Advanced Electric Drives

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Lecture - 34

Hello and welcome to this lecture on Advance Electric Drives. In the last lecture, we are discussing about the multilevel inverters, and how they can be used for drives application. The multilevel inverters can give us more than two level voltages. Usually in a two level inverter, we gets two levels of voltage either 0 or V dc. In the multilevel inverter, we can get more than two level, it could be three level, it could be four level, five level and so on. So, we have already seen that multilevel inverters can we broadly classified into three different categories, and they are the diode clamped multilevel inverter, the flying capacitor multilevel inverter, and the cascaded H bridge multilevel inverter.

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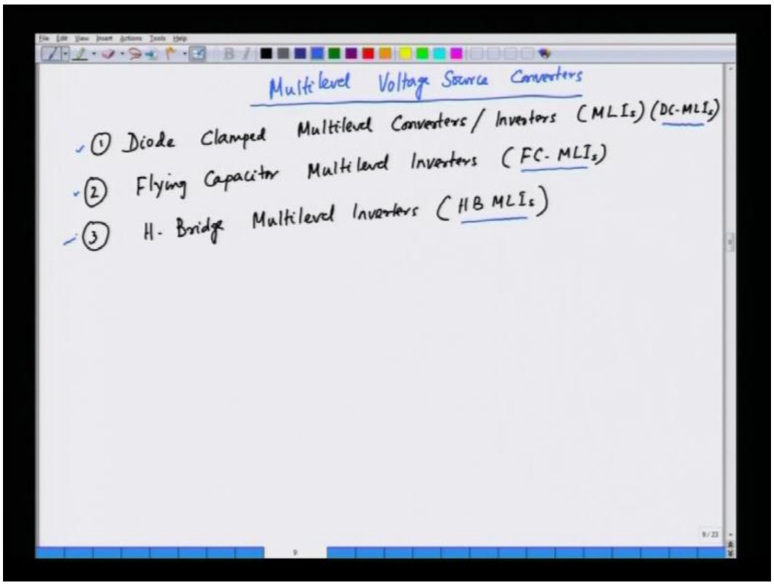

So, these are the three categories that we were discussing in the last lecture, the diode clamped multilevel inverter or DC-MLI or the flying capacitor multilevel inverter if FC-MLI, and H bridge multilevel inverter or HB-MLI. So, in the last lecture, we have already discussed number 1 and number 2, that is we have already discussed the diode clamped multilevel inverter structure, and also we have discussed about the flying capacitor multilevel inverter. Now, let us look at the H bridge multilevel inverter, that is the third category is H bridge multilevel inverter.

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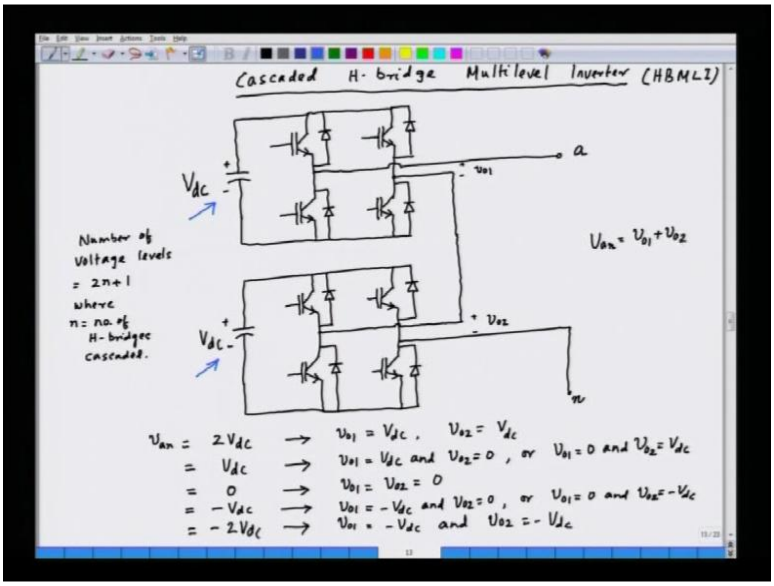

Now, let us look at this topology of H bridge multilevel inverter, so this is called cascaded H bridge multilevel inverter or we can just say this as HB, H bridge multilevel inverter, H bridge MLI. Now, in this case what we have, we have some any H bridge inverter connected in cascade so that, we can add or subtract the various voltages to get more than one level, more than two level and so on. So, let us take an example, when two H bridge inverter are connected in cascade, series.

So, we have two single phase H bridge inverter connected in series and what are the possible outputs that we have. So, we have the constructions like this, this is basically the DC capacitor that we have and then we have the IGBT inverter. It is a single phase inverter that we have here and they are all IGBTs, we have the anti parallel diode, the feedback diodes here and then we have the second and this is V dc, the dieseling voltage is here is V dc.

Similarly, we have second inverter also having the same dieseling voltage V dc and this is again one H bridge inverter, so this is H bridge inverter that we have. The second H bridge inverter is IGBT, which is and this is the output, let us say this is for phase a. So, we can call this to be phase a and this point is connected to the second bridge in the following fashion and this let us say, one phase we can have the neutral here. So, this is the neutral.

So, let us say, this is basically the two edge which inverter connected in cascade and each one having a dieseling voltage of V dc, plus V dc and this for a single phase. Usually, we have three phase drive, so we can half phase a, phase b and phase c, the similar construction will repeat for phase b and c. Now, if we have the structure like this, what are the possible output voltages that we can have. So, this V dc and V dc can add, so if we add this V dc and V dc, we get 2 V d c.

So, we have the first possibility that, we can have 2 V dc and let us say, we have v o1, this is plus minus and this is v o2, this is plus minus. So, for 2 V dc, we can obtain this 2 V dc, provided v o1 will give us plus V dc and v o2 will also give us plus V dc. And then if the two voltages are V dc and V dc, what we have v an, v an is V dc plus V dc that is, 2 V dc. So, we have v an here, now to voltage is equal to v o1 plus v o2, so this we are writing in this case v an.

So, v an is 2 V dc provided v o1 is V dc and v o2 is V dc, now let us say that, out of this v o1 and v o2, one of the voltages is 0. It is possible, because in a inverter, we can make the output voltage 0 by short circuiting the output. So, if v o1 or v o2 is equal to 0, we get just V dc. So, we can have here that is equal to V dc, provided v o1 is equal to V dc and v o2 is equal to 0 or v o1 is equal to 0 and v o2 is equal to V dc, this is also possible. So, if another voltages is 0 and other voltage is V dc, the output is going to be V dc and then we can have a situation, where booth v o1 v o2, both are 0.

If both are 0, the output v an is equal to 0, so we can have that possibility also, that is equal to 0 and this is true when v o1 is equal to v o2 is equal to 0. And then let us talk about the negative polarity, v o1 can be negative, so if v o1 is minus V dc, v o2 is 0 or v o1 is 0 and v o2 is minus V dc, output is minus V d c, so that is also one of the possibility we have. So, we can have that is equal to minus V dc, provided v o1 is minus V dc, in a inverter we can easily invert or easily reverse the output voltage, that is possible.

So, v o1 is minus V dc and v o2 is 0 or v o1 is 0 and v o2 is minus V dc, so this is one situation and then we have the fifth one is that, v an could be minus 2 V dc and that is possible when v o1 is minus V dc and v o2 is minus V d c. So, we can have that is equal to minus 2 V dc and this is true when v o1 is minus V dc and v o2 is also minus V d c.

So, how many levels we have, we have in fact, 2 V dc, V d c, 0, minus V dc and minus 2 V d c.

So, this consideration is able to us five different voltage levels, so with two cascaded inverters, H bridge inverters, we can get five level of voltage. So, it is basically a five level inverter, so the formula is this, if the number of basically cascaded is n, we can have 2 n plus 1 number of levels. So, number of levels here, number of voltage levels is equal to 2 n plus 1, where n is number of H bridges cascaded. Now, this is actually also employed in many drive system, but the main problem is this that, whenever we have such kind of inverters, we need to have independent DC voltages.

In fact, for this situation, we would have or we would require 2 V dc's, so if you have three levels or 3 inverters, H bridge inverters, you would require 3 V dc's. So, these are the voltage sources that we need, so we need independent source here, this will be isolated from this, there should not be any connection between one voltage source with the other voltage source, that is not possible, that should be avoided.

So, here we have two independent voltage sources then if you have one more bridge in cascade, we need three independent voltage sources and in general, we require n independent voltage sources. So, sometimes having independent sources is the problem, so although this is also employed in drive, it is not as popular as the diode clamp multilevel inverter, where we have three different levels. We can have multiple level also, but we can supply from a single voltage source.

So, this is an example of a multilevel inverter, where we can get multiple levels by cascading various H bridges. Now, out of this three, the diode clamp multilevel inverter, the flying capacitor multilevel inverter and H bridge multilevel inverter, we would select one of these inverters and go ahead with the drive implementation. The objective is to have high power drive, so we will choose out of this three, the diode clamp multilevel inverter for drive implementation. So, let us have a look at a three phase three level diode clump multilevel inverter.

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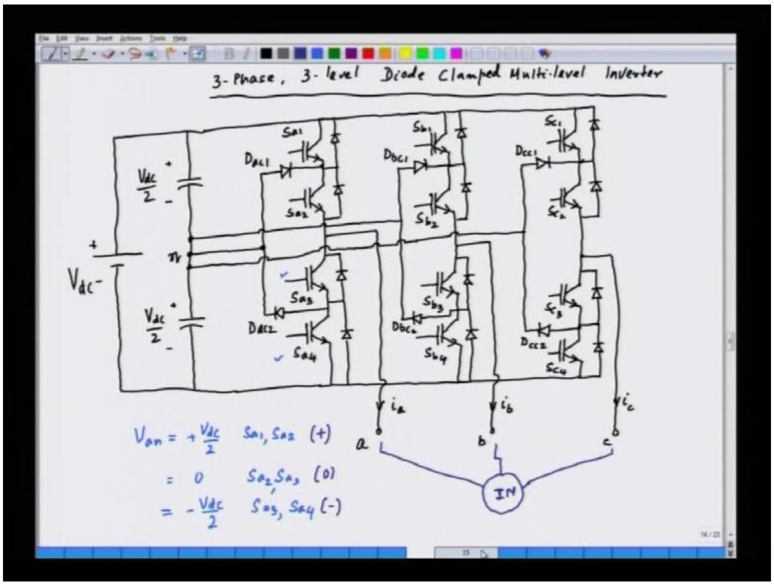

So, we are taking actually a three phase three level diode clamp multilevel inverter, let us first see the structure of this inverter. So, we have three different phases, so let us first draw this complete inverter. So, we have this DC link in this case and let two capacitors here, one capacitor and the other capacity. And then what we have here is that, we have four devices per phase, one this is one leg, second leg, this could be for phase b and then we have the third leg here.

So, each leg has got four IGBTs and each IGBTs will have the anti parallel diode, similarly here also, this is for phase a we are drawing. Similarly, for phase b we have the IGBTs here, this is for phase b and then we have for phase c and we can also name them accordingly, this is S a1, this is S a2, this is S a3, this is S a4. Similarly, we have S b1, S b2, S b3 and S b4, S c1, S c2, S c3 and S c4 and we have the outputs. And the outputs can be taken from this, these are outputs we have, this is for phase a, phase b and phase c.

We can have a load, which is connected to a, b and c, now this is actually the main inverter, but we also have the clamping diodes, that is why we call this to be diode clamp multilevel inverter. So, this is diode clamp multilevel inverter, so what are the clamping diodes, the clamping diodes are here. So, we have the clamping diodes, which are present here, this is one diode and this diode, we have the other diode here. And these two are connected to the midpoint of the battery, which are basically two capacities here.

And if this is V dc plus minus, so what we have here is plus minus and plus minus, so we have almost equal distribution of voltage. So, V dc by 2 and V dc by 2 here, now similarly for phase b, we have two diodes here, clamping diodes and this is for the upper switch. And we have the lower switch here and these two are connected together and then this is connected to the midpoint of the capacitor in the following fashion. For phase c also, we have two clamping diodes and this is for the upper bridge I mean, the same leg that upper to IGBT.

Then, we have the clamping diode for the lower switches and these two are connected together and then this midpoint of this is connected to the midpoint of the capacitors. So, these clamping diodes help to get the 0 level. So, we have to each phase can give us three independent level, each phase can give us plus V dc by 2 minus V dc by 2 and 0. In fact, this we have already discuss in the last lecture that, in a diode clamp multilevel inverter, we have three different levels for three level inverters, it is plus V dc by 2, minus V dc by 2 and 0.

Let us concentrate on phase a, in phase a we have switches S a1, S a2, S a3 and S a4, now when we turn on S a1 and S a2, when we switch on these two switches, the voltage v a, we can call this to be the neutral point n, this point we can call the neutral point here, v an will be plus V dc by 2. So, if we write down the voltages v an here, it could be plus V dc by 2. When we switch on S a1 and S a2 and then it could be 0, when we switch on S a2 and S a3.

So, when we switch on S a2 and S a3, the voltage output is 0, v an is 0, so if we switch on S a2 and S a3, what happens here, we are having a clamping diode, this is basically the point here, which is connected to this. So, if the current is positive here, the positive current will flow through this diode and this IGBT S a2 and will go here. Positive current means current is coming out of this, we can call this to be i a, the direction of positive current.

Similarly, for phase b, we can we can say, this is i b, the direction of the positive current and for phase c, we have i c, the direction of the positive current coming out of this inverter. So, if we turn on S a2 and S a3, this point a is clamp to the neutral point and neutral point is having 0 voltage. So, this diode and this IGBT will be connecting this a to the neutral point, which is positive. If the current is negative it means, the current is going into this inverter, so S a3 will be carrying this current, because S a3 has been applying a triggering pulse.

So, S a3 will be conducting, will carry current through this diode, this will be connecting to the point m. In fact, we can call this to be the clamping diode D ac1 and D ac2, the clamping diode 2. Similarly, we can call this to be D bc, phase b clamping diode 1 and this is D bc2, the clamping 2 diode for phase c. Similarly, this is the clamping diode for phase c, upper diode and D cc2 the lower diode. So, clamping diode helps connect that point to the neutral point or n of the power supply and hence we can have a 0 voltage.

Now, if we switch on let us say that, we switch on S a3 and S a4, now if we switch on S a3 and S a4, clearly an, this voltage a with respect to the neutral point would be minus V dc by 2. So, we can say here that, v an is equal to minus V dc by 2, if we switch on S a3 and S a4. The same thing is true, similar thing will be true for phase b and similarly, we can have the same similar thing for phase c. So in fact, for every phase, we can have three different levels and hence, when we connect a drive, the load in this case could be an induction motor.

So, in this case, we can have a load here and this load could be an induction motor, so we can supply this from the three phases of the inverter and with proper control, this motor can be made to respond to a given speed or given torque. So, we can have a closed loop torque control or we can have closed loop speed control. So, when we apply this to an induction motor, we can have lot of possibility, we had. in fact, here 12 switches, so four in each leg S a1, S a2, S a3, S a4.

So, per phase we have 4 IGBTs and for three phases, we have 12 IGBTs, so what we do here is that, when all the phases will be switched, we get some space vector and how many space vector we have, space voltage vectors. As we have the voltage vectors in a two level inverter, similarly we can have the voltage vectors in a three level inverter. So, each phase has the three possibility, so we can show this by, this is called plus, positive voltage, this is called 0 voltage and this is minus is a negative voltage. So in fact, for phase a, we have plus, 0, minus, similarly for phase b also, we can have plus, 0, minus. These are the various status, phase c also we have plus, 0 and minus. So, if we analyze this, we get some space vectors and the space vectors can be represented in the space as follows.

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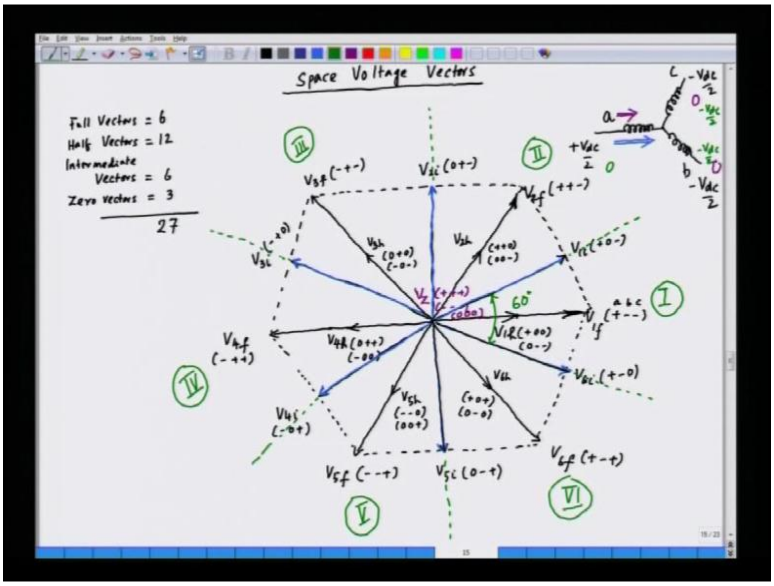

So, we are drawing here space voltage vectors, so we start with let us say v 1, now what is this v 1, v 1 is the meaning of this v 1, so we can call this to be v 1f, the full voltage vector, here we have plus minus and minus. So, this plus, minus and minus correspond to, this plus correspond to phase a, minus correspond to phase b and this correspond to phase c, so we show it in a same phase sequence plus minus minus. So, when we apply plus minus minus, the voltage vector is in this direction.

So, it means, the machine has the three different phases in this case, phase a and again we have phase b in this case, so this is phase a and this could be phase b, this could be phase c. So, when we apply plus minus minus, so basically phase a is applied with plus V dc by 2 and phase b is applied with minus V dc by 2 and phase c is applied with minus V dc by 2, plus minus minus. So, this will be creating a vector, which is equivalent to a vector in this direction.

And then we go one step forward, we can draw another vector that is v 2, v 2 is 60 degree ahead, so we can call this to be v 2f. Similarly, we can have another vector here that is, 60 degree from this, so this is v 3f and we have another vector, we have v 4f, this is v 5f and this is v 6f. Now, when we write f, f means full vector and then what is this, so v 3f is minus plus minus and v 5f is minus minus plus. So, v 2f would be plus plus minus, v 4f would be minus plus plus, v 6f would be plus minus plus.

Basically, the vectors which are diagonally opposite, are opposite to each other, say for example, v 1f and v 4f are opposite vectors. So, v 1f is plus minus minus, v 4f is minus plus plus, so we can construct this voltages, these vectors and these vectors would represent the I mean, if you join the tip of these voltage vectors, what we obtain is a regular hexagon, as we have obtained in case of a two level inverter. So, if we join the tips of these voltage vectors, we get a regular hexagon, as we have obtained in case of a two level inverter.

Now, we have some more vectors also, now we can also apply half voltage vector, half means the voltage is half here. So, we have the full voltage vector v 1f, what about v 1h, so we have one another voltage vector called v 1h, just exactly have, but direction is the same. The direction being the same, we can get here v 1h and what are the various status in this case, the status could be in this case plus 0 0 or it could be 0 minus minus. So, we have two possibilities 0 minus minus and plus 0 0, imagine the situation where we have replace this by 0 1 0 here, 0 voltage here and 0 voltage here.

Earlier we had minus V dc by 2, when we say apply minus V dc by 2 to phase b and phase c, we apply zero voltage vector or zero status there. So, when we apply 0 voltage to phase b and c, the amplitude of vector is half, the direction is the same, we have plus 0 and 0, the direction is stir in this direction, but the amplitude is half. But, instead of applying minus V dc by 2, we have applied a 0 here, the voltage is reduced. So, the voltage is reduced, the amplitude is reduced however, the direction would be the same.

There is one more possibility, we can have the same voltage vector by having 0 in phase a, so we can have another possibility that, we apply 0 in phase a, but apply minus V dc here and minus V dc by 2 here. So, in this case also, the effective vector is minus V dc by 2, so it is again minus V dc by 2, so again it is half. So, we have two possibility it means, the half voltage vector can be obtained by two possible combinations. For example, v 1h can be obtained by plus 0 0 or 0 minus minus, that is possible.

And similarly, we can have half for v 2 also, so this is v 2h and this is possible by applying plus plus 0 or 0 0 minus. So, we have two possibility and similarly, we can have half for v 3, so we can call this to be v 3h and that is possible by applying 0 plus 0 or we can have minus 0 minus, that is also possible. And we can have v 4h, v 4h is somewhere here, half of v 4f, so it is v 4h, the half voltage vector and that can be obtained by applying 0 plus plus or we can have minus 0 0.

Similarly, we can have a half voltage vector here, v 5h and that is possible by applying minus minus 0 or 0 0 plus. And we can have the sixth half voltage vector, here half of that, so this is v 6h and that is possible by applying plus 0 plus or 0 minus 0, so these are the half voltage vectors. So, do have any other voltage vectors, because we have to find all possible combinations, which are relevant here. Now, we have intermediate voltage vectors it means, in between v 1f and v 2f, we have one v 1i and that is called an intermediate voltage vector.

So, that is shown in the following fashion, so we have the voltage vector, which is in between this and this is called v 1i, the intermediate voltage vector and this is possible by having plus 0 minus, so it is in between v 1f and v 2f. Similarly, we can have a intermediate voltage vector here and that is v 2i, so we have v 2i here and similarly we can have one vector here that is, v 3i. We have one intermediate voltage vector here that is, v 4i and this is v 5i and we have again another voltage vector here that is, v 6i.

So, we have the intermediate voltage vectors as well, so we have six intermediate voltage vectors and they are basically in between two full voltage vectors. Say for example, in between two and three, v 2f and v 3f, we have v 2i. So, when we switch from v 2f to v 3f, we have plus plus minus to minus plus minus, so the intermediate state is 0 plus minus, so we have to go through this state to which is v 3f. Similarly, when we switch from v 3f to v 4f, we change from minus plus minus to minus plus plus and hence the intermediate vector here is minus plus and 0.

So, what we have here is minus plus and 0, similarly from v 4f to v 5f, we go from minus plus plus to minus minus plus and the intermediate voltage vector v 4i is minus 0 plus. Similarly, v 5i is in between v 5f and v 6f, so and that is basically 0 minus plus and v 6i is between v 6f and v 1f and that is plus minus zero, so these are the six intermediate voltage vectors. Apart from this, we have also three zero voltage vectors, the zero voltage vectors does not have any magnitude and also has not got direction and these are applied when we have the short circuiting of the three phases.

If we sort a b and c, we essentially obtain a zero voltage vector and that means, these all three phases should be connected to either plus or minus or 0 and the zero voltage vectors are located at the center of the hexagon. So, we have in fact, v z and v z is located at the center, this is v z and this v z is obtained either by plus plus plus or minus minus minus or 0 0 0, so we have three different possibility. So, if we apply plus pus plus plus or minus minus minus or 0 0 0, that will result in zero voltage factor.

So, how many possible voltage vectors we have here, so we have in fact, if we list here full voltage vectors, so we have full voltage vectors or full vectors, how many full vectors we have, we have six full vectors. And then we half vectors, the amplitude is half, so we have 1h, for 1h we have two different combinations, one isto 6h and for each one, we have two different combination, so we have in fact, 12 half vector. So, we have 12 half vectors then intermediate vector, we have 6 intermediate vector and we have in fact, the zero vectors, we have 3 zero vectors.

So, if we had this four possible vectors, the full voltage vectors, the half voltage vectors, the intermediate voltage vectors and zero voltage vectors, we get in total 27 voltage vectors. So in fact, in a three level three phase diode clamped multilevel inverter, we have 27 voltage vectors, out of which 3 are zero voltage vectors. So, the total number of voltage vectors here is 27, so when we feed induction motor from this multilevel inverter, we have in fact, lot of possibility it means, we have lot of flexibility in control.

And hence, we have better control of torque, may be the torque ripple is reduced here, in two level inverter, we just had 8 voltage vectors, 6 are non zero voltage vectors and 2 are zero voltage vectors. As oppose to two level voltage source inverter, in a three level diode clamped multilevel inverter, we have 27 voltage vectors and hence, we have more flexibility. So, we will be discussing about the director controlled inductions motor drive fed from a three level diode clamped multilevel inverter.

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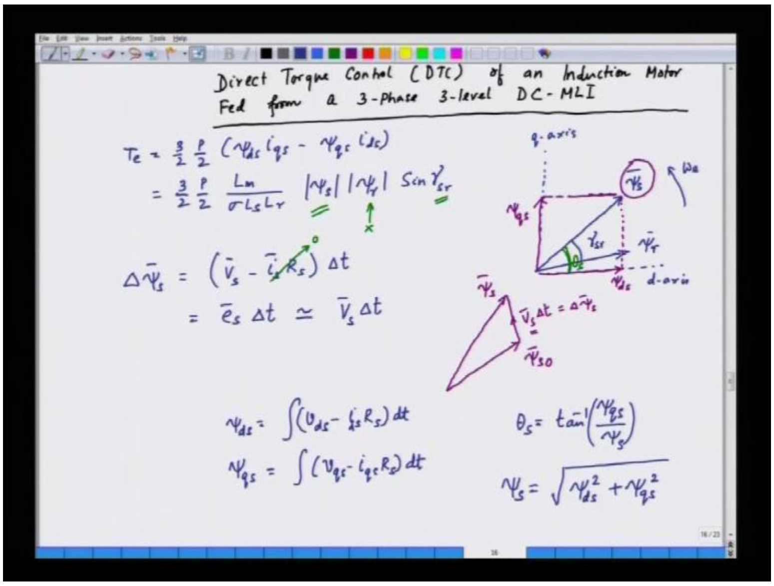

Direct torque control, this is also called DTC of an induction motor, fed from a three phase three level diode clamped multilevel inverter DC-MLI. So, what we have is the following, we have the inverter structure and in the inverter is feeding an induction motor and we have 27 voltage vectors. Now, if we go back to our previous diagram, in this case, we can divide this space into 6 sectors. So, what we have here is the following that, we have 6 sectors here, we divide the complete region into 6 sectors and each sector is 60 degree.

So, this is one sector 60 degree, so this is sector 1, this one is sector 2 and each one is 60 degree, the speed is 60 degree, we have sector 3 here, sector 4, sector 5 and sector 6. So, we have six different sectors and depending upon the sector, in which we have the flowers vector, we can choose a corresponding voltage vector. We have already seen, the control aspects of a two level inverter fed director control of induction motor, there is some similarity between the director control with two level inverter and that with three level inverter.

But, in the three level inverter, we have more flexibility, because we have more number of voltage vectors. So, let us recapitulate some of the equations that we derived for a two level inverter fed director control induction motor drive. So, we will just recapitulate of few equations, so first of all we understand that, the torque is basically the product of flux and current, psi ds i qs minus psi qs i ds and this can be simplified in the following fashion, that is equal to 3 by 2 into P by 2 L m by sigma L s L r psi s amplitude and psi r amplitude and sin of the angle between them.

So, this basically the very fundamental torque equation, which will help us understand the director control of induction motor. Now, here the torque is proportional to the amplitude of the stator flux, amplitude of the rotor flax that is, psi r and the sin of the angle between them. So in fact, what we have here is the following, we have psi s, the stator flux linkage, it is a vector and then we have psi r, is the rotor flax linkage, it is also a vector and the angle between them is gamma sr.

So, we have the d axis and the q axis, the stationary d axis and the q axis and these are the rotating flux, the flaxes are rotating at speed of synchronous speed omega e. So, both psi s and psi r are rotating at omega e, the synchronous speed and the angle between this is constant in the steady state condition and the angle between psi s and psi r is gamma sr. Now, when we want to control the torque, we have two possibilities, either we can control psi s or we can control the angle between them.

So, we can control the torque by controlling the flux or controlling the angle between the two fluxes, psi s can be control directly, we do not have any hold over psi r, the rotor flux. The rotor flux reduced from the stator side, so this we cannot control, we can only control psi s. So, how we control psi s, so we can control psi s by this following equation, so delta psi s vector is equal to, basically what we have, we can take the voltage minus the resistance drop i s R s into delta t and that is equal to e s, the induced EMF into delta t.

So, basically the flux can be changed by changing the induced EMF, if you apply the voltage then we saw an induced EMF and the induce EMF will change the flux. And if we ignore the resistance drop, the induce EMF is approximately same as the applied voltage. So, if we ignore the resistance drop in this case, so we can assume that, this is 0. So, if we do that, what we obtain here is that, that is approximately equal to V s in to delta t.

So, it is basically a vector equation it means, the incremental change in the flux linkage, delta psi s is the change in the flux. Suppose, I have the original flux in this direction that is, psi s and I want to change psi s by some amount, so I will apply voltage vector, which is V s, this is the V s and the V s is applied for a time that is, delta t and that is equal to delta psi s, it is also a vector. So, when we have two vectors, we can find out the resistance of the two by completing the triangle.

So, here we can find out the change of the flux is delta psi s, the resistance in this case, this psi s is psi s naught the initial value, the final value is psi s and hence, we can achieve the change both in amplitude and angle by applying a voltage vector. So, this is the principle and we have to apply this V s and V s is one of the 27 voltage vectors that we have. So, we have got six different sectors, as we have already seen and the sector information is obtained by tracking this psi s.

We are basically controlling the stator flux, the stator flux is controlled, the stator flux vector can be in any one of the six sectors. So, normally we can find out the sector by finding out the angle of the stator flux vector with respect to the d axis. So, we have this flux in this case, so we can define this angle in this case to be theta s and theta s can be obtain in the following fashion. So, we can resolve this into two components, the d axis and the q axis component.

So, we have one component in the d axis, we can call that to be psi ds and the other component in the q axis, we can call that to be psi qs. And how do we find out psi ds and psi qs, psi ds and psi qs are found by the corresponding voltages. So in fact, we can say here that, psi ds is equal to integral of v ds minus i s R s dt, i ds R s dt. So, we know the voltage in the d axis, we know the current psi ds, so we can find out psi ds. Similarly, psi qs is obtained by integrating v qs minus i qs R s dt, so the applied voltages are known, v ds and v qs are known.

So, we can find out psi ds and psi qs and theta s is equal to tan inverse of psi qs by psi ds and once you know theta s, we can find out the sector information about the flux. And the total flax in this case can also be calculated, psi s amplitude is equal to under root of psi ds square plus psi qs square. So, this computation have to be done in real time to obtain the amplitude of the flux that is psi s and also the angle that is, theta s, from which we can obtain the sector information. So, this is the control principle of induction motor with director control, now when it is far from the multiple inverter, we have lot of possibilities. In fact, we have 27 voltage vectors and how we can appropriately apply this voltage vectors to control the torque and flux effectively, and this will be discussing in the next lecture.