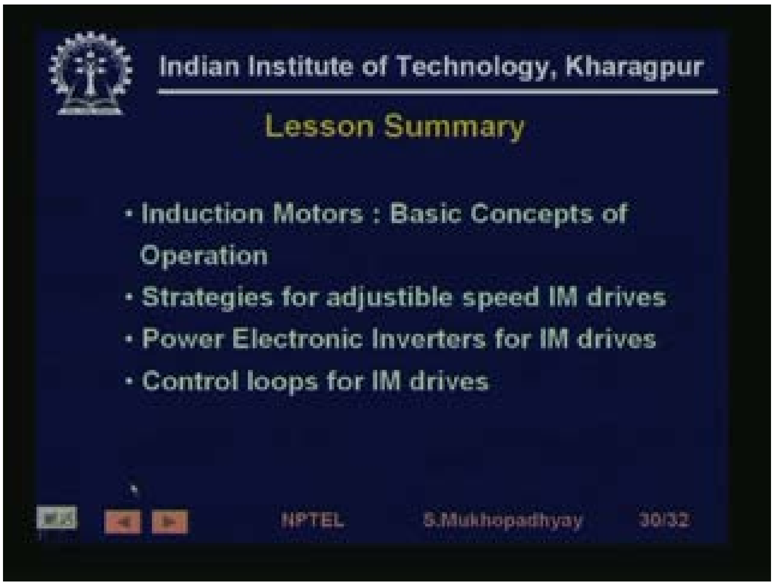

So, what did we do today, we looked at the induction motors, how they basically operate looked at synchronous rotating flux, how torque is generated, how braking is done etcetera saw the torque speed characteristics. Then we saw that if we want to vary the torque speed characteristic according to load and operate at various points, how we should drive the stator, what are the basic idea, so vary variation of voltage and frequency. Then we saw, what kind of circuits we should use for varying this voltage and frequency, and then finally we looked at the looked at the one control loop for induction motor drive.

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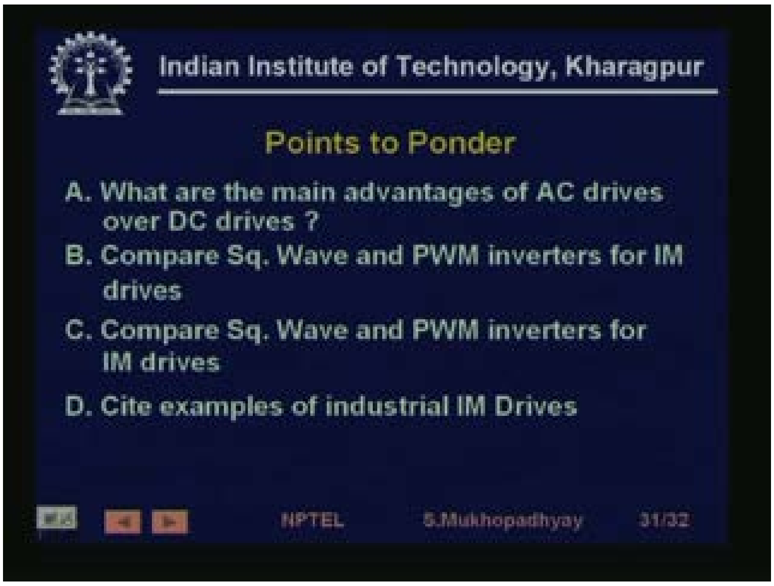

So, coming to points to ponder you can think of these things, what are the main advantages of AC drives over DC drives, you can try to the list them. Compare square wave and PWM inverters for induction motor drives in terms of complexity, in terms of harmonic content, in terms of transient response etcetera. This is a repetition, then you can think of find try to find out from the internet or from other books examples of some industrial IM drives, so that brings us to the end.

Thank you very much.