Advanced Electric Drives
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Lecture - 35

Hello and welcome to this lecture on Advance Electric Drives. In the last lecture we are discussing about the director control of induction motor drive, when field from a 3 level inverter. Now, when we have a 3 level inverter, we can apply this for high power application, by hyper application we mean beyond 1 Megawatt, so when we have a large induction motor drive, and usually for large drive the voltage rating of the motor is also high.

So, we can think of a multi level inverter feeding an induction motor drive, and we selected a diode clamp multi level inverter for controlling the induction motor, and one of the popular methods of control is the director control. These were we discussing in the last lecture, that in director control the torque equation is given in a very simplified form, basically proportional to the product of 2 fluxes the stator flux i s, the rotor flux i r that we were discussing in the last lecture.

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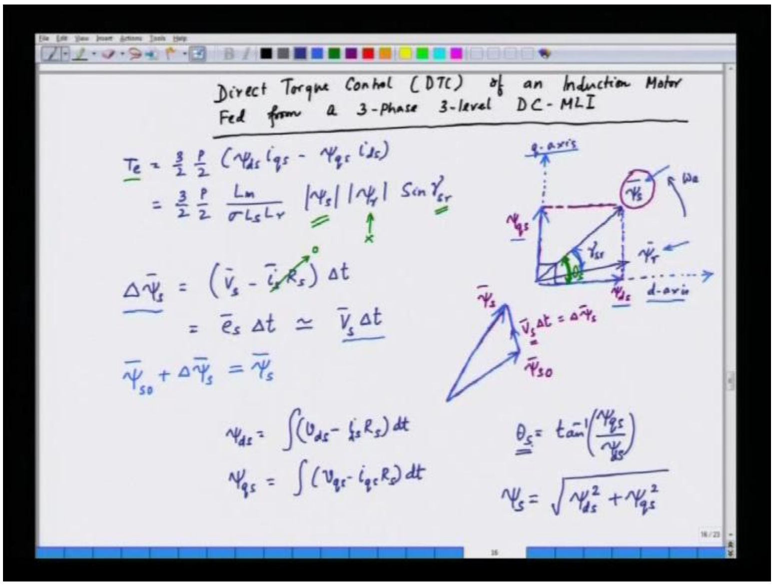

That T e is equal to the constant 3 by 2 into p by 2 L m by sigma L s into L r, and then psi s is the amplitude of the stator flux, psi r is the amplitude of the rotor flux, then sin gamma s r, this gamma s r is the angle between the 2 fluxes these angle. So, we have the stator flux is psi s, the rotor flux is psi r, the flux vectors and then gamma s r is a angle between the 2 fluxes these angle.

So, what we can do here, we can control the torque by controlling gamma s r, gamma s r is a angle between the 2 fluxes, so we can have a direct control over the stator flux by applying the various voltage vectors. Now, we have seen that in the last lecture that in a 3 level inverter, we have got 27 possible voltage vectors, so we have more flexibility. So, we can apply 1 of this voltage vectors to control the stator flux in an induction motor, so when we apply a voltage vector the flux will change as for this equation.

So, we have psi s the change in the flux is a vector, and if we ignore the resistance drop, resistance drop is i s into r s, this is applied voltage v s, voltage vector v s minus i s into r s into delta t is a time interval. So, what we finally, obtain is v s into delta t, and we know that the stator flux the initial value is psi s naught, and we have a change in the value that is delta psi s.

So, if you add this vector really, what we obtain is the total flux vector that is psi s, so this basically a vector triangle, so one side is psi s naught, and other side is delta psi s, and the third side is psi s. So, these are the 3 sides, and by applying a voltage vector that is v s, we can control the stator flux effectively, now we can find out the magnitude of the various fluxes psi d s and psi q s.

So, we have this is our d axis and this 1 is a q axis, d and q axis respectively, the stator flux vector psi s can be resolved into 2 different components. And one component is along the d axis, and we call that to be psi d s, and the other component is along the q axis, and we call that to be psi q s, so we have 2 components of the stator flux linkages. And we can find out this angle theta s, this is the angle theta s that we discussed in the last lecture, this is angle, so this angle theta s is given as tan inverse of psi q s by psi d s.

So, we have this angle theta s is tan inverse of psi q s, so psi q s is a q axis flux, and psi d s is a d axis flux, so if we take this is basically an orthogonal axis, d and q axis are perpendicular to each other. So, if we take the inverse of this tan inverse of psi q s by psi d s, we get theta s, so this theta s will help us locate the flux in various sectors. So, we have seen that we have 6 different sectors from 1 to 6 that, we have already seen in the last lecture.

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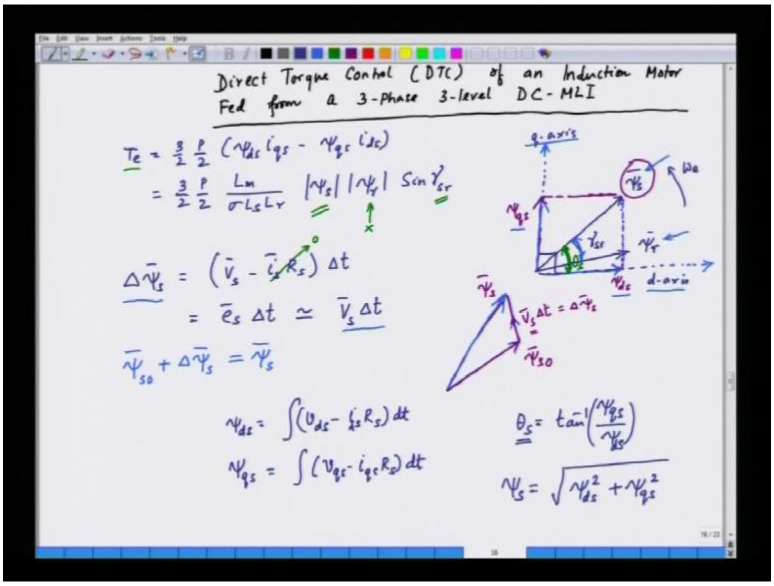

These are the various sectors sector 1, sector 2 between this and each one is 60 degree interval, sector 3, sector 4, sector 5, and sector 6, so we have 6 different sectors and the flux vector can lie in any 1 of 6 sectors. And that can be found out by calculating theta s, so theta s will help us know the position of the theta flux vector, and hence we can find out which vector can be applied, so that we control flux and the torque respectively.

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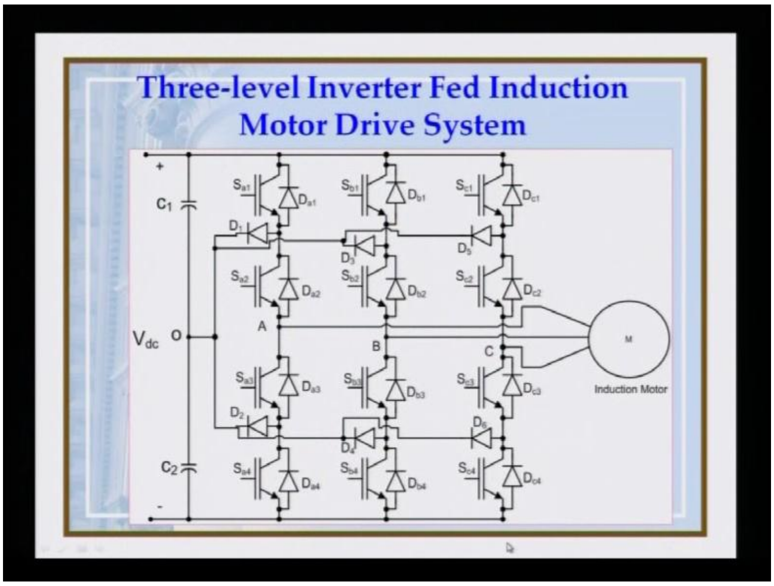

So, if we see this in the in the form of block diagram, this is actually our 3 level inverter, we are feeding a induction motor in this case, and we have 3 different lakes here. Phase a phase b and phase c, and these are the various diodes, the feedback diodes and the clamping diodes, and these are clamp to the midpoint of the input voltage. In this case V d c by 2 and V d c by 2, the total being V d c the total voltage here, the d c voltage here is V d c, and the voltage drop across c 1 and c 2 each capacitor is V d c by 2.

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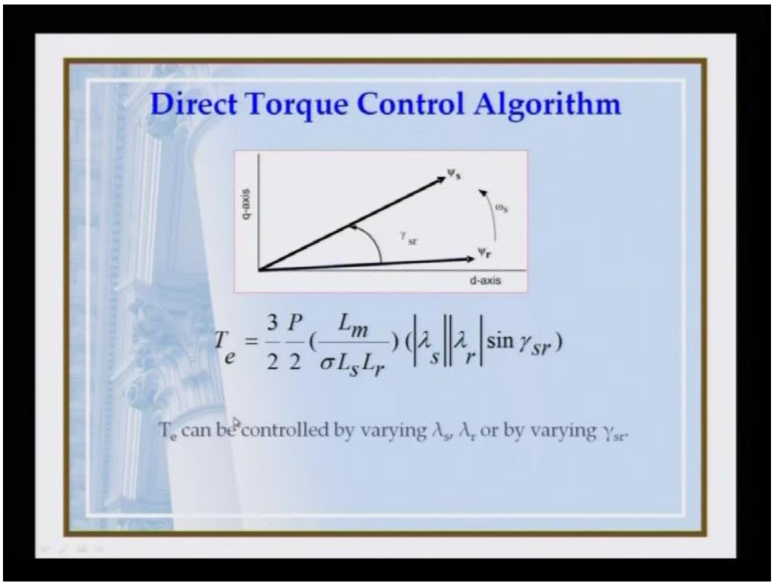

And then these are the flux vectors, the stator flux is psi s and the rotor flux is psi r, and then we can calculate the torque, in this case 3 by 2 into p by 2, we have a constant here lambda and the psi are the same. The flux the stator flux into the rotor flux into the sin of the angle between then gamma s r, and gamma s r is a angle between psi s and psi r. So, the torque can be controlled by varying lambda s is same as psi s, and lambda r is same as psi r, so we can vary this torque either by varying lambda s, lambda r or by varying gamma s r.

Now, we know that flux variation is not preferred, because if we vary the flux then will be delay associated with the flux change, further mode a variable flux machine is not very attractive, if we increase the flux the machine may saturate, if we decrease the flux the machine may under flux. So, the saturated machine will have higher coal loss, and the flux reduced the power level also will reduce, so the first reason is that the flux change will be accompanied by a delay and secondly a machine with variable flux may sometime saturate and may lead to higher coal loss.

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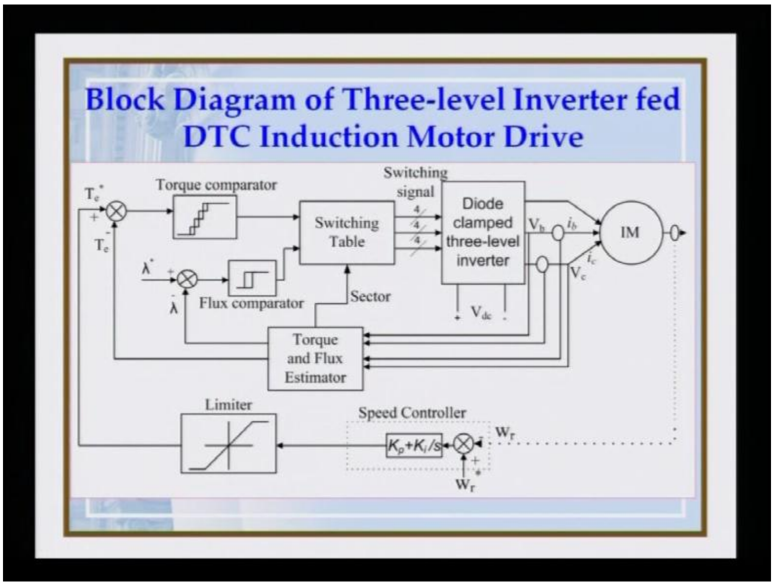

So, what we do we control the torque by controlling gamma s r, the angle between the 2 fluxes this is the angle, and what we obtain finally is a closed loop block diagram of speed control. So, we have the induction motor here, and we have a speed sensor the speed sensor gives us the speed, and what we get here is actual speed, it is fed back here. And we have a reference speed that is omega r star, and we compare the actual speed with the reference speed, and then it was speed controller or p i controller k p plus k i by s.

And then we have a limiter, because this p i controller kept sometimes integrate the error, which may reach every high value, so to limit the torque to a practical limit what we do we limit the torque to a positive limit and a negative limit. Obviously, in a machine we will have a maximum possible torque, because torque and the currents are related, so we limit the torque to a maximum limit and a minimum limit, and hence we need a limiter

And then this limiter will limit the value of the torque, and it give basically the torque reference, if the value is in between this limit, whatever is the output of the speed controller will be the torque. And if it is higher than the positive limit, the torque will be limited to the positive value, and if it is low than the negative limit, basically for the breaking operation or for negative speed, again the value of the torque will be limited to the negative maximum value.

So, the speed controller gives the torque reference, so the this torque reference T e star is compared with the actual torque, and the actual torque is obtained from a torque and flux estimator. So, how can we estimate the torque and flux we will see little later, and this feeds to a torque comparator, the hysteresis comparator. So, if this actual torque is not same as the reference torque, we get an error and this is process to a hysteresis comparator, this will be giving us the torque status, I have in case of d t c of a 2 level induction motor drive.

And we have the reference flux here lambda star, and that is compared with the actual flux lambda, and it is fed to a flux comparator. So, we have a torque comparator and a flux comparator, and a sector information is also obtained by finding out psi d s and psi q s, so we know in sector the stator flux is laying, whether in 1 2 or 6. So, we can find out the sector information, and by sector information we can know which vector should be applied to the induction motor, because we have various voltage vectors.

So, they will vary depending upon the various sectors, the sector information will help us apply the appropriate voltage vector to the induction motor. So, this is what we have here and then the output of this is the voltage vector, and when we know the voltage vector we can find out the switching signals. We have, in fact a 3 level inverter, and in a 3 level inverter what we have here is we have 12 possible switches per phase, we have 1 2 3 and 4. This is for phase a, and similarly for phase b we have again 4 switches, phase c also we have 4 switches, so in total we have got 12 switches.

So, this information this phase per phase we have got 4 switching signals, these are the switching signals for phase a 4, phase b 4, and phase c 4, and the switching signals are fake to the diode clamped multi level inverter 3 phase inverter. And what we obtain is the output voltage, voltage for phase a phase b and phase c, and these voltages will pass some current, we have the induction motor here.

And we take this feedback of the voltages and the currents, we have the current sensor here, and we have the voltage sensors here. So, we can take this information to the torque and flux estimator, which will give us the flux magnitude for the fed back, this is basically the calculated value of flux, the torque magnitude for fed back the torque of the motor, and the sector information about the stator flux psi s or lambda s.

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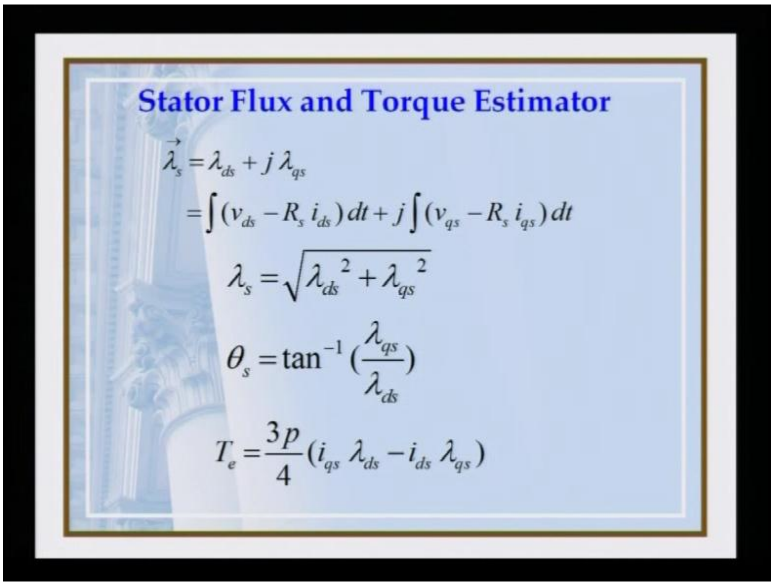

So, we will see how this flux and torque estimates the flux and the torque respectively, now we know that flux psi s or lambda s, as got 2 components lambda d s and lambda q s. So, we can calculate the biggest components in the following fashion, this have got 2 components lambda d s and lambda q s, so we can integrate the corresponding voltages v d s minus r s i d s.

So, this v d s is basically the die taxies voltage in the stationary reference frame, R s into i d s is the resistance drop we can measure the current by halls sensor, in fact what we are doing here we are measuring not v d s, v q s, we are measuring v a, v v and v c. And when we are measuring v a, v v and v c, we can transform them into d q by a here stationary transformation, because this lambda d s and lambda q s are the flux linkages in the d and q axis in the stationary reference frame.

Similarly, we can have sensors to measure i a i b and i c, and we can transform this i a i b i c into i d s and i q s by a stationary transformation. So, in this equation we know v d s, we know i d s, and we know v q s, also we know i q s, we can calculate this to flux components psi d s and psi q s or lambda d s and lambda q s. So, lambda d s is a total flux that is equal to under root psi d s square plus psi q s square, and theta s is obtained by tan inverse of lambda q s by lambda d s, and the torque once we know this corresponding fluxes lambda d s and lambda q s.

We can calculate the torque by this equation 3 p by 4, p is the number of poles 3 p by 4 into i q s into lambda d s minus i d s into lambda q s. So, we can find out the magnitude of the flux linkage that is lambda s, also the magnitude of the torque, so these are basically used for the feeding back the values for control, we have a flux controller, we also have a torque controller. So, we compare the reference values with the actual values, and the actual values are estimated, using the estimator and from theta s, we can find out in which sector the flux vector is lying.

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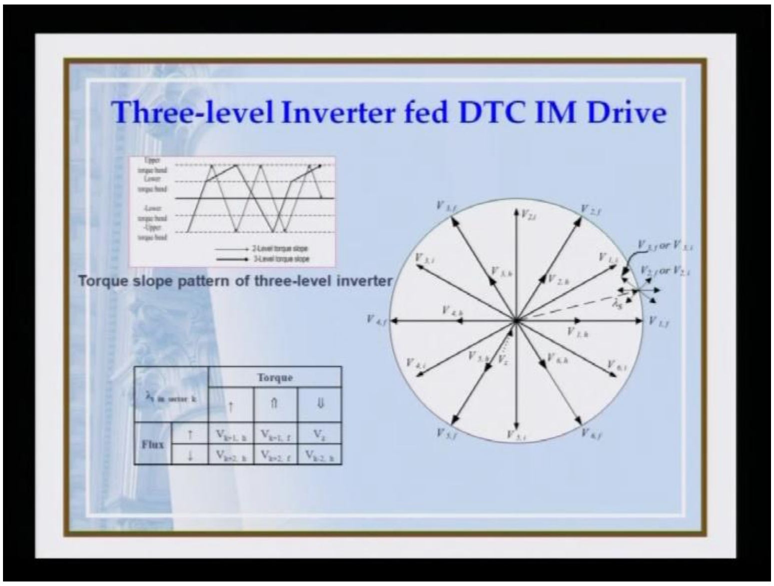

So, if we try to see the various voltage vectors this recapitulation of what we have done in the last lecture, so we have, in fact we have 27 possible combinations, and we have, in fact the full vector v 1 f, and v 1 h. Similarly, we have v 2 f the full vector, and v 2 h the half vector, and v 3 f and v 3 h, and v 4 f and v 4 h, similarly we have v 5 f and v 5 h and v 6 f and v 6 h.

So, we have 6 different main vectors and a half vectors, and in between we have intermediate voltage vectors, for example we have here v 1 i the intermediate voltage vector and v 2 i, v 3 i, v 4 i, v 5 i and v 6 i. So, when we control the flux lambda s, lambda s can be anywhere here, and what are the various sectors, that we have already discussed that. This is a sector 1, then we have sector 2 here, sector 3 between this 2 i and 3 i, and then sector 4 between 3 i and 4 i, sector 5 between 4 i and 5 i, and sector 6 between 5 i and 6 i.

So, we have basically 6 sectors here, and since we have a 3 level inverter, we have got the band the torque band is divided into 4 zones, the lower positive torque band, the upper positive torque band, and a lower negative torque band, and upper negative torque band. So, we can see here that we have upper torque band here, this is basically the reference torque shown here. And then we have we have the various torque bands in this case this is the upper torque band, and this 1 is a lower torque band and then we have a negative low torque band and negative upper torque band.

Now, if we go for the control of a 3 level inverter, just like a 2 level inverter we can also have a director control, but in that case we will be switching this 3 level inverter as a 2 level inverter. We would not have the full advantage of the 3 level inverter the flexibility that it offers having, so many different voltage vectors cannot be exploited. So, if we go for a 2 level switching, we will be basically switching from low to upper like this, so this is basically a 2 level torque slope here.

So, we apply a full voltage vector from negative band to the positive band, it increases like this, and then we apply a full voltage vector in the other direction it goes down, so this basically the switching, so this is this is one way. So, in this case you know that we have got higher torque cripples, so instead of that we do in this case is when it reaches the upper band, instead of a full voltage vector we apply a half voltage vector.

So, that basically reduces the slope of the torque, and hence we have a smoother operation, so here what we have in this case is this that, from the negative upper band to positive lower band, this basically the torque need to be increased. So, we have increased the torque here, and then when it crosses the lower torque band the torque need not be increased with that rate, so what we do here we replace the full voltage vector by a half voltage vector.

And thus the slope is reduced in this case, and very torches the upper torque band, what we do here state of by applying a full voltage vectors, we apply 0 voltage vector, so when we apply a 0 voltage vector, the torque decreases. And then here we apply again a full voltage vector, and ready reaches the lower torque band the full vector is repress by half vector. So, basically we can see that the switching frequency is also red oust here, and also the rate of change of the torque is also every lays, and hence the motor response batter to this kind of web form.

So, if we see in the form of table, so what we have drown here is lambda s, lambda s in sector k. So, we have some we sectors is in this case, this is basically fast sector, sector 1, sector 2, 3, 4, 5 and 6, so if it is in sector k, when you want to increase the flux, and increase the torque, so torque can be increased or increased with more value. So, this is basically when you have small arrow here it is just increase, and when you have a large arrow this is more increase.

So, let us see that we want to increase the flux and increase the torque, and we are in sector 1, 1 is basically this sector from this to this, we apply v k plus 1 half voltage vector, so v k plus 1 is v k is 1 here, k plus 1 is 2, so basically here we apply 2 h. So, when were in sector 1 and we want to increase the flux and the torque simultaneously, and torque increase is not that fast, so we apply we 2 h, 2 half vector, half vector means here, this is the full vector.

So, we apply the half vector v to h, the flux increase in this case v 2 f, so it increases not we that fast, it basically increase their slowly. And then if we want to increase the flux, but increase torque more we apply the full voltage vector, v k plus 1 f, so we can apply we full here, and in this case if we want to decrease the torque, we apply v z the 0 voltage vector.

So, when you apply a 0 voltage vector the torque reduces, so the voltage goes down here, I am in the torque goes down, similarly we can think of a situation, where we want to reduced the flux. Now if the flux is reduced we want to reduce the flux, but increase the torque, second situations here, so we want to reduce the torque, but increase the flux, but increase the torque, we will have v k plus 2 h, what is k plus 2 k is 1 here 1 plus 2 is 3. So, here we can apply voltage vector like this, 3 f here, so this 3 f will reduced the flux, the flux is reduced, because it is d magnetizing the flux lambda f.

And if we want to increase the torque more, instead of full vector, we have half vector we apply full vector, and then if we want to decrease the flux, and also decrease the torque it is v k minus 2 h. So, k minus 2 k is 1 here, k minus 2 is 4 h, so what is 4 here, so in this case 4 is this vector, so in this case if you want to increase 5, so if want to decrease the flux, and decrease the torque we apply 5 h, so what we do here we apply 5 h here.

So, if we apply 5 h both the flux and the torque will reduce, corresponding to this situation, so what we see here that when we have a multilevel inverter, in this case the example has been sold for a 3 level inverter. We have more flexibility, and more flexibility will result in less switching, the switching frequency will go down, and will have better torque response, because the torque triple can be reduced using a 3 level inverter.

So, and this is also applied for very high power application, and in high power we do not go for very high switching frequency, the switching frequency should be as low as possible. So, this is basically the director control of an induction motor phase from 3 level inverter, now we will see some classification of induction motor inductions motors or induction motor is call work horse of the industry. We can have large specification of index motors; however, we can classify them into various like class a b c d and so on this have been done by NEMA, and this NEMA ossification help us choose this induction of very specific application.

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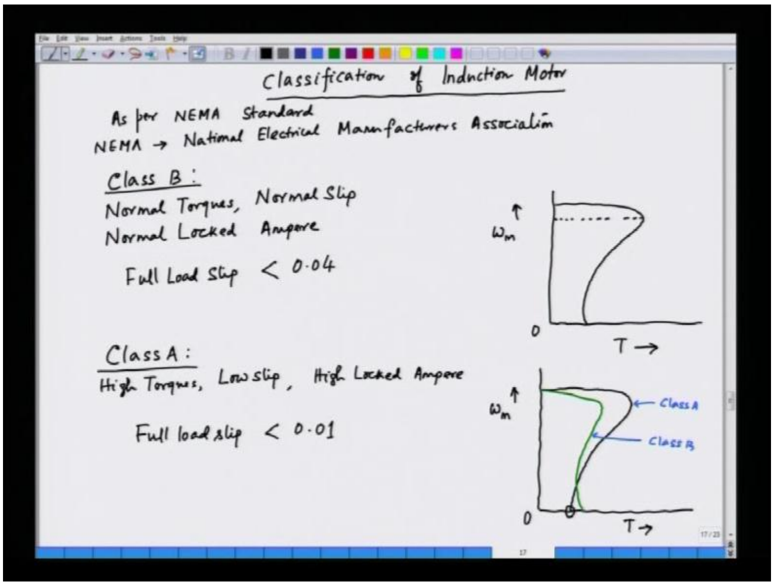

Now, we will see some classification of induction motor, so will be discussing about classifications of induction motor, and this is as per NEMA of standard. What of this NEMA stand for, NEMA stand for National Electrical Manufactures Association. Now, in this case we can classify the induction motors in various categories, and these are suited for some specific application, we will start with class b. Now, class b induction motor is very basically a normal motor, having normal torque and normal slip, they can use for with general application, we start with class b.

Now, class b has got normal torque, normal slip and normal locked ampere, and the full load slip is less than 0.04. So, this is basically the specification of class b motors, normal torque, normal locked ampere are the starting current takes, normal starting current and the full load slip usually less than 4 percent. Now, if we draw the torque speed idiotic of this motor it basically is a normal speed idiotic, and has got very general application, so let see torque as idiotic of class b motor.

So, we have torque speed characteristic like this, this is the torque and we have the speed in the y axis, and the torque speed characteristic is a normal speed characteristic. So, we have we have the maximum torque here, and this is the starting torque is not very high, but it is moderate, and this has got normal rotor resistance the rotor resistance is not very low, because it is very, very high. Now, if you want to very high torque and very efficiency, it may not possible to have using class b motors, class b motors are normal motors.

Now, if somebody want to very high torque, very high torque means in the full load condition the torques will be very high, so if you want to a very high torque, the torque can be increased by reducing the rotor resistance. If you reduce the rotor resistance, and also reduce the rotor inductions the leakage inductions torque can be increased, so class a motors have got high torque and low slip the slip is low and hence the efficiency is the better.

So, we will see the specification of class a motors, so we have high torque, low slip, high locked ampere or high very high starting current, so the torque b identical given like this. So, we have the speed here, and we have the torque is the x axis, so this is basically class a motor, now if we compare with this class b, the class b will like this, so this is class a and this one is class b.

So, if we compare these 2 motors, we see the class b have higher torque, and of course how is the torque made higher, the torque is made higher by reducing the leakage inductions and by reducing the rotor resistance, and the slip is also reduced, the slip the full load in this case is less than 1 percent. So, we can see here that the full load slip here is less than 1 percent, and that is possible we can reduce the rotor resistance, and the slip is reduced the losses are also reduced, because the motor operates a reduce slip the rotor copper are reduced.

And hence, the efficiency of this kind of motor are high, now we are seen actually class b and class a motor, and we understand that class a motors are upper to resistance. And hence, that has got higher torque unfortunately the starting torque is slow, because the rotor resistance is low the starting torque of the class a motors are low. So, we can see that; that means, of the speed characteristic we object here, the starting torque of class a motors and smaller compare to that the class b, and if class b motors also having low starting torque.

Now, if specification or if we application demand that is we have a higher starting torque, we should have a higher with starting torque, and the application also demands that the rounding torque also be quite high. So, we have 2 conditions or 2 specifications that, we should have a higher starting torque as well as higher owning torque. So, if we have both requirement of higher starting torque and can higher owning torque, we go for class c motors, in fact class c motors and manufacturing in a different way.

The rotors are as not usually rotors, they are double cage or deep bar rotors, so we will see the characteristic of class c motors. So, in class c what will have we have high torques, and normal slip, and we have normal longed ampere, so we can draw the torque speed characteristic, so this is the speed and the torque here.

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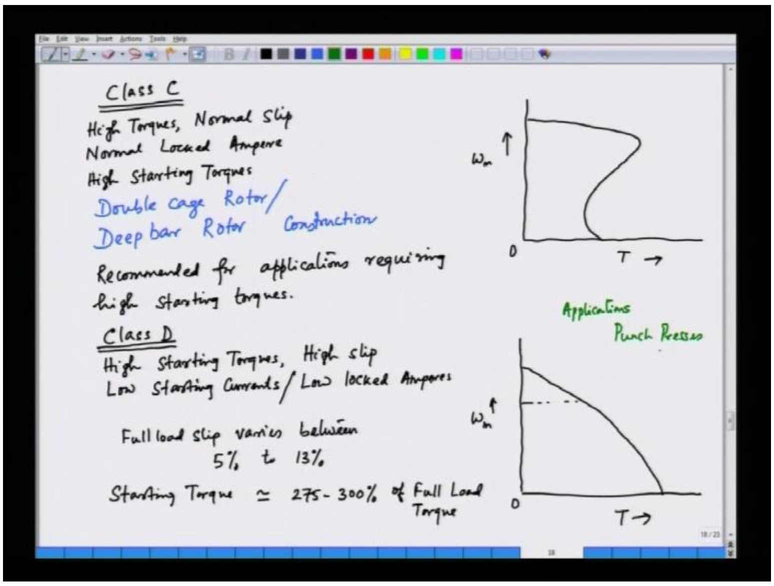

So, we can also say high starting torque, so in this case the torque speed characteristic like this, we have reasonably have high starting torque may not be very high, but it is very high starting torque. And we also have normal slip, the slip is normal slip about 4 to 5 percent full load slip, but the starting torque is quite high, and even in the running condition the torque is quite significant.

So, here what we use in this case is double cage rotor, so this motor have 2 cages in the rotor 1 is the upper cage, and the other is lower cage and this combination of the 2 cages help obtain higher starting torque as well as higher owning torque. So, we have a double cage rotor construction or deep bar rotor construction, and these are recommended for load require high starting torque, recommended for application, requiring a high starting torque.

And then we have another class of motor curve class d motor, class d motors have got very high rotor resistance, when the rotor resistance is increased last yearly the locked dump is reduced, at the starting current is reduced. There are so many applications, which require frequent stars and stops, so for example the punching machine, the press now when we think about this kind of motors or this kind of machines, there requires frequent starts and stops.

Now, if a machine as got large starting current, there be voltage deep or frequency certain stops may not be acceptable, so this class of motor which are class d motors. I have got large rotor resistance, and hence the starting current quite low, on the other hand the starting torque quite significant, because of higher starting power factor. And hence, these classes of motor are implied in loads like punching machines, and press and things like that.

So, in class d motors we will see now the class d motors, so what we know here we have high starting torque, and high slip, naturally these goes to high slip, the slip will be high here, and low starting current same as low locked amperes. So, if we see the characteristics of this class of motors, we will have the torque speed characteristics like this, this is omega m here, and we have the torque in this case. And here what we has in this case is that, we have high starting torque, but we have high slip as well the full load slip is quite large, this is the full load slip.

So, the full load slip varies between 5 percent to 13 percent, and the starting torque could be 275 to 300 percent of full load torque, so these classes of motor are applied with punch presses application. So, this is basically class d motor having large rotor resistance, and there applied it those applications, where we require high starting torque, these are the classification of the induction motors. Now, when we go to manufacture an induction motor we can manufacture either normal induction motor or a high efficient induction motor, the high efficient induction motor, we mean special consideration have been taken to maximize efficiency of the motor.

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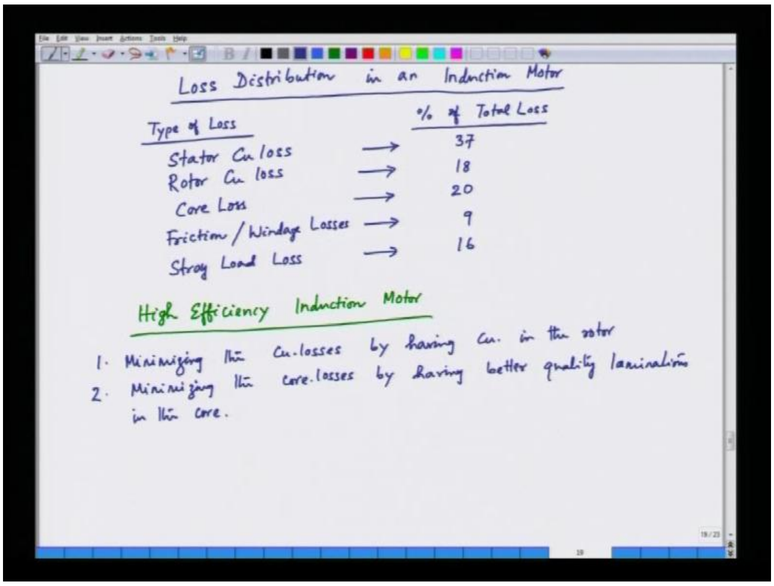

And how can we maximize efficiency of the motor, the motors have good various losses and the various losses or of this percentage, if you take a typical induction motor the losses will be of this percentage. So, if we see the losses in an induction motor loss distribution in an induction motor, so these are the various loss we have, what are the various losses. This is the type of loss, and here we have percentage of total loss what are the various losses here, we start with a stator copper loss, and this is about 37 percent of total loss.

And then we talk about the rotor copper loss, rotor copper loss is about 18 percent and the core loss is about 20 percent, and frictional or winding losses is about 9 percent, stray load losses is about 16 percent. So, these are the various losses of an induction motor, now how can we minimize the losses, the loss can be minimize for various aspects, we have the loss in the copper. The copper in the stator and the copper in the rotor, usually the rotor are made up of aluminum di cost, they pore mold in a aluminum on to the rotor to manufacture the rotor bars for rescues the induction motor.

Now, we can put more copper in the rotor, so if we have more copper in the rotor, the resistance will be less, and losses will also be less. So, we can maximize the efficiency or minimize the loss in the copper by having copper in the rotor, also we have more copper in the stator, that is one aspects. So, one thing is that the rotor bars are made up of copper, so we can discus about high efficiency induction motor, so we can achieve that by minimizing the copper loss the copper losses by having copper in the rotor.

So, if we have copper in the rotor the losses are also minimized, and hence we have higher efficiency, and then the next loss is basically the core loss, core loss is occurs in the core of the stator, the core of the rotor. So, we can minimize the core loss by having good quality stamping, we can, in fact minimizing the hysteresis and eddy current loss in the core by having good quality material. So, the material as to be improved to minimize the core loss, and the laminations up to be thinner in size to minimize the core losses, so minimization of the core loss by having better quality laminations.

So, minimizing the core loss by having better quality laminations in the core, and of course the friction on the winders losses or path of the machine that cannot reduced by significantly, the friction would be there, the winds losses will be there. So, if we have reduce losses sometimes the motor is equipped with extra cooling fans, so if the losses are minimized the cooling fans can be response with, if the cooling fan is removed or it is not available with the motor, the winds losses will also be reduced.

So, we can reduce the windless losses by having, in fact having reduce core loss and reduce copper loss, there by distancing the need of having a extra cooling fan. And then the straight load losses of course, is not measurable, it is not attributed to a single factor, and hence that loss its will still be there. So, we can reduce the various losses in this case, and hence we have a high efficiency motor, so this is basically the ways to minimize the losses of the motor, and to half better efficiency of induction motor.

So, in this lecture we have seen the high power induction motor drives, we have seen the director control of induction motor fed from a 3 level inverter, and the various classifications of induction motor based on NEMA. And we have also seen the last distribution of induction motors, and also ways to reduce the losses are also discuss, in the next lecture we will through some lighten the thermal aspects of the motor. The motor as got an electrical aspects also has a thermal aspects, now when we pass currents in the windings there will be losses, and this losses will raise a temperature of a machine. So, we will see how we can find out the temperature raise of the machine by having a thermal model of the overall motor drive system.