Power Electronics
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Lecture No. 23
Current Source Inverter

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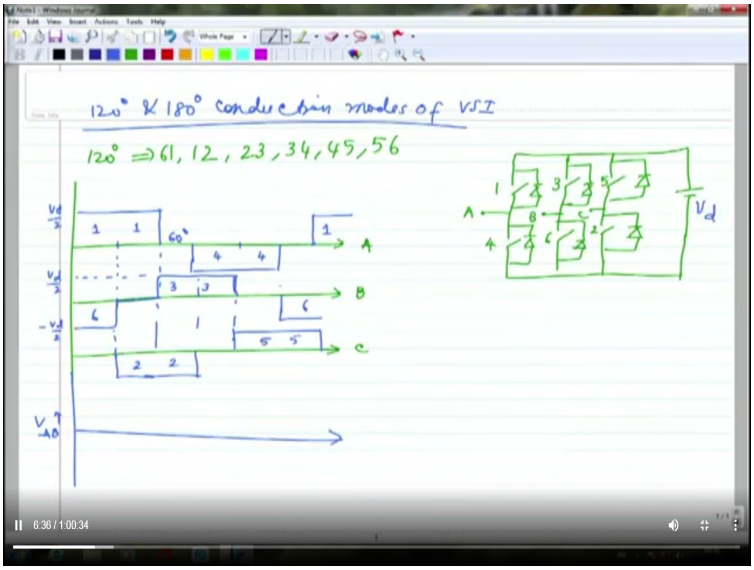

So, I am just recalling 120 degree and 180 degree conduction mode of VSI. So, 120 degree very clearly indicates, which is very similar to what we saw in rectifier. So only two devices will conduct at a time, whereas 180 degree very clearly indicates that three devices will conduct at a time because we are looking at the sequence in such a way that if it is 120 degrees.

I am looking at every pattern probably prevailing for 60 degree only, but it will consist of two devices in pair, two of the devices will conduct together. So, I will essentially have one to rather 6 1, 1 2, 2 3, 3 4, 4 5 and 5 6. These are going to be the patterns. So, these are going to be the patterns basically. So, in 120 degree mode, let me again draw the inverter. So, this is the inverter that we are talking about.

So, this is 1, this is 4, if I am calling this as A phase, of course, there will be diodes in parallel. And I am going to have diodes here, too. So, this is 3, this is 6, this is 5 and this is 2. So, this is the way the devices are connected as we talked about earlier, and I am going to connect a DC supply on this side. And this is say A phase, this is going to be B phase and this is going to be C phase. So obviously if I am having only two devices conducting at a time and I am applying V_d the voltage across each of the phases will be $\frac{V_d}{2}$.

So, we are going with that and then we are going to say that if I am having, let us say this is corresponding to A phase, this is corresponding to B phase and this is corresponding to C phase. So, let me first of all show the firing signals because it is 120 degree conduction. I am probably going to have one for 120 degrees, for 60 degree nothing will conduct, then I am going to have 4 for again 120 degrees, again 60 degree that will be a dead band and then I am going to have 1, like this.

So, I am showing the firing signal corresponding to A phase. So, I am saying that, this is 1, this is also 1 and I am taking each of them to be 60 degrees. Then this is 4, this is 4, this is also 60 degree interval. And then this is again 1. This is the way it is going to be. And along with 6 I have to have another negative device joining hands. So, if I draw the negative device clearly until here, it should be 6.

And after that B phase should have a dead band for 60 degrees. Then I should have 3 starting from here and maybe 3 will go on until here. And after 4 finishes, I will have 6 again starting from here. So, we are essentially drawing each firing signal that is going to each of the devices to be about 120 degrees corresponding to every cycle. And similarly, I should be able to draw this is corresponding to 2, and 2 will continue until here. So, this is going to be 2 and 2 and then I am going to have essentially 5 starting after 3 finishes.

So, I am going to have 5 continuing like this. So, this is the way I am going to have the firing signals. So if this is the firing signal then clearly I will have if 1 and 6 are conducting together I will have $+\frac{V_d}{2}$ coming up in A phase and plus, minus $\frac{V_d}{2}$, I may say that as $-\frac{V_d}{2}$ because with respect to neutral if I look at the B phase terminal it is going to be at a lower voltage. So that is $-\frac{V_d}{2}$.

So, essentially the same thing becomes the phase voltage as well. Whatever I have given as the signals, firing signals, the same thing become actually same things become actually my phase voltage as well. So, this is going to be $\frac{V_d}{2}$ and this is going to be $\frac{V_d}{2}$ as well. And this is of course $-\frac{V_d}{2}$ and so on and so forth.

So, now with this we should be able to calculate V_{AB} and so on, V_A-V_B, whatever you are getting, so we are just recalling VSI one in 120 degree and 180 degree conduction mode. And 180 degree conduction mode, how is it going to be? That is what we will have to check. So V_{AB} I am sure you guys can draw, so I am leaving it. We had done it earlier. So, I think you should be able to complete this V_{AB}, this is not $\frac{V_d}{2}$, its V_d. If I had written this then that is definitely wrong. This is V_d.

I am giving V_d then I am getting $\frac{V_d}{2}$ on either of the phases. The supply I am giving is V_d. I did not realize I had written $\frac{V_d}{2}$. So, this is corresponding to 120 degree conduction mode.

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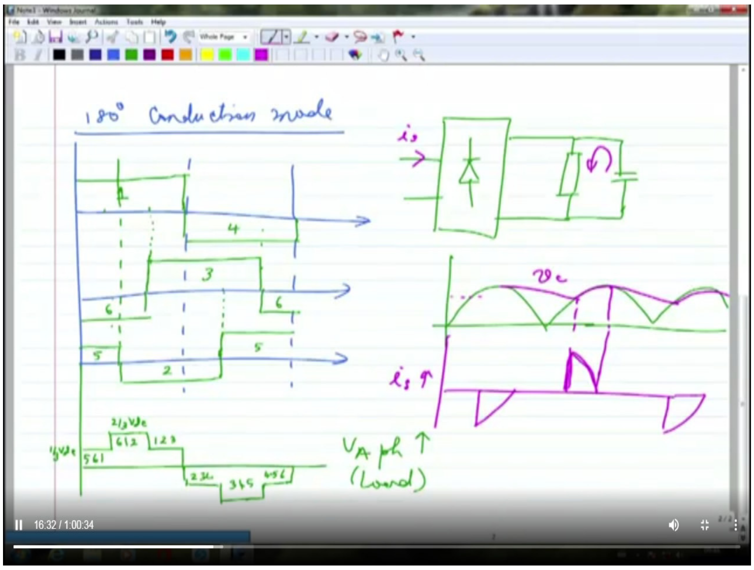

Let me just take up again 180 degree conduction mode. So, in 180 degree conduction mode, what we did was to allow each of the phases to conduct, for each of the devices to conduct for

180 degrees. So, we have to deliberately introduce a dead band very clearly in this particular case because between 1 and 4, there is no gap that is the way it is going to be.

So, if I am talking about this has one cycle and this is going to be roughly half the cycle, I will have basically this will be 1 and this will be 4. This is how my firing signals will be for A phase. Whereas, if I try to look for where I have to fire 3 has to be fired 120 degrees away from the beginning of firing of 1. So, if I divide this into 60 degree intervals, that is why I have shown this as 3, so 3 will continue until this point. 3 will continue until this point and 6 will continue here, 6 will also continue here. This is how it is going to be, so this is 3 and this is 6.

And similarly, if I try to look for where 5 will be fired, 5 will be fired again 120 degrees away from this. So, I am going to have 5 getting fired here and then it is going to probably continue until this point. And here, I am going to have 5 again. So, this is the way it is going to be. And only thing the voltage calculation we did exactly like what we did in space vector.

Because if I am going to have for example 1, 6 and 5 initial 60 degrees, I see that it is 1, 6 and 5 because 5, 6 and 1 are conducting, there are two positive devices, one negative device. So I am going to have $\frac{1}{3}V_{dc}$ coming up across the positive side and $\frac{2}{3}V_{dc}$ coming across the negative side, that is what is going to happen. So I should be able to draw the levels generally shift from $\frac{1}{3}V_{dc}$ to $\frac{2}{3}V_{dc}$ to $\frac{1}{3}V_{dc}$. Then $-\frac{1}{3}V_{dc}$, $-\frac{2}{3}V_{dc}$, again $-\frac{1}{3}V_{dc}$ and so on. So, I will essentially have a step waveform.

So if I am looking at A phase, for example, I will have $\frac{1}{3}V_{dc}$ then when I have this is corresponding to 5 6 and 1 and I am going to have now 6 1 2 which will correspond to $\frac{2}{3}V_{dc}$. Then after that another 60 degrees. I will have 1 2 3 so that is going to be clearly plus $\frac{1}{3}V_{dc}$. So, this is a kind of waveform I am going to get. Then again, I do not know whether I have just adhere to the same 60 degrees, but please understand each of them is 60 degrees.

So, this is going to be 2 3 4 then I am going to have 3 4 5 and then I am going to have 4 5 6. So this is how the waveform would be. So, I should be able to draw V_A like this, V_B will be exactly 120 degree shifted from this. So, this is V_A phase waveform. If I try to look at what is the voltage between the neutral of the load and the A phase terminal of the load.

So, in voltage source inverter because we gave, we assume we are giving a constant voltage even if it is a rectifier, which is giving you the DC output that is going to be filtered and it is steady DC voltage because of which what we get here all these voltages are steady. They are not having any ripple. Otherwise if I am looking at a rectifier, which is actually giving me the output I will see ripples normally. So, in actual practice, we will see small ripples. We just cannot help it, we will see small ripples depending upon what is the kind of capacitor voltage I am using.

And you also have to remember one more thing that what we talked about earlier in a rectifier. If I am looking at a single phase rectifier, for example, the output voltage what I get, that is going to be having a complete ripple like this. This is how it is going to be full ripple, from minimum value to maximum value. Minimum value being 0 and maximum value being V_M. So, if I put a capacitor here rather than a load RL load or something, because RL load is essentially reflected from the inverter.

If I connect this to it an inverter, the inverter will have motor load or whatever RLE load that will be reflected actually onto the terminals, output terminals of the rectifier. So, if I put a capacitor in all probability, I am going to have at least average voltage maintain somewhere here depending upon what is the value of capacitor. So, what I am going to see is, it is discharged and again charge here, again, it will discharge, charge here and so on. This is the kind of waveform actually I will see across the rectifier output.

So, the charging takes place for a very, very short while. The higher the capacitor value, the charging time is going to reduce further and further because the capacitor would be able to retain the voltage quite well, if I have a larger value of capacitor. So, if I want to make the DC really steady at the output of the rectifier, I am essentially using a larger capacitor value. I am shrinking the time for which the charging current flows, which means I am probably going to have the charging current somewhat like this.

Maybe I will have a very high sudden rise in the current and it will slowly come down to 0. So, if I try to look at the current here which is coming from the rectifier input side that is going to be far from being sinusoidal. That is all I'm trying to get it. So, I am essentially looking at a current which is probably at a very high value while it is starting to charge, and it will come down to 0 as soon as the capacitor reaches whatever is the peak value.

After that when the capacitor discharges, there is nothing to do with the supply side. It is only unloading itself on the load. It is essentially supplying the load. So, the capacitor is really not going to, so if at all I see the capacitor voltage being discharged it is essentially into the load, nothing more than that. So, there is no connection between the supply and the load during this particular portion because all the diodes will be reverse biased. The capacitor voltage happens to be a larger than whatever is the supply voltage. So, obviously none of the diodes will conduct.

So, I will essentially see currents, if at all I see the input current, I may see, if I say that this is positive half cycle. This will be the kind of current and similarly, I will have some current like this. So, this is going to repeat itself. This will be the supply current if may call this as I_S. And this is essentially the VC waveform, capacitor voltage will look like this. I am just paving the way for power quality issues. So, these are serious power quality issues we face because of the presence of rectifiers, inverters and so on.

Whenever we have a voltage source inverter, we want to have a steady voltage, if I want to have a steady voltage, I put a bigger capacitor, if I put the bigger capacitor the current get spoiled like this. I am not going to have a good current waveform. It is far from being sinusoidal and power system authorities are definitely not happy with these things because they are going to see that you draw very peaky current for some time and after that you just keep mum.

That is not good for them, because they have to put conductors which are thicker, much thicker. Even if it is for a shorter duration. If it has to carry hundreds of amperes of current, then you have to, I mean they have to install a very thick conductor. So, these are some of the power quality issues that are created by power electronic engineers. So, we have to find solution for that also.

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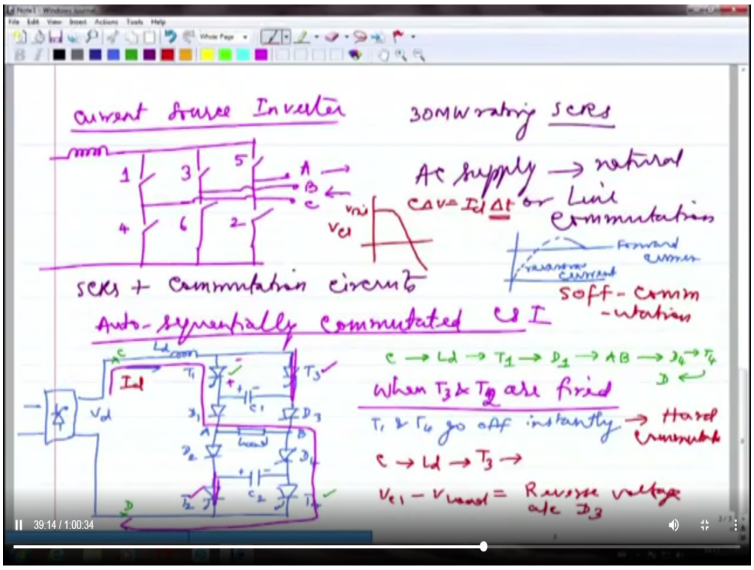

So, migrating from here from VSI, we are slowly now getting into CSI, current source inverter. So, if I try to design a current source inverter instead of a voltage source inverter the same way. Let us say maybe I have six switches like this. Please note I am not showing any feedback diode.

So, I have switch 6 which is like this and I am essentially going to have a large inductance sitting here. And I may have a DC voltage source, which can be derived from a converter or a rectifier or it can be directly given to a battery. Invariably current source inverters are used in very, very large capacity drives, hardly ever they are used for any other application. So, current source inverters are generally used with high capacity drives. I forgot to give the, so it is always used with high capacity drives.

So, this is A, this is B, this is C. This is going to be 1, this is going to be 4, 3, 6, 5, 2. So if I have constant current flowing from the front end, then whenever I switch 1 and 6 together, I am going to have the same current flowing through 1 and 6. Which means through A phase and B phase the same current will flow, but the voltage will now depend upon whatever is the load impedance. So, it is just a duel of what we saw in voltage source inverter. Voltage source inverter, the voltage is fixed. The voltage is going to be fixed and I will essentially have the current being determined by what is the load impedance that I am connecting because if I am applying 100 volts and if I have only 20 ohm resistance, I will have 5 amperes of current.

So, the current is decided by whatever is the load I am connecting. Whereas, here the current is already set in stone. It is at a particular value and that current source is being injected into the inverter devices which actually passed the current through the load. So, A phase load and B phase load maybe it is returning the current depending upon whether 1 and 6 are on at this juncture. And whatever is the current because that is fixed, now I have the load impedance, the load impedance multiplied by this current will determine what is the load voltage.

So, if I want to operate this in PWM and so on and so forth, I should be able to switch this large current in a very quick succession. And generally, because these are used in megawatt level drives, we are not going to look at current source inverter with IGBTs or IGCT or never with MOSFET. Never ever. We will never see a MOSFET with current source inverter. Most of the times you will see either GTO or thyristors because current source inverters basically are operated at high current levels and possibly, they cannot be operated at a high frequency because it is very, very high current.

Normally, we are not going to operate them at high frequency because turn on and turn off becomes extremely difficult. It will not be possible to turn on and turn off at a very quick way. And one more thing is that because it is a very large capacity drive, operating many of them in parallel and series, the devices, it can become a little bit of an issue. So, thyristors single handedly are available in 30 plus megawatt rating. Single handedly thyristors are available for 30 megawatt rating easily, not GTO. I am talking about normal SCRs. These are available for 30 megawatt rating.

So, if I can use a single device to operate a 30 megawatt drive nothing like it. So, I would be able to employ six such thyristors and then I would be able to operate this current source inverter. But when I employ a thyristor, please remember you can only control the turn on, you cannot control the turn off in a thyristor. To control the turn off, you have to have commutation circuits, if you do not have commutation circuit, so it is going to be a big issue. So, I have to have normally SCRs plus commutation circuits associated with them, so that I would be able to operate, that is on and off. I will be able to control both of them.

So, whenever I have a DC supply, I have a DC to DC conversion or DC to AC conversion and along with that if I have to use a thyristors circuit, I necessarily need to have a commutation circuit as well. When the input is AC. I do not have to worry because input is AC, automatically the voltage will go into the negative direction after some time. So, the thyristor will have automatic turn off or line commutation. We call that as line commutation or natural commutation whenever I am going to have AC supply voltage, the device will go through line commutation or natural commutation. Which means the devices will be turned off when the supply voltage is coming to their reverse half cycle.

Whereas when I am feeding them with DC, I necessarily need to turn them off. So, if I do not turn them off, then I am not going to get an AC at the output. I am essentially looking at turning on for some time turning off for some time. That is the reason why I am getting an AC. So, one of the popular circuits with SCR, which is working as a current source inverter, so auto sequentially commutated current source inverter. This is actually one of the very well-known circuits of current source inverter. This is with thyristors and we will try to take a look at how this works.

First of all, let me start off with single phase case, then we will migrate to three phase case. So, this circuit structure is somewhat like this. I have one thyristor, then there will be one diode, there will be one more diode and one thyristor. So, this consists of one leg. And there will be one more leg. So, this is going to be the kind of two legs that we have. So, let us say this is T1, this is T2, this is T3 and this is T4 and I am having a large inductance being connected to a DC source.

Generally current source inverters are not connected directly to the battery. They will be connected to a controlled rectifier. I think I mentioned right in the beginning when we started off on inverters, that we normally have a controlled rectifier by adjusting the firing angle of the controlled rectifier. We would try to adjust whatever is the voltage that is coming up here at the DC link because of which we have actually modified the current that is going in because this particular voltage is going to set the tone of the current whatever is flowing through this DC inductance.

If I may call this as L_d, DC link inductance, this could be as high as 10 or 20 mH for a very large current rating. That also imagine if it is hundreds of amperes of current and 10 or 20 milli Henry DC that too not high frequency you are going to have really a bulky inductor, normally. We talked about flux density being related to the size of the transformer or inductance core. So if it is

DC, obviously, I am going to have a huge core, large core. So now the load will be connected here.

I will need a commutating element for this circuit. So, the commutating element for this circuit happens to be a capacitor. So, I will have a capacitor somewhat like this. Two capacitors will be connected, one for commutating the upper device, one for commutating the lower device. So, I will not require any additional inductance. In many cases, we might require an additional inductance and so on and so forth.

Whereas here at least we are minimizing the number of additional components we are including for commutation purposes. So, what we are including is one diode and one capacitor in common to two SCRs, that is what we are doing. So, the basic working is somewhat like this. So let me name these devices also, so this is D2 and this is D4 and this is load. Let me call this terminal as A and this terminals B.

The capacitors have to be pre charged. If I know that I am going to start with T1 operation with T1 and T4, because opposite devices have to be triggered so that the current has continued, and I can never open circuit this. If I ever open circuit this, I am going to have a big problem because $L\frac{di}{dt}$ will be huge across this conductance. So, it is exactly the dual of voltage source.

So, if I have open such a by chance, maybe I did not give firing pulse or the filing pulse did not go through and I am open circuiting one of the devices really a huge voltage will be induced across the DC link inductance. So, it is definitely not safe to open circuit this circuit as such at any point in time, because I am going to have a constant current flowing through this and a huge current normally.

So, let us say the capacitor is pre charged with plus here and minus here. And similarly, this will be pre charged with plus here and minus here. I hope I have marked the directions correctly. So, let me call this as C_1 and this as C_2. They are pre charged already maybe to a good amount of voltage because my input voltage may be V_d. Let us say from here. This is V_d but the voltage to which the capacitor is charged will be much higher than this V_d. Because inductance stored energy will also be dumped into capacitor. Hopefully, initially if I had just charged this.

So, I am going to have a good amount of voltage across C_1 as well as C_2. Now initially when I give the firing signals to this T1 and T4, I have given the firing signals to T1 and T4. The path will be somewhat like this. I am going to have, let us say this is C and this is D. So from C it is going to go to L_d, from here it is going to go to T1. Then it is going to go to D1 then A B which is the load and then it is going to go to D4 and T4 and back to D. This is going to be the path for the current.

So, I am going to have the path somewhat like this. So, let me draw that also, so it is going to go like this, go like this. You may think that the diodes are unnecessary. We will see about it. So, it is essentially going through like this. Now let us say out of 20 milliseconds, 10 milliseconds are over T1 and T4 have conducted. Now it is time for them to go off. If they have to go off, then let me fire T3 and T2.

Let us see what happens when I fire T3 and T2. Now because this capacitance is connected exactly between these two thyristors, I am going to have once this becomes a short circuit, I am going to have minus being applied here and plus being applied here because of the capacitor. The same thing is going to happen here as well. Plus will be applied here and minus will be applied there, when this is working as a short circuit.

So, I am going to say when T3 and T2, I am going to have automatically the other two thyristors will be commutated instantaneously, immediately. I hope you understand why, because if I have a good amount of voltage and there is no resistance, it will try to force a current in the opposite direction. So, whatever is the forward current will be quenched right away and opposite direction current thyristor cannot carry.

So, it has to be essentially, switched off. It will be switched off but for at least for the turnoff duration, it should be reverse biased. Unless it is reverse bias that leaves for certain duration of time which will allow it to recombine, it is not going to go into off condition immediately. So, during that situation I am going to have essentially let us look at the path when T3 and T2 are fired. First of all, T1 and T4 go off instantly, immediately. So, we call generally this kind of commutation as a hard commutation.

We just switch off lights, immediately strangulate them literally, which say that, you cannot carry the current anymore. Instantaneously they are turned off. We probably looked at one circuit right in the beginning of our course where there was L and C both, the current was rising slowly and then it was going higher than the positive current after some time. If you may recall, that is what we had done in the one of the earlier circuits. So there what happened was if this is the load current, the reverse current was rising like this, actually.

This was the forward current, this was the forward current and this was the reverse current which was trying to rise slowly because of LC oscillations. Here, there is only C. So that is the major difference. If I have an L and C in the commutation path. Here there is no L and C in the commutation path, that is only C. Whereas, if I have L and C in the commutation path, the current in the reverse direction will rise slowly because of which I am definitely going to have slowly the devices, pulled out of conduction.

Initially it may be carrying 100 amperes then it becomes 90, 80, 70 like that and then ultimately it comes down to 0 when it tries to go in the negative direction the device will be switched off. So this kind of commutation is generally specified as soft commutation. Please look back into your notes when we were talking about SCRs earlier. In that the circuit we had discussed for commutation was soft commutation circuit. Maybe it is there in tutorial sheet 2 or 3 or something like that. And this one what we have got is called hard commutation.

And please note, the current that is going here is Id which is a constant value. We are saying that it is constant at least for those 20 milliseconds or 40 millisecond of duration. This is a constant. Now if I look at the path, it has to go something like this, I have from C, L_d, I will have T3, C_1 is actually coming in series. I hope you look at the voltage, minus and plus, so it is essentially coming in series. This is plus and it is coming like this. This is minus and plus, so they will be in series, it will get charged further in the opposite direction?

So it is going to come like this, come like this, come like this, like this, like this and goes back, long path, definitely. Let us try to look at whether D3 and D2 will conduct or not. D3 voltage is actually decided by what is the voltage across this capacitor and what is the voltage across the load. Voltage across the capacitor is quite large, it could commutate it, but it does not really passed any current. So it will slowly get charged in the opposite direction which means the voltage right now is negative on the anode of the diode, large negative value and I have to also include whatever is the load voltage.

So it will be like V_{C1}-V_{load} because this will be plus and this will be minus if the current is going in this direction. So V_{C1}-V_{load} is going to be the reverse voltage across D3.

So, unless I have that to be 0 or in the reverse direction, I will not be able to turn on or the device D3 will never be turned on. So device D3 will not start conduction right away. VC is slowly coming down. VC 1 is slowly coming down, as it comes down, I will have at some point that D3 getting into conduction. So if I look at V_{C1}, V_{C1} is actually at some value, like this. This is the voltage initially. So this is $V_{initial}$, now it will actually get charged in the other direction means it will go through complete reversal.

This is the way it is going to get reversed and it is a linear charging. If I assume that this I_d happens to be a constant, CV equal to Id. So, I have to essentially write $C\Delta V = I_d \Delta t$, where Δt is the time taken for changing the voltage from a particular value to another particular value. And what I am looking at is how long this is going to be reverse biased.

Unless this is reverse biased for sufficiently long duration to allow recombination, I am not going to be able to turn off the device successfully. The outgoing device can be turned off. This is the outgoing device, and this has been the incoming device. So, the outgoing device can be turned off successfully only if I am going to have this Δt value, which is actually taking the voltage from $V_{initial}$ to 0 because until it comes to 0, the thyristor will be reverse biased. After that the outgoing thyristor will become automatically forward biased.

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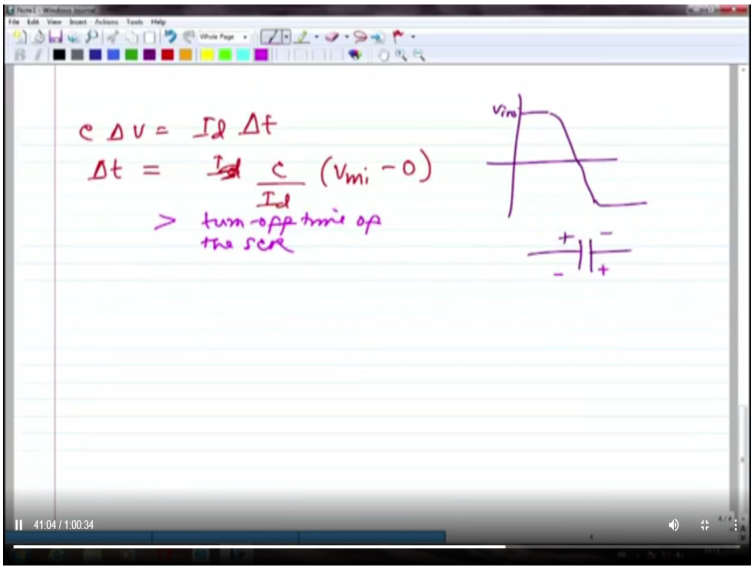

So I necessarily need to look at this $C\Delta V = I_d \Delta t$. So, I should be able to calculate $\Delta t = \frac{C}{I_d}(V_{ini} - 0)$. Until the voltage comes down to zero. So, I am looking at actually the voltage starting from V initial and it is slowly coming to 0 and then it is going to go into the opposite direction.

It is getting charged further and further. So initially I had shown the charge of the capacitor somewhat like this. This was plus and this was minus. Now it has to become this as plus and this as minus, completely reversed after the charging is successfully done. So, this duration is of utmost importance for us because this is the one which determines whether the outgoing device will be turned off successfully or not. So, this Δt has to be greater than turn off time of the SCR.

So, when I design the capacitor, this equation is the one which decides really whether I have the capacitor value sufficiently large enough or whatever, to give me, successful turn off of the outgoing device.

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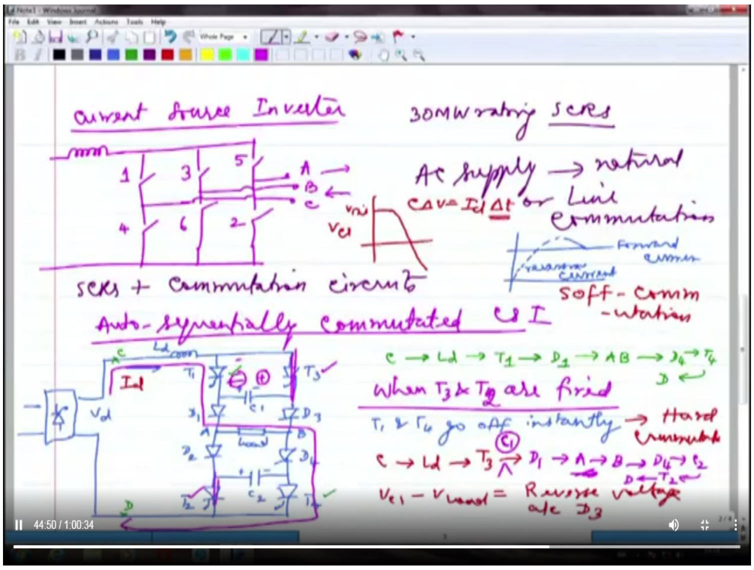

Now I am going to have the current I had left it halfway Ld, T3, D1, A B D4, C2 and C1, D1 and so on C2 and then T2 and then D. But this continues only for some time until VC1 minus V load is able to reverse bias this diode. But the moment VC1 minus V load is not able to reverse bias the diode, this will also jump into conduction. Then there will be two parallel paths.

One is going to be something like this, and it is trying to pass like this. Another one will try to actually go through this and then so there will be two opposing currents. It looks as though it is flowing through the load actually, but it is essentially like a tug of war between these two, these two diodes. So, in fact, I would request you guys if you can do a small simulation for this PSIM, try to put this single phase inverter, try to design the capacitor value. I have told you how to design the capacitor value, try to see what kind of waveforms you get for each of this.

So, when this jumps into conduction depends upon whether V_{C1}-V_{load} is able to maintain the forward biasing or able to forward bias this diode. Once this is forward bias, this is going to go away automatically. By then the capacitor must have charged to the maximum value as well.

So, then the capacitor reverses its value like this. This is plus and this is minus. After it reverses, we are now having the negative half cycle completely coming into picture, where I am going to have the current flowing in the opposite direction like this directly. None of the other intervening components are coming up.

But at that point, the capacitors have reversed the charge and ready to commutate these when they become the outgoing devices, and these become the incoming devices. You are going to have whatever you called as the incoming device now, they have to be commutated after T/2 after the complete half cycle is over, negative half cycle is over. So, you have seen that already the capacitors are ready.

And this poses a limitation on the switching frequency that we can adopt. If I want the commutation to be successful for the next pair of devices also, that means, I should have had this reversal completed. If the reversal is not completed, then I will not be able to turn off this particular device, T3 and T2, I would not be able to turn off. So, which means I have to look at what is the time duration.

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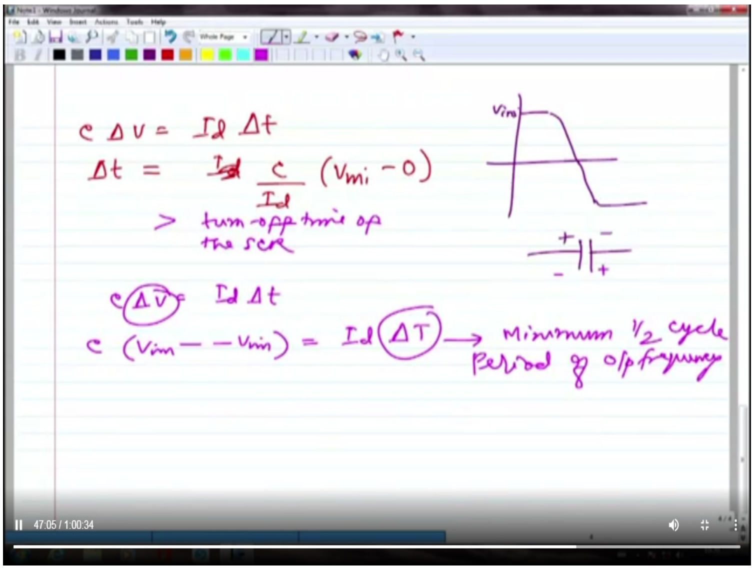

This is $C(V_{ini} - -V_{ini}) = I_d \Delta t$. The first one is for turn off time of the device. The next one is essentially putting a minimum, duration, I have to keep each of the devices on.

Unless I keep this device on for at least this much of time, the capacitance will not reverse its charge only when the capacitance reverses its charge. It will be in a position to commutate the next pair of devices. So, I have to say $C(V_{ini} - -V_{ini}) = I_d \Delta t$ or something like that where this is the minimum half cycle period of output frequency, or output voltage, or output current, whatever.

Because unless I reverse the capacitor voltage, I am really not in a position to, make sure that the next pair of devices can be turned off. So basically, what I have is a couple of constraints for the design here. I have to make sure that the frequency does not go higher than whatever is stipulated here. The last expression we have written and similarly the turn off time if I know for the device, which will be generally given in the data sheet. I should be able to design what is the kind of capacitor that I need to adopt provided I know what is the I_d value that I am planning to demand from my load side. So, this particular inverter circuit is generally called as auto sequential commutation.

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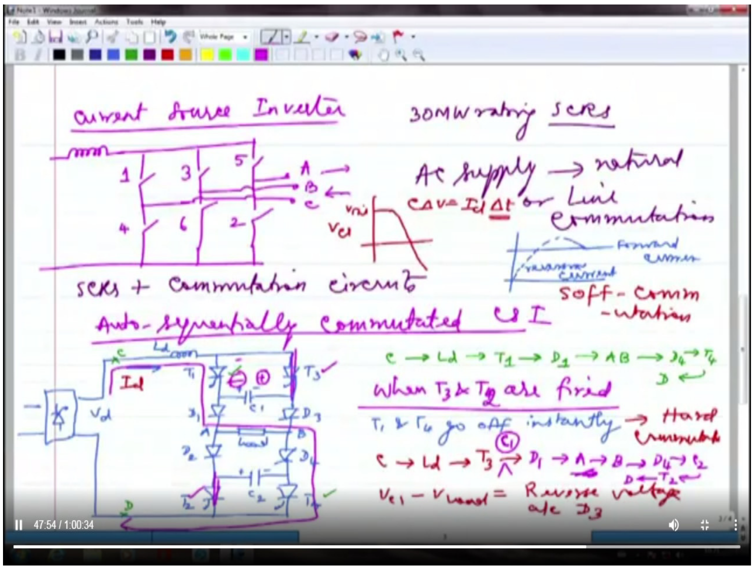

Because I am essentially looking at whatever is the next device that is being fired that is able to take care of the turning off of the previous device. So that goes on and on. So sequentially whatever I am firing that is able to take care of the commutation of the previous device. So, we say that it is auto sequentially commutated current source inverter. So, this is essentially in the single phase case, three phase case I do not want to discuss the dynamics. But basically, I am going to have a circuit with three legs like this. So obviously I need to have three capacitors also which will be connected in delta.

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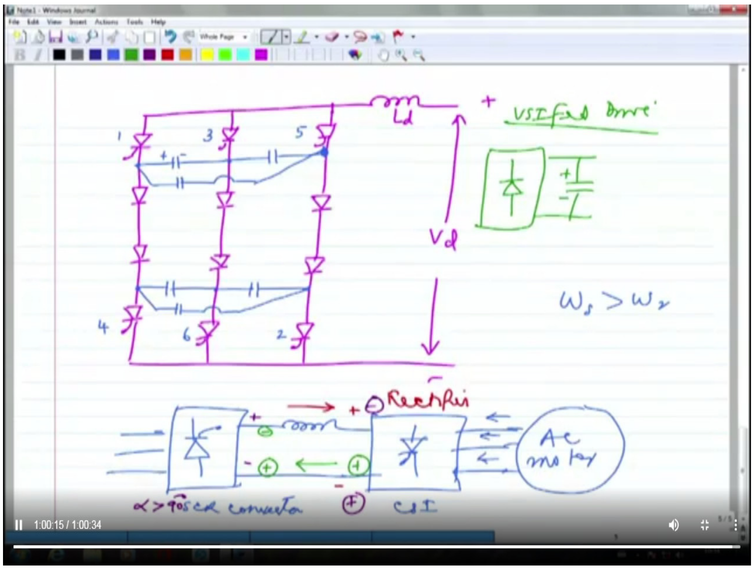

So, I am going to have one thyristor here, one diode, one more diode and one thyristor. The diodes are essentially allowing the capacitors to retain their charge. Otherwise if I had directly connected, I could have very well connected it to the load through which automatically the capacitance may be discharging. Maybe again, if you have the time you can try to remove the diode and see obviously the inverter will fail, it will not work. So, this is one leg.

The second leg will be somewhat like this and this is the third leg. And I am going to have of course an inductance and here is the DC voltage which is coming out of maybe my rectifier. I will have clearly three capacitors one is this, one will be this and the third one will be something like this. They are delta connected.

And similarly, here also, I have to have delta connected capacitors. This is how the delta connected capacitors will be connected. And here also I will go by sequence clearly, if I call this as 1, 3, 5, I will call this as 4, 6 and 2. So clearly when I want to turn off 1 and when I turn on 3, I should have plus here and minus here. I hope you understand. If I am turning on 3 to turn off 1, I should definitely have this capacitor charged as this plus and minus, plus will come to the cathode and minus will go to the anode.

So, the auto sequential commutation very much applies here because in a sequence I am going to fire 1, 3, 5. So whenever I fire 3, 1 will be commutated. Whenever I fire 5, 3 will be commutated and so on and so forth. So, this is actually a pretty complex working of the circuit. So, I am not really going into the detail. This is definitely a little bit more complex, but I would request earnestly that you try to simulate at least the single phase CSI, so that you get a feel for what kind of wave forms you are getting across you put a very large inductance, no problem, in the input.

But you can essentially look at what happens exactly in a current source inverter. Just to conclude, it is so complex then why would I use it? That is the question anybody might think. We told that, thyristor can handle large capacity, power all those things are fine. But more than all that, one major advantage of the current source inverter fed any motor drive for that matter is, if I have on one side a rectifier and I have an inductance like this and on the other side I have this current source inverter.

This is the thyristor rectifier, and I am having three phase voltage here. I am having three phase current coming out here and this is my AC motor. If I am talking about regeneration. Let us say, I am using this kind of a configuration in Delhi Metro, maybe a station is coming up. So essentially, I have to reduce the speed of the motor. So, when I reduce the speed of the motor, the rotor is still actually rotating maybe at a good speed.

So, I will be able to find think about induction machine. For example, we always say $\omega_s > \omega_r$ in an induction machine. But if I just make the other way around, if I make $\omega_s < \omega_r$ because I have ω_s under my control completely. It is with inverter. I am giving ω_s. So maybe I was making the machine rotated 1500 rpm, close to 1500 rpm and my frequency was corresponding to 1500 rpm, which is 50 hertz.

Let us say I bring down the frequency suddenly to 45 or 42 hertz, which I can do, because it is under my control. When I do that, the machine will start working as a generator. The fundamental requirement for an induction machine to work as a generator is that its revolving magnetic field speed has to be smaller than the rotor speed. So, slip becomes negative. When the slip becomes negative, automatically this machine is going to work as a generator.

When it works as a generator, it is going to feed the power clearly back to the means. It is not going to take the power. It is going to give back to the mains. When it gives back to the mains, I have not connected the mains here right away. What I have done is basically to connect a current source inverter. The current source inverter, because it is after all having thyristors, I can always make this work like a rectifier or inverter. Nobody can refute that; I can always take these voltages as references. I can fire this at alpha less than 90.

It is all right, because I have a sinusoidal voltage. I have the firing circuit. I can always fire this at $\alpha < 90$. Then what I called as inverter can now work as a rectifier. If it works as a rectifier, I am going to have the current still flowing in this direction. Previously, this was plus, and this was minus. Now this will become plus, and this will become minus, when it is working as a rectifier.

If I am looking at the same circuit working as an inverter, we serve it rectifier. I am going to have the reversal of polarity of the DC voltage. Like what we saw in the rectifier case earlier $\alpha < 90$ and $\alpha > 90$. Now I have got this working as a rectifier. I can always make this $\alpha > 90$, that is also under my control. If I make this $\alpha > 90$, what will happen? This will have its DC link voltage also reversed.

So rather than getting plus here and minus here, now I would have plus here and minus here. And this is plus here. The current is flowing from the plus of the so called inverter to the so called rectifier. So, which means the power flow has reversed its direction from this plus it is flowing into this plus. So, I have got very nicely regeneration taken care of without adding any extra component.

Now the capacitors and those diodes and everything become redundant. They are not needed anymore for me. When it was working as a current source inverter, I required the capacitor, diode everything. Now I do not need the capacitor and diode there. Let them be there.

So, I would be able to implement regeneration really successfully, when I am having a current source inverter being fed by a thyristor converter. Because both can have reversal of voltage, but both cannot have reversal of current and they go hand in hand very nicely and they can handle extremely large power ratings.

And then I am talking about large capacity drives, it is very essential to have energy saved as much as possible wherever we can economize, we should try to do that. And that is one reason why for large capacity drives we go for current source inverter, which means I have to look at the flipside in voltage source. In voltage source, I am going to have essentially a diode converter most of the times which will not allow me to take a feedback.

Even if I change it to thyristor converter it is going to be difficult, because I will put the large electrolytic capacitor anyway, because I do not want to tolerate any voltage fluctuation. So VSIs because of this presence of capacitor, I will not be able to reverse the voltage even if I want to. I will not be able to reverse the voltage. So, it will have a voltage only in one direction and current cannot be reversed because front end if I use only a diode rectifier or thyristor rectifier, I will not be able to reverse the current.

So, it is a big problem if I want to really want to have regenerative braking in the case of a voltage source inverter fed drive. In those cases, regenerative braking is not automatic or not natural. I have to spend a lot of effort, a lot of energy to make sure that regenerative braking happens in this particular case.

I have to probably put a dual converter which we studied. If I put a dual converter, yes, it may be able to work. But then also the capacitor could be. No capacitor will not allow voltage reversal at least current reverse is possible. So, dual converter will work. I can put dual converter that will work. That means I am increasing the cost quite a bit.

I am talking about megawatt level drive. So obviously I am going to increase the cost tremendously if I try to put a dual converter. So, it is not really the complex issue of the voltage source, or current source inverter that matters, but then we are looking at actually the entire drive system, we have to concentrate basically on energy conservation. Thank you.