Power Electronics
Professor G. Bhuvaneswari
Department of Electrical Engineering
Indian Institute of Technology Delhi
Lecture 11 - Dual Converter and Commutation Overlap

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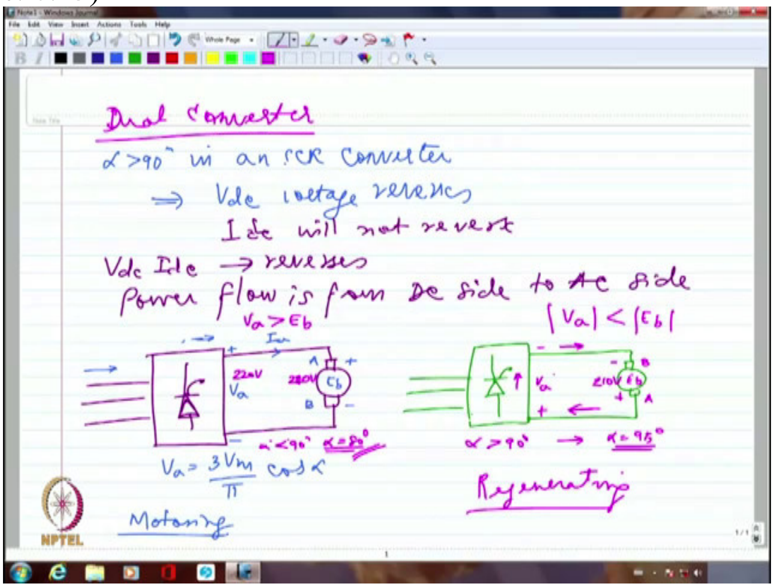

So last class we had started on Dual Converter. We in fact migrated from the discussion of the DC to AC conversion using the same thyristor converter. When we make $\alpha > 90°$, in an SCR converter, we are normally going to see that the DC voltage reverses. We are not going to see a reversal in the polarity of the current, so I_{dc} will not reverse. I_{dc} will not reverse but V_{dc} will reverse. So $V_{dc}I_{dc}$ reverses which means power flow is from DC side to AC side. But if the power has to flow from the DC side that means the load has to be active.

That is what we said when we were talking about a single converter when it is feeding a DC motor drive. And if the DC motor drive speed has to be reduced, let us say we want to break, we want to reduce the speed of the DC motor drive. In that case, we said that the kinetic energy stored in the machine, machine's rotating parts that can actually drive the machine as a generator.

Rather than the machine working as the motor it starts working as a generator because of which the power could be fed back to the AC mains provided we make the converter conducive for the operation as feeding back the power from the DC side to AC side. For that, we said α has to be greater than 90. So, we actually took an example also saying that if this is my overall converter which I am showing in the form of a block diagram, if I show it like this and this is my three phase input and here is the DC motor drive which is connected. So originally when I might have connected this as a motor, I would have had A here and B here. So plus, and minus somewhat like this with the back EMF being E_b here.

Now the current must have flown from this portion which is V_a the armature voltage. The armature voltage what is available depends upon what is the value of firing angle at which I am firing this converter and what is the kind of AC voltage that I am having.

So I am going to have the voltage here $V_a = \frac{3V_m}{\pi}\cos\alpha$ as per what we derived earlier if it is a fully controlled converter. So maybe this $V_a = 220V$ and the back EMF is 210 V. And then I am going to have the current flowing in this particular direction which is actually my I_a . So the power is flowing from the AC side through the converter to the DC side which we call as the normal motoring operation.

If I want regeneration, so this is motoring operation and if we want really the generating operation, maybe we will need it when we want to reduce the speed of the motor drive. We do not want to waste the energy. So we want to reduce the kinetic energy by converting that amount of kinetic energy into electrical energy if it is possible so that we save on some amount of electricity indirectly.

So in that case, we may have to have again this is my converter, I am not changing the connection of the converter electrically. It is the same converter and I am having the three-phase supply here. And here is my motor drive and this is how it is connected still. But only thing is that I want to make this $\alpha > 90°$ whereas here the $\alpha < 90°$. When $\alpha < 90°$, I was having plus here and minus here.

When $\alpha > 90°$ the same cosα is going to become negative because of which this will become plus and this will become minus. So, if I make $\alpha > 90°$ I will have plus here and minus here for the same V_a . But the direction of current cannot change, the direction of current has to be still the same which means the current has to flow in the same direction.

But I will be able to change the direction of the Back EMF by either reversing the armature terminal. So, I can make A here and B here. If I disconnect and reconnect, it will take some time. It will definitely have a large current being interrupted and again reconnected, these are hazards, no doubt. But we have to weigh basically what is the advantage we get in terms of feeding back the power vis-à-vis what is the kind of hazard that I am going to face.

So, if I am able to handle it, I would be able to feed a significant amount of power. So, I would like to rather experiment with this and then make A and B in the reverse direction. So, I am going to have plus here and minus here. Please remember I have not changed the field current direction, I have not changed speed direction.

Speed might have been at 1500 rpm, I want to bring it down to 500 rpm or 0 rpm depending upon at what point I want to stop and then go back to steady state operation. But I am not changing the direction of rotation. Because I am not changing the direction of rotation, back EMF now will have plus and minus in the opposite sense because of simply reversing the armature connection. Now if it so happens that originally this was to 220 volts and this was 210 volts and maybe α was 80 degrees, this is what we had taken earlier arbitrarily. If now I want to have the same 210 volts here, it is still 210 volts because I assume that the energy of the motor drive is not small. The speed will not change significantly quickly.

So this is 210 volts, so if I want the current to flow from the machine's plus terminal to the plus terminal of the line commutated converter. I am not calling it as a rectifier anymore. I am calling this as a line commutated converter. So, line commutated converter is a general term used for either a rectifier or an inverter which will allow power flow from the DC side to AC side or AC side to DC side. But normally it will be made up of SCRs, thyristors because they will require some kind of reference for firing.

So, if I say α is less than 90, I would call that as a rectifier or a line commutated converter working as a rectifier. Or if $\alpha > 90°$ it will be a line commutated inverter. So, in line commutated inverter you will need a sinusoid. The reference sinusoid has to be there. If the reference sinusoid is not there, you do not know at what α you are operating. So, you should know that you are operating at an α which is greater than 90.

So, in this particular case, I might have to operate it if I want equivalently the same amount of 220 volts if it comes but with plus minus in opposite direction. The current will not be able to flow from here to here because this is 210 and if this is 220, the current cannot flow like this. So, it has to be much less than 220V.

So instead of 220 here I might have to have 200 or 190 or something like that for which instead of having an α of 80, I should have probably had closer to 90. Only then I would have had lower and lower voltage. So, I might have to have just α equal to maybe 92 degrees, 95 degrees or something like that.

It is still greater than 90 but it is not really equivalent to having like 80 degrees if I want to have exactly, on the other hand I should have had 100 degrees. Cosα in one case is cos(80), in the other case it will be cos(100). But cos(100) will be a negative value but I do not want that value. I want it to be less than that, so that is why I would have it closer to 90 degrees.

As close as possible to 90 degrees in which case I would be having less amount of voltage here. So, the current would start flowing like this. So, this is typically a line commutated converter operation, this is how it is going to work like an inverter. So, this machine is having 210 volts at this speed. Now because it is 95 degrees, the current will start flowing like this. Now because this is generating power and releasing the power in the form of electricity to the three-phase grid, the speed will come down further.

The speed will come down from maybe 1500 rpm to 1200 rpm by then E_b would have decreased again from 210 volts to maybe 208, 205 volts whatever. Then correspondingly I might have to again go more and more towards 90 degrees. So, I have to repeatedly adjust the firing angle as per E_b, and E_b gets adjusted as per the speed. So theoretically we will be able to achieve regeneration almost down to 0 speed if we are able to adjust all of them in a very fine manner.

So, you should know that this particular operation of the line commutated inverter that is an SCR, rectifier working as a line commutated inverter allows you to feedback the energy and then allow you to undergo regenerative breaking using your DC motor drive which can save a lot of energy.

That will do the job from which we actually migrated to dual converter. So, coming back to dual converter, so this is motoring, and this is regenerating. And here V_a has to be greater than E_b, very clearly here V_a magnitude has to be less than E_b magnitude ($|V_a| < |E_b|$). I am carefully writing magnitude because I do not want you to confuse yourselves with the minus sign and say which is greater, which is less and things like that. So I am saying that V_a magnitude has to be smaller only then the current will flow from the E_b side to V_a side.

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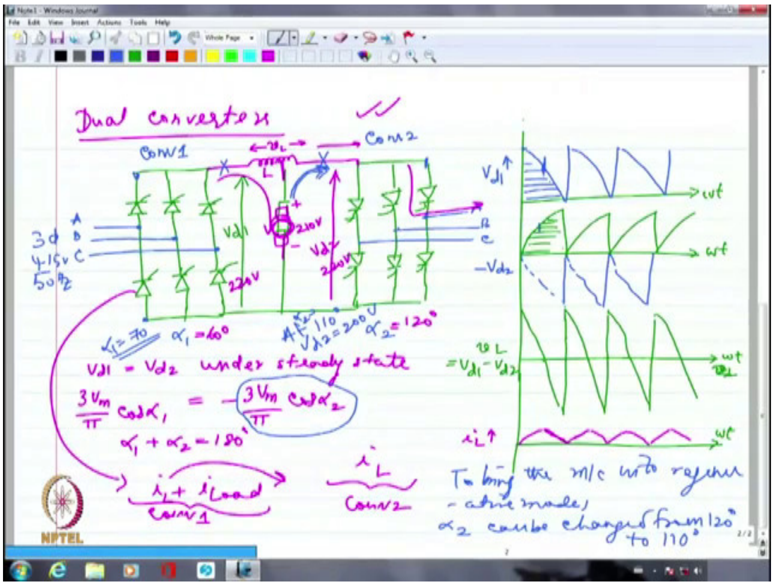

Now let us go to dual converters. So, in dual converter what we said was that we are going to have one set of converters similar to what we discussed so far with respect to rectifier. Of course, it has to be fully controlled, it has to be fully controlled because we want the voltage to go in both the directions.

It should be possible for me to do that and on the other side I am going to have again a similar converter connected in antiparallel direction. So, these two are in antiparallel and I am going to have this as the DC link. Maybe my load whether it is a DC motor drive or RL load it does not matter. This is how it is connected.

And I am going to have the three-phase supply connected here. So, if I say this is the A, B, C of three-phase 415 volts, 50 hertz, the same thing is going to be connected here as well, so this is also the same A, B, C. Although I am showing two different terminals but they are connected together to the same three phase supply.

Now 1 is fired at α_1, let me call this as converter 1 and the other one is converter 2 and this is fired at α_2. Both are being operational, and we called this voltage as V_{d1} and let me call this voltage as V_{d2}. In fact, I would have liked to connect these two terminals directly, but instantaneous voltages could be slightly different. We spoke about in DC machines if you may recall, lap finding when you have several parallel path, the voltages could be slightly different.

So, we connect them together using an equalizer ring. And so, it will be like a thick copper rod which is connecting all of them together. So, it is something similar that we are going to have probably a thick reactor coil which is connecting these two together. Let me call this as L and the voltage across this as v_L.

So, we drew the waveform last time for α_1 which is coming out to be 60 but we also said that we want $V_{d1} = V_{d2}$ under steady state condition so that the circulating current does not become too much. Between the two converters I do not want huge amount of circulating current coming up. So, under steady state they should be true which means I should have $\frac{3V_m}{\pi}\cos\alpha_1 = -\frac{3V_m}{\pi}\cos\alpha_2$.

So, we wrote the equation $\alpha_1 + \alpha_2 = 180$. So, we said $\alpha_1 + \alpha_2 = 180$ degrees, this is what we got as the solution for this. So, if 1 is going to be having 60 degrees, the other one should be having 120 degrees, so similarly 180 degrees and so on. So, if I assume α_1 as 60 degree, I am going to draw waveform for that. This has to be drawn for $\alpha_2 = 120°$, that is how it can be drawn.

Now so let us try to first of all recall the waveform what we drew last time also. So, this is I am going to draw with respect to 60 degree firing angle. I hope so that you remember already this is the way the 60 degree firing angle waveform would look like, this how it would be. So, this is what is my V_{d1}. If I try to draw corresponding to V_{d2} as such, it is actually the inverse of $-V_{d2}$.

And we drew for $-V_{d2}$ last time for 120 degree firing angle, it came out somewhat like this. If you actually recall it was something like this. So, it is just the opposite of this but below 0. So, the entire thing looks as though the whole thing is negative, so this actually corresponds to what is $\frac{3V_m}{\pi}\cos\alpha_2$ without a minus sign. So, this is essentially $-V_{d2}$ waveform. So, if I try to draw the actual V_{d2} waveform, I have to just invert that. It is as though in CRO you put a 180 degree shift, that is it. So, it is going to look somewhat like this.

On an average basis both these voltages will have the same value. If I look at the area under this curve vis-à-vis, the area under this curve, they should essentially have the same area because it is again the 60 degree span and it is starting from probably 120 degree point in one case and coming down to 180 degree point. This is like 120 degree point of V_{AB} and then it is coming down to 0 because 180 degree degree point is that particular point.

The same is true even in the other case although it is starting from 0 and maybe going up to 60, that is all. Both are essentially similar but instant to instant if I look at the voltage, the voltages are different, here it is 0 whereas here it is maximum. And here this is 0 but here this is maximum. So, if I look at the voltage at this point and this point on an average basis although they are the same, instant to instant the voltages happen to be different. Only point where exactly the voltages are the same will be somewhere in the middle because in the middle here as well here it will be whatever is half the value or more than that, whatever is the value corresponding to that particular angle.

So, I am going to have the exact same value only at one particular point where both of them happen to be having the same value of sine of that particular angle. So, if I try to draw what is the voltage across the inductance v_L, so let me try to draw that voltage what is v_L. So, $v_L = V_{d1} - V_{d2}$. So, $V_{d1} - V_{d2}$ if I try to look at it, only at this point it will be zero. So, if I try to draw for every 60 degrees, only in the midpoint it is going to correspond to 0. And it is going to start from a high value which is corresponding to that $V_m \sin 120$.

So, it is going to start from a high value, come down and then come to the negative. Again, do the same thing, it will repeat itself, this is the kind of waveform I am going to have for the inductance voltage. The voltage across the inductance is going to have some positive portion for half. For rest of the half it is going to have negative because I have to subtract from this value. I have to subtract whatever is the value that is available from the other V_{d2} .

So, I have to realize that I am going to have this portion whatever is the area under this curve will be equal to the area under this portion. So, the net voltage across the inductance happens to be 0. If I try to calculate it even for 60 degrees, the voltage across the inductance is positive here, voltage across the inductance is negative here. So, fluxing happens in one case, defluxing happens in the other case.

So, this is going to repeat itself until time immemorial as long as it operates. So, if I try to plot what is the inductance current, just the inductance current alone, forget about the load current, inductance current is, it can be calculated using $L\frac{di}{dt} = v_L$. So, *di*, I should be able to say whether it is positive or negative. So, if I say during positive voltage, I am going to have increase in the current, during negative voltage I am going to have reduction in the current.

So again, increase in the current, reduction in the current. This is how the current waveform is going to be if I am looking at the voltage continuously increasing only for 30 degrees, decreasing for 30 degrees, again increasing for 30 degrees, decreasing for 30 degrees. So, I am going to have the current also increasing for 30 degrees, decreasing, increasing, decreasing and so on. This is i_L alone.

Of course, there will be a load current, maybe there is a huge amount of load current being drawn. The load current drawn is being supplied by the rectifier, it will also pass through at least part of the inductance, no doubt about that. But load current if it becomes almost like a steady current it is not going to contribute to inductance stored energy. Because $L\frac{di}{dt}$ only will be contributing towards the inductance stored energy. So, the steady load current will not contribute towards really storing energy in the inductance.

So, if I look at the rectifier side current, that is converter 1 current, this will consist of $i_L + i_{Load}$. Both will be supplied by the rectifier whereas the other side this is not going to carry the load current. This only helping in making sure that, that inductance circulating current is going back again to the three-phase mains. That will go through this to the three-phase mains. So only the inductance component of current will be carried.

So, this is converter 1 current is both these put together whereas converter 2 current will have only i_L, nothing else. You have to understand that if this converter had not been there, the second conductor had not been there at all, still the load current would have been carried by the converter 1. So, the converter 2, 1 is just doing its job. It does not care about anything else whereas converter 2 is actually right now redundant.

It may not be there, I have put it there only in case I want to reverse the direction. So, because I have put a second converter for facilitating the reversal, I will have to add the inductance and so on and so forth, add a firing angle which is actually $180-\alpha_1$. Because of which what happens actually is there is a circulating current, that circulating current is actually going to pass through the inductance through this, through this back to the three-phase mains. That circulating current is the inductance current alone, that is not anything to do with the load current.

So, converter 1 supplies best part of the load power and a small amount of circulating current. Converter 2 essentially receives the circulating current. It does not receive the load current because the load current will go only within the load and converter 1. So, converter 2 will take that circulating current, feed it back to the mains. But you are not going to have much of losses because it is inductance, therefore, no power loss.

There may be small resistance which will definitely have some amount of power loss. But much of inductance it will not have any significant power loss. So, it will not tell on the efficiency so much for the converter and so on.

Student: How can we have $\alpha_2 > 90°$ if the converter two is not supplying power?

Professor: If the converter two supplying power, how can you have the $\alpha > 90°$? You just cannot. If all $\alpha > 90°$ it can only do one job. It can take the power from the DC side and feed it. It cannot really supply the power. Rectifier can supply the power from the AC side to DC side.

Inverter can supply the power only from the DC side to the AC side, not otherwise. And currently I am drawing a lot of power from the AC side towards the load. So, load is eating away everything, whatever it is doing it is doing some work. So, what is actually going as the circulating current is the small portion of the power or you can say reactive power in this case probably which is going back to kind of AC mains, nothing else.

So, this is clearly working as a rectifier and this is clearly working as a line commutated inverter. So, whenever I am talking about dual converter, we will have dual roles for both of them. So, you are going to have basically the converters, among the two converters is if one is working as the rectifier mainly that is working as a source of power. The other one which is working as an inverter is only sitting there to take over the operation if I need some regeneration or something like that.

So just to mention for continuity sake, if this α is 60 and this is α=120 and instead of this load if I now connected DC motor drive. Imagine the same situation as what we said earlier. At α= 60, so this will also be 220 Volts obviously. Because only with the opposite sign and maybe this is 210 Volts, Back EMF. I want to bring down the speed.

If I want to bring down the speed of this particular DC motor drive by doing breaking, previously what I should have done is to reverse the direction of the armature, make α originally what was 60, maybe I have to make it on the other side. It is a big task because suddenly I have to jump from $\alpha < 90°$ to some $\alpha > 90°$. It is not going to be easy whereas in this case already there is one converter working with $\alpha > 90°$.

And that converter is ready to carry the current and everything in whatever direction I want. If I want now the current to flow from here to here rather than flowing from the rectifier which was flowing originally from the rectifier, it was flowing into the motor drive. Now I wanted the other way around because I want the machine to work as a generator and feedback the power.

If I want the current to really flow in this particular direction, that means first of all I have to make sure that this voltage V_{d2} becomes less than whatever is my Back EMF. My back EMF is 210 Volts. Back EMF is 210 Volts that means my terminal voltage has to become less than 210 Volts which indicates that instead of α= 60 on the rectifier side, I might have to adopt 70 or 80 degrees. Correspondingly I have to change the other side firing angle. Instead of 120 degrees, I have to bring it down to 110 or 100 degrees.

If I do that, automatically I am going to reduce the V_{d2} value. Whether I like it or not, it will automatically come down. So, to bring the motor or bring the machine into regenerative mode, α_2 can be changed from 120 degrees to say 110 degrees. I am just saying 110 because I am assuming that 110 maybe I would have already gotten 200 volts or 205 volts. So now if I have only at 110 degrees, if I am going to have V_{d2}= 200 volts then what will happen? Automatically this current will start flowing from the machine into converter 2.

Now converter 2 will take the lion share of the current. It is still working as an inverter, no doubt but it is taking all the power that is being generated by the machine transferring it over to the AC side, passing it onto the AC side. Now the rectifier is not supplying much power, it cannot also because its voltage has now become 200 volts. How can it supply current now? It is not possible.

The other one is now taking over the operation completely by adjusting the firing angle. It has essentially taken over all the power that was actually saved in the form of kinetic energy in the machine. It is being converted into electricity by generator operation and that is being fed through this to the three-phase mains. That is what is going to happen.

Now as it feeds back, you are going to have less and less amount of speed. Because it is essentially releasing its kinetic energy, so obviously the speed will become down. Once the speed comes down, you have to again adjust the firing angle as per your requirement. Here you did not have to do any change of connection. All you needed was to shift the firing angle originally which was 120, you have shifted it to 110, eventually you might shift it to 105, 100, 95, 90, that is it. Once you have come down to 90, you do not have any more margin left, that is the end of inverter operation.

Student: (())(36:12)

Professor: Yes, it is, that is true. But the motor inductance again you have to compare the armature time constant, compare to the mechanical time constant. How much is the mechanical time constant? It will be in terms of at least seconds. Armature time constant, a few milliseconds.

So, compare the two time constant, you would realize that the reversal of armature current can take place much more quickly compared to the machine coming down to lower speed. Because machine will take a few seconds to show any significant change in the speed whereas the armature current can reverse quite quickly or change quite quickly within a matter of a few milliseconds because armature circuit time constants are generally not large, that is the reason.

The inductance you are externally putting can put a hindrance, I agree with that. So, it is a double head fault, you cannot eliminate it completely but you have to choose it very carefully. It cannot be too high, it cannot be too low, that is what it is.

Student: Ma'am, we are not changing α to let us say, (())(37:36)

Professor: No, no, only not all, when I am changing α_2 to 110, α_1 should have also changed to correspondingly 70. Both would change, I will not change only one alpha at a time. If I do that, my DC link had it.

Now we have two converters, I wanted to eliminate reversing the armature connection or reversing the field connection, that is why I have put the second converter. We are putting second converter only to take advantage of that particular situation.

So dual converter gives you the liberty to change over from one mode of the machine operation to the other mode of machine operation without really changing the connections, by just making small modifications in your control. So, control what you are making as modification is your firing angle control, nothing else. So that is the major advantage of using a dual converter.

So normally dual converters are employed only in those applications where you expect frequent reversals. And you also expect a significant amount of saving in energy because of regeneration. Because any industry will check us out if we are not able to justify the cost. If we are putting something costly you better justify why you are putting it there. What kind of savings you get by putting it? It is very important.

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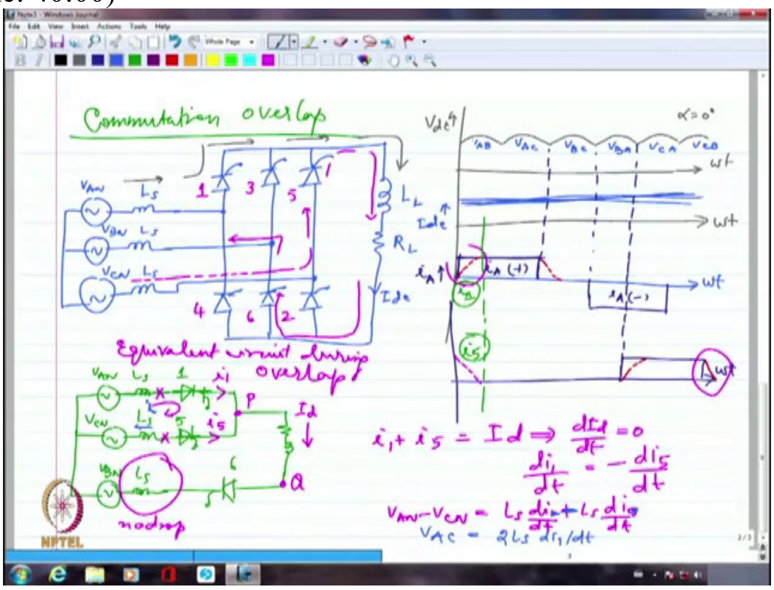

So, we are now moving to the last topic that is commutation overlap, the last topic on AC to DC conversion. All along we assumed that the sources are ideal. What we have considered as the AC source is ideal, there is no impedance, there is no resistance, transmission lines are all ideal. Excellent, if it is like that, the world is definitely not ideal. So, we are not going to have a source without some amount of inductance and resistance. We do not care much about resistance.

Resistance is actually a less evil structure than inductance in one sense. Because resistance will maximum dissipate power, it will not harm the current from getting transferred from one line to another. But inductance is not like that, it is very vicious. And the conduction happens for longer than what it is supposed to happen normally. So, if I have let us say three inductances along with the source, I am showing this inductance because it could be of transmission line, it could be a transformer leakage inductance because I may have a transformer in my industry. When I have factory and may have an incoming transformer, what I get from the grid may be 11 kV, what I require in my industry may be 415 volts, so I may have a step down transformer sitting in my incoming supply point.

So, this indicates essentially the leakage reactances of my transformer if I am talking about a factory. If I am talking about a big traction kind of thing, it may be transmission line inductances.

Now I have my converter, I am showing of course one converter, there can be n number of converters like this, connected but I am showing one converter connected here. And let us say it is connected to highly inductive load, maybe a DC motor drive, maybe something else whatever. So, this is how it is connected, and let me take whether it is thyristor or diode, it does not matter at all in this case. But I am just taking thyristor so that everything will look uniform.

So, I have let me again name this as V_{AN}, V_{BN}, V_{CN}. Let me call this as L_s source inductance. Let me call this as L_L load inductance and R_L which is the resistance of the load. And of course, let us go by the same normal numbering, so this is 1, 3, 5, 4, 6, 2. Let us say I am planning to fire this 1 at this point in time, maybe α is 30, it does not matter, whatever α, it is does not matter. But it is uniform α for everything.

Obviously, the current has to come from 5, originally 5 was conducting. And I am firing 1 now, so 5 and 6 were conducting together. Then I fire 1, 5 is supposed to give up instantaneously and 1 is supposed to take over instantaneously, that is what we were expecting. If 5 is conducting the current would have gone somewhat like this, it would have gone like this, it would have gone like this and it would have gone like this and it would return through 6 like this through B. This is how it would had returned. This is the path for the current.

When I fire 1, I will have the current actually going from here. And then it should go like this, it should go like this, all this is the same. Load current, as far as load current is concerned there is no problem at all, the load can carry the current directly. Because already it is carrying the current, the same current is going to be carried now by the load, only thing is it is going to be supplied by 1 instead of 5, that is all. It does not make a difference as far as the load is concerned whereas for these devices it makes a big difference.

Originally this L_S was carrying full current whatever is the load current. Let us say the load is highly inductive, maybe it is getting 10 ampere or 15 amperes of current. That 15 ampere is steadily flowing through this inductance, so this inductance is supposed to give up that 15 amperes of current in no time as soon as I fire device number 1 which is not going to happen because the inductance current cannot really go down to 0 from 15 amperes in no time, that is not possible. So, the moment I consider that there is some source inductance, I cannot say that the current transfer would take place instantaneously from one phase to another phase or from one device to another device.

So, what will happen during that time? That is known as the commutation overlap interval. What we mean by commutation overlap is there is an overlap of conduction between the outgoing device and the incoming device. The incoming device is 1, the outgoing device is 5, both are going to overlap with each other at least for a short while. How short a while, how long a while that depends upon several factors which we are going to analyze.

So, commutation overlap will come into picture only under a couple of situations. The major one is source inductance has to be there. If source inductance is not present, there is no question of commutation overlap. And the second one is the load current has to be continuous. The load current is not continuous, who cares? The source inductance would also have given up. If there is no current, why should that inductance bother? It will bother only if it has stored some energy. If the current has already gone down to 0, it has given up.

So only if the load current is continuous, I will have to worry about it. And the second thing is the source inductance has to be present and it has to be fairly significant. It has to be visible. Its effect has to be felt. If it is micro Henry or nano Henry who cares? So, it has to be significant. So, these are the two things which are very important if I have to observe commutation overlap. So, let us try to first of all look at the normal waveforms what we drew earlier if you may recall.

If I am talking about a simple α= 0 degree condition, we normally said that I am going to have a waveform something like this. This is how the waveform is going to be. So, this is how V_{dc} waveform will be for α= 0. And I am going to have probably highly inductive load, so this is V_{dc}.

So, if I am talking about a highly inductive load, I will have a current somewhat like this. It will be straight current. I should show like this. I have drawn very badly but that is how it will be a straightforward current. If it is a highly inductive load, if I am talking about I_{dc} or I_{Load}, if I call this as I_{dc}; I_{dc} will look like this, it will be a straightforward current, nothing more than that. And if I say that this corresponds to V_{AB}, this corresponds to V_{AC}, after this V_{BC} , then V_{BA} then V_{CA} and then V_{CB}. This is how it will be normally. The sequence you guys must have gotten used to now hopefully. 6, 1, 1, 2, 2, 3, 3, 4, 4, 5, 5, 6, that is what I am writing in terms of voltages.

So correspondingly if I try to draw the current, I should have whenever there is A phase conducting, I should have my current like this, positive current like this. And whenever I am going to have A phase negative conducting, I should have had the current going like this. So this is i_A, this is again i_A. So, this is positive side, this is negative side. So this is what I can draw as the current.

But this is all well and good if I am talking about abrupt rise in the current. Please note I have shown as though the current is having an abrupt rise but that abrupt rise is not going to be possible if I am having some source inductance. At the same time in fact, if I try to draw actually the current through device number 5, device number 5 is conducting here. Device number 5 corresponds to this, CA and CB because wherever C is positive, that is device number 5 current.

So, device number 5 current should be having somewhat like this, it should have started like this and then it should have gone like this. This is how it should have been. It should have again conducted abruptly, and it should have ended abruptly after 120 degrees. And after 120 degrees I fire 1, and 1 should start conducting, that is how it should be. But now because of the commutation overlap maybe I am going to have the current rising slowly. It will not really rise abruptly but it will rise slowly like what I have shown here.

And similarly, when it has to fall it is probably not going to fall abruptly, it is going to fall slowly. It is like an RL circuit. So, it will essentially be exponentially increasing or exponentially falling. So same will be the case for 5 as well, so this will be falling slowly, this is how it will be. Now I superpose this particular portion with this particular portion, because please understand 5's falling current will coincide with 1's increasing current. Both of them are happening simultaneously.

When 5's current is falling, 1's current is increasing. So, I should show it here as though, 5's current is falling like this, when 1's current is increasing here. Around the same time both of them are actually happening simultaneously. So, this is actually going to be the current of i_5 and i_1 respectively. So, I am talking about i_1 here, i_5 here. And the rate at which i_5 is falling hopefully should be the rate at which i_1 is rising. Both should be really in great synchronism, otherwise you will not really get the same amount of DC current all the time.

Let us try to now draw the equivalent circuit of this converter only during the interval when 5 and 1 are overlapping with each other. So, let me first of all take your help in drawing this, this is V_a, and this is L_s. 1 is conducting, so I am going to show as though 1 is closed, this is closed. Hopefully they started conducting, so I am showing it as though it is closed, so this is inductance, fine.

Now this is conducting, I will have to have V_{CN} please note I am writing V_{CN}, this is L_s, this is 5, this is 1. Both are conducting, so A phase as well as C phase both are active. And now this is connected together and here is my RL load. And the return is through 6, so there is only one device which is 6 and then I am going to have L_s and I am going to have V_{BN} and then this is finished.

This is really the circuit during the overlap interval, so this is a circuit during overlap. Now if I try to look at it, this is point P. Let me call this as point Q. So, between P and Q whatever is the voltage, that is what is my output voltage. The current that is flowing I am assuming it to be a constant current I_d. We did not want it to change, we said highly inductive load. So, we said it is I_d, we have neglected the ripple.

If this is I_d, I can say for sure that there is no variation in I_d, so $\frac{dI_d}{dt}=0$. If $\frac{dI_d}{dt}=0$ there is no drop in this inductance. So, inductance drop is 0, $L\frac{di}{dt}$ in this particular case definitely will be 0 because the return current is the constant current I_d. So, this does not have any drop. Now I can say this is i_1 and this is i_5 , so I can say clearly $i_1+i_5=I_d$.

Both of them make up for total I_d. And both are returning ultimately through the device number 6 that is why we said device number 6 is carrying a constant current. Now because I know $\frac{dI_d}{dt}=0$, I can say $\frac{di_1}{dt}=-\frac{di_5}{dt}$. This we already said, the rate of rise of current in one should be equal to the rate of fall in current in 5.

Now I have to say what is the voltage at this point and what is the voltage at this point. They are not going to V_A and V_C respectively, because the currents are increasing in one direction, the currents are falling in the other one. So $L\frac{di}{dt}$ is definitely not equal to 0 in those cases. I am going to have the voltage at this point as $V_{AN}-L\frac{di_1}{dt}$. And similarly, here it is going to be $V_{CN}+L\frac{di_5}{dt}$ because di_5 is a fall, so that is what I am going to get as the voltages.

So, let me try to first of all see whether I can write the KVL equation for this and write the whole thing, at simpler. So, I can say KVL equation for this will be $V_{AN}-V_{CN}=L_s\frac{di_1}{dt}+L_s\frac{di_5}{dt}$ or $V_{AN}-V_{CN}=L_s\frac{di_1}{dt}-L_s\frac{di_5}{dt}$ because the current is in the opposite direction. I am assuming ideal devices, so if we include the device characteristics also, we are in for major trouble, that is why we are not doing that. We are only taking care of the transformer here, that is it.

So, I should be able to write this as $V_{AC}=2L_s\frac{di_1}{dt}$. Because $\frac{di_5}{dt}$ and $\frac{di_1}{dt}$ they are of opposite, so have I written something wrong here? Is it plus or minus? Is it really minus? Look at that. I have written $V_{AN}-L_s\frac{di_1}{dt}$ on this side, agreed. This will be $V_{CN}+L_s\frac{di_5}{dt}$. So, I am writing for some general current i, so I should write this as i and this also as i. So, it should have been minus, this is general current i.

So $L_s \frac{di_1}{dt}$, and then the current is in the opposite direction, we are taking this current in this direction which is opposite to that of i_5 . So, it is minus, so because of which it will become, this is minus clearly, this has to be minus. Because if you are taking this common current as i, it is in the opposite direction of which is i_5. So, I will get $V_{AC} = 2L_s \frac{di_1}{dt}$. It is the very very important result which we will be using repeatedly.

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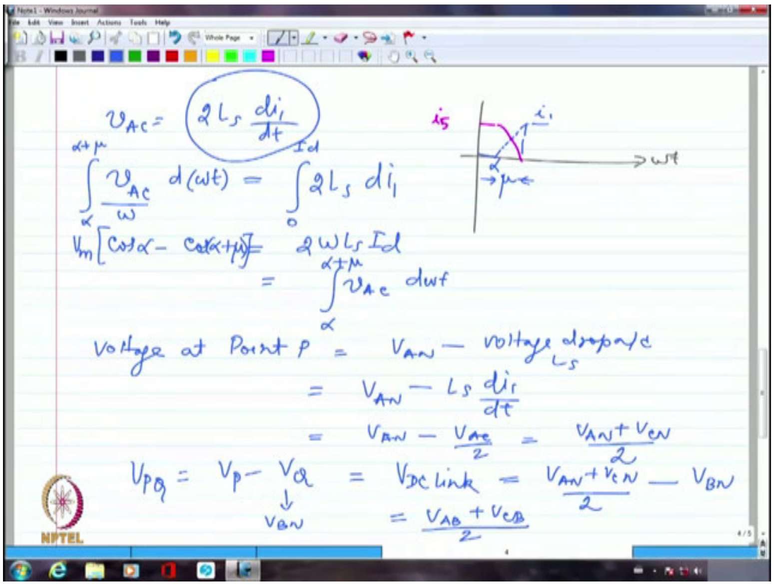

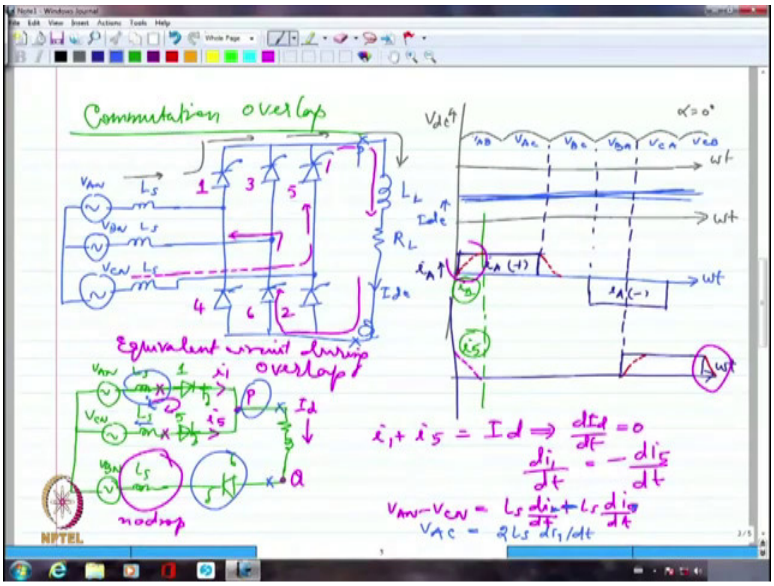

So, let me write first of all $V_{AC} = 2L_s \frac{di_1}{dt}$

Now I can write this as V_{AC}, instead of writing dt let me write $\frac{d\omega t}{\omega}$. Then $\frac{V_{AC}}{\omega} d\omega t = 2L_s di_1$.

I have not done anything else, just dt I have brought it on the other side. Instead of writing dt, I have written $\frac{d\omega t}{\omega}$, so I have written ω at the bottom, that is all nothing more than that. So, let me just redraw again, this is ωt, I am going to have actually the current originally was like this and then it is coming down as far as device number 5 is concerned, this is i_5.

As far as device number 1 is concerned it is 0 and then it is rising slowly like this. So, this is i_1, that is all. And 1 was fired at α, I expected the current to abruptly rise to full value, it did not happen and there is an overlap. That overlap interval, many of the books call as μ, so I am going to use the same notation μ. So, for duration of μ, this rise in the current happens slowly. And the rise in the current is happening slowly because of the source inductance. That is what is actually making it slower.

So, let me integrate this from α to α+μ and let me integrate this also from α to α+μ but my limit is i_1. So, I better say it is starting from 0 to I_d. So, it will go from 0 to I_d. Now let me take this ω there itself, so let me write this as $2\omega L_s I_d$. That side is very simple, not a problem. Now on this side I have to write $V_{AC} d\omega t$, α calculation is always done based on V_{AC}.

$$\int_{\alpha}^{\alpha+\mu} \frac{V_{AC}}{\omega} d\omega t = \int_{0}^{I_d} 2L_s di_1$$

So we are very clear V_{AC} can be written as, $V_{AC} = V_m \sin \omega t$. So, I can simply write this as

$$V_m \left[\cos\alpha - \cos(\alpha+\mu)\right] = 2\omega L_s I_d$$

$$= \int_{\alpha}^{\alpha+\mu} V_{AC}\, d\omega t$$

So this is essentially $V_{AC} d\omega t$ integrated from α to α+μ, that is all.

Now if I try to look at the voltage at this point, I told you already that it is either $V_{AN} - L_s \frac{di_1}{dt}$ or $V_{CN} + L_s \frac{di_5}{dt}$. So, this point P is not anymore just V_{AN} or V_{CN} , it is not. So, let us try to find out what is the voltage that will come up across the load actually during the overlap interval. It is not going to be just V_{AB} or it is not going to be just V_{CB}, it is going to be something else.

So, what is that something else, I have to check also because I do not know what is the voltage at point P. So, I need to know the voltage at point P. So, I should say voltage at point P which is actually the top of the DC link, that has to be essentially V_{AN} minus whatever is the voltage drop across L_s.

I am talking about point P as the point here, and this I am calling as point Q. So, I am talking about voltage of point P which is at the top of the DC link.

$$\text{Voltage at point P} = V_{AN} - \text{voltage drop across } L_s$$

So, this is $V_{AN} - L_s \frac{di_1}{dt}$ and we said that $V_{AC} = 2L_s \frac{di_1}{dt}$. So, I should be able to write $\frac{V_{AC}}{2} = L_s \frac{di_1}{dt}$. So I can say this as $V_{AN} - \frac{V_{AC}}{2} = \frac{V_{AN} + V_{CN}}{2}$. Just arithmetic manipulation, nothing more than that. Now voltage at point Q, is V_{BN} itself, there is no drop in the inductance and there is a current flowing. So, this device is a short circuit, so V_{BN} is the voltage at this point at V_Q. So I can say, $V_{PQ} = V_P - \underbrace{V_Q}_{V_{BN}} = V_{DC\,link} = \frac{V_{AN} + V_{CN}}{2} - V_{BN} = \frac{V_{AB} + V_{CB}}{2}$

If I had been conducting, I would have gotten $\frac{V_{CB}}{2}$, only one had been conducting I would have gotten V_{AB}. So, it is the average of the two, that is what it means.

So, I am going to have this to be $\frac{V_{AB} + V_{CB}}{2}$ which is the average of either 5 conducting alone or 1 conducting alone. So now I have to compare the voltage without overlap with overlap. Without overlap I would have gotten V_{AB}, with overlap I am getting $\frac{V_{AB} + V_{CB}}{2}$.

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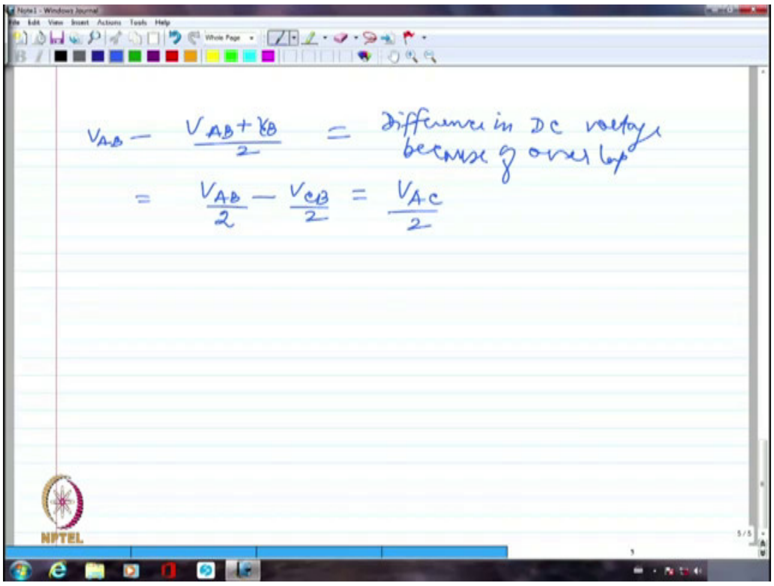

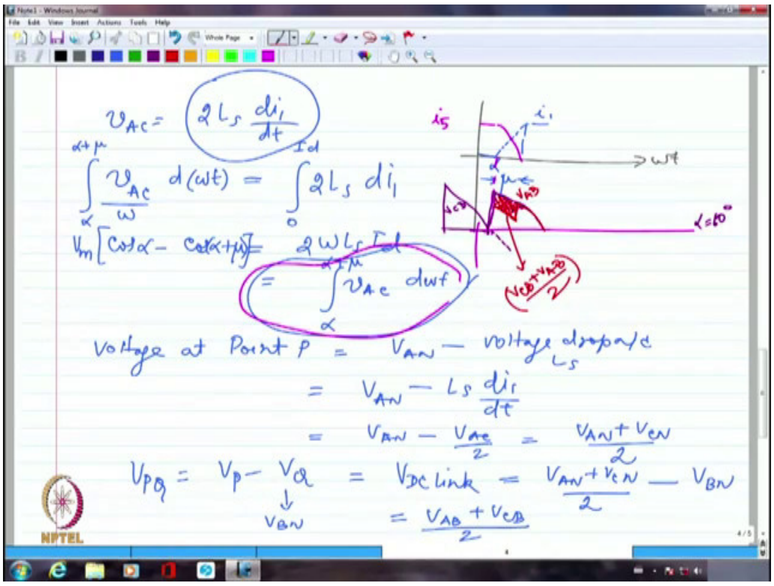

So, $V_{AB} - \frac{V_{AB} + V_{CB}}{2}$ = Difference in DC voltage because of overlap

So, this is going to be $\frac{V_{AB}}{2} - \frac{V_{CB}}{2} = \frac{V_{AC}}{2}$, everywhere this V_{AC} is coming. Wherever we look at any increase in the current, any detriment to the increase in the current, any drop in the voltage, everywhere this V_{AC} is the fellow who is influencing because we are transferring from 5 to 1.

5 is C, 1 is A so we are getting V_{AC} repeatedly coming up. And this $\frac{V_{AC}}{2}$, we already said we had integrated this if you may recall, we said integral $\int_{\alpha}^{\alpha+\mu} \frac{V_{AC}}{\omega} d\omega t = \int_{0}^{I_d} 2L_s di_1$. So if I integrate $\frac{V_{AC}}{2}$ from α to α+μ where I am having this as the voltage drop or reduction in the voltage in the DC link, that will correspond to $\omega L_s I_{d0}$ to $\omega L_s I_d$, instead I will have $\omega L_s I_d$.

I am trying to recall this. Basically, I am saying that if I do the integration for the duration from α to α+μ, at what point overlap is happening, that is where there will be a drop in the DC link voltage. And the DC link voltage is dropped by a factor of $\frac{V_{AC}}{2}$, that is what we decided just now and $\frac{V_{AC}}{2}$ is dropped which has to be integrated from α to α+μ.

So, let me draw the waveform here. If I had drawn the waveform corresponding to the actual value of voltage, I should have drawn the voltage. α had been 60 degrees for example, I should have had the voltage like this which should have been the voltage V_{AB} without commutation overlap.

If I had drawn the V_{CB}, V_{CB} should have been like this previously. Without commutation overlap this should have been V_{CB}, this should have been V_{AB} and so on for α=0 degree for example. Now, α= 60 sorry, if I am talking about overlap, at this point I am not going to have the overtaking of, so I am going to have V_{CB} coming up as the average between V_{CB} and V_{AB} as the DC link voltage.

So V_{CB} is coming down further like this, V_{AB} is like this, I should take the average between the two. The average between the two will be somewhere here. Because this is V_{CB}, V_{CB} is definitely going below 0. So, I am going to have during the overlap, this is going to be the output and then it is going to jump up to V_{AB} again. So, this is V_{AB}, this is $\frac{V_{AB}+V_{CB}}{2}$. So, for some time it is going to dwell on the average between V_{CB} and $\frac{V_{AB}}{2}$.

And then it is going to jump up to V_{AB}. So, this is the portion which is lost because of the commutation overlap. So, the DC link voltage is going to come down because some amount of voltage is dropped in the inductance. Just cannot help it because the inductance will not allow abrupt changeover of current from 0 to maximum value or maximum value to 0 value right away. So, it happens slowly, in the process there is an inductance drop. That drop is manifested in the form of a DC link voltage drop.

So, I have two simultaneous happenings because of the source inductance effect. One is I am going to have reduction in the DC voltage and the second one is, there is going to be definitely a delay in the current taking over from one device to another. What are the further repercussions of commutation overlap? We look at it in the next class and wrap it up.