Power Electronics

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Lecture - 21

Last class we discussed the principle of operation of a single phase switched mode rectifier and we found that the essential condition for the circuit to work satisfactorily is that the magnitude of output voltage should be higher than the peak of the input voltage. Why? It is because we found that when I closed the switch, current in the inductor increases. Now, when I open the switch, current in the inductor should fall so that when I close it in the next cycle, current will again increase.

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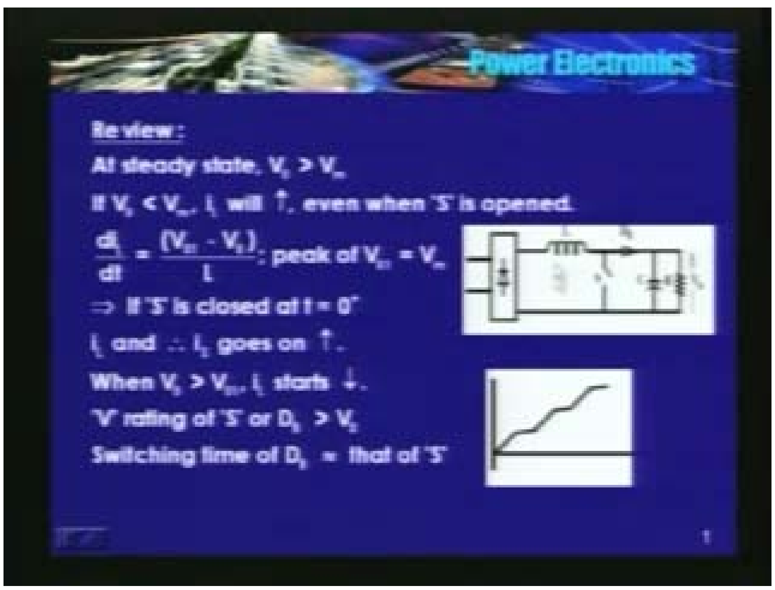

So, in the circuit if you see, when I open the switch, voltage across the inductor is V_{01} minus V_0 because diode DB is conducting, V_{01} minus V_{0L}. So, this should be negative. It can happen only when V_{01} is higher than $V_{0.}$ The peak value of V_{01} is the peak value of V_m itself because V_{01} is held constant and V_{01} is continuously changing. It is full wave rectified. So, V_0 should be higher than peak of $V_{01.}$

I also told you that I will energize the circuit and I will not close the switch S immediately. In other words, I will allow the circuit to attain a steady state. So therefore, I said average value of V_{01} is equal to average value of V_0 because inductor average value, average voltage across inductor is 0. Now, in case, assume that I have energized the bridge at t is equal to 0 and I started operating the switch at t is equal to 0 plus. Output capacitor is completely discharged and we know the capacitor voltage cannot change instantaneously.

What will happen? When I am closing the switch, current increases, when I open the switch, the very first cycle V_0 is 0, V_{01} is positive. So, voltage across inductor is still positive, current increases. So therefore, if you see, this is current increase, now when I am closing opening the switch, whatever the stored energy in the inductor is being dumped to the capacitor. Capacitor voltage starts building up.

Now, during transistent V_0 is continuously changing and so V_0 is less than V_{01}. So, di by dt is still positive. It increases, may be, slope will not be the same. So, in the second cycle, again I am closing the switch. Current increases, now, may be, capacitor might have attained some voltage. So, when I open the switch, V_0 is still less than V_{01}, current continuously increase but may be at a different slope and so on, it goes on till V_0 becomes higher than $V_{m.}$

So, if I start energizing the switch at t is equal to 0 plus, inductor current, therefore, a source current continuously increases and after some time it attains a steady state. It decreases and depending upon the control strategy, current increases and decreases. So, in the circuit, what is a voltage rating of the diode DB and what is a voltage rating of the switch S? We found that when you close the switch, the entire V_0 appears across the diode. If you see in this circuit, when I close the switch, this V_0 appears across DB. This potential, this point gets connected to this.

So, DB should block $V_{0.}$ Also, when I open the switch, diodes starts conducting. So, this V_0 appears across S. Therefore, the voltage rating of S and DB should be higher than V_0 and not $V_{m..}$ What happened to the switching times? When I close the switch, diode should stop conducting and immediately the current should start flowing through S and when I open the switch S, immediately diode DB should turn on. Otherwise, we are breaking an inductive circuit because you have opened the switch, diode is taking its own time to turn on. So, momentarily, you are breaking an inductive circuit. So, there will be a spike and may be a device may fail.

So, in other words, the switching time of S and DB should be the same. Otherwise, in other words, DB should be a switching type of diode, whereas, the rectifier diodes at the input side, the bridge, you can use ordinary rectifying diodes. So, DB should be a switching diode, a fast recovery diode, whereas, these 4 diodes could be of ordinary type or ordinary rectifying types.

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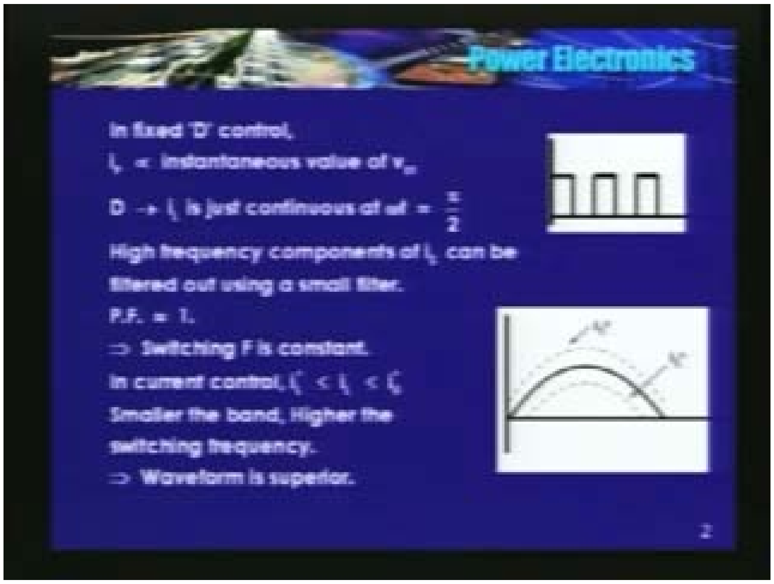

A second point that we found was in a fixed duty cycle control, we kept the switching frequency constant and we kept T_{ON} also constant. But I_p, the peak value of the inductor or the source current is proportional to the instantaneous value of V_{01}. So, we chose the value of D in such a way that the inductor current or source current is just continuous at omega t is equal to pi by 2. That is because at omega t is equal to pi by 2, when I close the switch for a fixed D, it has attained a maximum value.

But then at omega t is equal to pi by 2, when I open the switch, decay is very slow and therefore, if the current is just continuous at omega t is equal to pi by 2, it will be, definitely be discontinuous in the entire remaining period, whereas, if you keep the current just continuous at omega t, at the near the 0 crossing, it has attained a very small current, dies down very faster. So, if it is just continuous near 0 crossing, it will so happens that in the subsequent switching cycles, inductor current may build up and it may damage the circuit. So therefore, D is chosen in such a way that current is just continuous at omega t is equal to pi by 2. So, the peak value of the inductor current is proportional to V_{01} which is nothing but a sinusoid. So, source current is approximately a sinusoid, has a high frequency components. Now, I can use a very small filter to eliminate these high frequency components.

Power factor is approximately equal to 1. If i is a very small filter, source current will be a sinusoid and it is in phase with the input voltage. So, the power factor is unity. In other words, this bridge represents a purely resistive load to the source. Hence the name, resistance simulation, this I have discussed yesterday.

So, what are what did you do for the current control? We did, we took a reference sinusoid, a rectified sinusoid, we call it as I_{ref}, we selected upper band and said as i_u star, called it as i_u star. Then a lower band as I_L star. We control the inductor current within this band. So, when the inductor current touches a lower band, I close the switch, current increases. When it touches the upper switch, upper band, I will open the switch, current decreases. So, current is lying within this hysteresis band. So, current looks almost sinusoid and it looks almost a sinusoid.

Smaller the band, current will be current waveform will be more superior. But then smaller the band, it implies that we are switching the device at a much faster rate. So, it will so happen that switching frequency increases, losses increases, temperature rise and therefore high bigger heat sink. But then the source current waveform is superior. So, that is what, whatever you do in your life, you have to pay a price. Smaller the band, waveform is superior. The inverter efficiency may come down.

I have not told you anything about the switching frequency in this case. I will tell you sometime later, whereas, I told you that switching frequency is held constant in fixed D cycle. Nothing I have told you for this scheme? So, first we will discuss how to choose this magnitude of I_{ref} then we will see what happens to the switching frequency?

What is the purpose of this circuit? I told you that I want to keep the output voltage constant. Take any example, take any application, one of the requirement is maintain the output voltage constant. So definitely, I need to know what is what is the actual value of the output voltage? I know what is to be maintained. I have to compare it. That can be done using a simple power amp. So, depending upon the error, in other words, depending upon the difference between the desired value and the actual value, I need to take a certain corrective action.

Now, what sort of corrective action do I need to take? Assume that capacitor voltage remains constant. How constant is that I will address it after discussing how to determine the magnitude of magnitude of source current. When the capacitor voltage will remain constant? If there is a perfect balance between the input power and the output power, in other words, capacitor does not supply any power or does not receive any power, at that time capacitor voltage will remain constant.

In other words, when the input power is equal to the output power, capacitor voltage will remain constant. So, if the capacitor voltage increases, what does it indicate? It indicates that source is supplying more power than the required and in case the capacitor voltage is falling, it implies that the power supplied by the source is less than the required. So, what do I need to do? We found that source power factor is unity. So therefore, power supplied by the source is V into I. If the capacitor voltage is increasing, you reduce the magnitude of source current.

So therefore, power supplied by the source to the bridge reduces and if you find that capacitor voltage is falling, now you need to increase the power supply by the source. You increase the magnitude of source current, same thing is true for fixed duty cycle also. If the capacitor voltage is falling, energy stored in the inductor had been transferred is less, may be. So, increase the value of D and vice versa.

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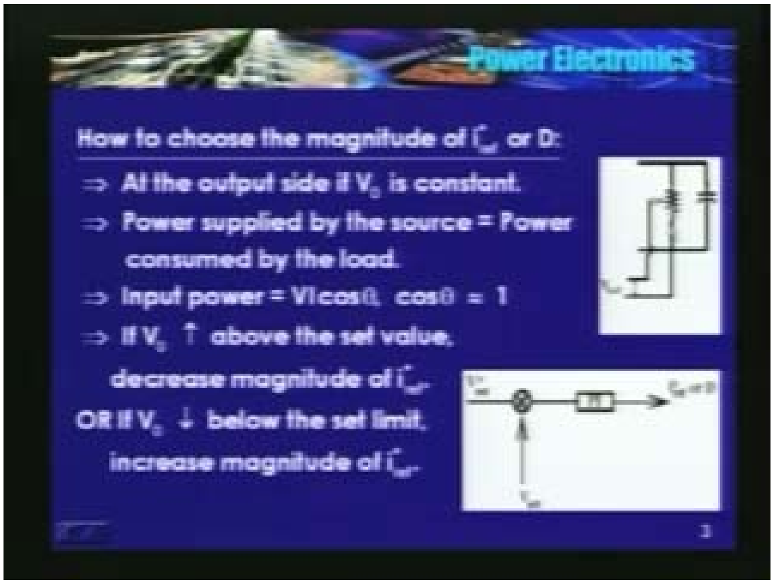

So, here is the loop. I have put a big register here, a potential divider. There are other ways to sense the capacitor voltage also. A very crude method may be a large register here, a small voltage I will take. So, this is V_{actual} with respect to the negative DC bus. This is the reference value. This is required, given by the application. I will find out the error which is nothing but V_{ref} minus V_{actual}. V reference minus V actual is the error here. I will give it to a controller. Out here, I have selected a PI controller; P stands for proportionate, I stands for integral, PI controller because I have taken integral action so that at steady state, error is 0.

You might have studied this in a control theory and the PI controller determines magnitude of I_{ref} or D. Of course, there could be or other block also, may be a saturator. This is the broad philosophy. This need not be that actual version here. It is just a PI control determining I_{ref} or D, need not be true. There may be additional blocks also. So, if you find that V_{actual} is higher than V_{ref}, controller may reduce I_{ref} and vice versa.

Now, what will happen to the switching frequency in the current control? Assume that there is no load, assume. If there is no load, source need not supply any power to the output. Theoretical no load or there is a load or the converter is lightly loaded. So, the power supply by the source is negligibly small that means I do not need to store the energy in inductor and dumped it to the output.

I will repeat; there is no load or load is very small, I have charged the capacitor, capacitor voltage is maintained constant there, does not change. No load, so input power should be approximately equal to output power. So, it is 0. So, I do not need to store any energy in the inductor and dump it into the capacitor. If I do that capacitor voltage is going to increase. So therefore, ideally, there will not be any switchings at all. Ideally, there will not be any switchings at all.

So, switching frequency is approximately 0 and if the load starts increasing now, I have to supply more energy, store it dump it, store it dump it, so I have to switch the inductor. Therefore, switching frequency increases. Therefore, in a current control, switching frequency is a function of load, remember. In lightly loaded condition, switching frequency may be very low and as you increase the load, the switching frequency also increases.

So, what if the switching frequency is increasing or varying or it is a function of load? I told u that source current is approximately a sinusoid. So, to make it a perfect sinusoid, I may have to use a very small filter. Now, I can design a filter, provided, I know the harmonic spectrum and in all this converters the thumb rule is that the frequency of the predominant harmonic that is present in the source current depends on the switching frequency.

So, as the switching frequency varies, the frequency of the predominant harmonic also changes. So therefore, how do I design a filter? So, designing a filter becomes difficult because cut off frequency I have to choose, that cut off frequency depends on what harmonic I have to eliminate or that frequency itself is changing.

So, in other words, designing a filter at the input becomes difficult. Also, if I switch it at a very low frequency, it may come down to your audio range and it may produce a noise. Therefore, it is always desirable to have a constant switching operation. So, in the current control which I discussed, I choose upper band and the lower band frequency is a function of load. There are various techniques reported in a literature to make this frequency constant. I will not go into detail. May be, if you find time, you read the literature and try to understand and for the first course, it may not be required. But only thing you remember is that it is possible to keep the switching frequency constant in a current control technique.

Now, coming to the capacitor voltage will there be any low frequency ripple in the output? Source current is sinusoid, we found that source current is a sinusoid, source voltage is also a sinusoid. So therefore, power supplied by the source to the load that is including the convertor and capacitor and load whatever, is pulsating, single phase power. Instantaneous value of V and instantaneous value of I, both are sinusoids. So, the instantaneous value of power is a constant term and pulsating at twice the supply frequency.

Remember, in the single phase case, if both the source current as well as source voltage are sinusoid, single phase power input, instantaneous power is not constant, it has a constant term as well as it has a pulsating component. So, if the power input to the bridge itself is pulsating at twice the supply frequency, at 100 hertz in this country, capacitor voltage will also have a second harmonic component, remember. It has a second harmonic component. So, capacitor voltage will have a second order harmonic component. It is not constant even if the source current is sinusoid, remember.

What happens in the 3 phase case? We will see when we discuss the 3 phase convertor. By the way, I have connected a resistor across the capacitor and assumed that capacitor supplying load need not be all the circuits that we studied; single phase bridge, 3 phase bridge, single phase SMR. These are one of the blocks of the various power electronic equipments we will be studying in detail. In this case, I just connected resistive load. These are the building blocks for the various equipments, we will be studying details.

In the previous case, in SMR we are connected the inductor and the DC side. We rectified the AC then in between the bridge and the switch we connected an inductor. Now, we can shift that inductor to the source side. Operation of the circuit is the same.

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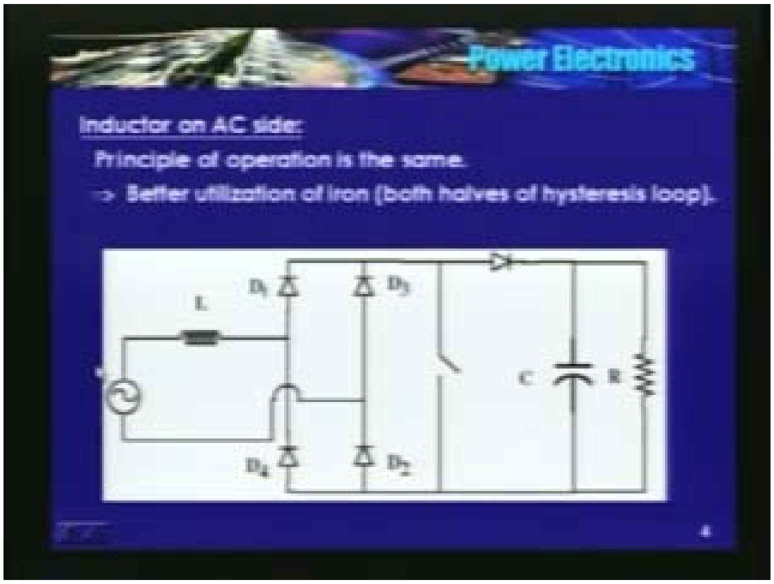

So, when I close in switch in the positive half, you have D_1 conducting, switch, D_2 conducting and when I open the switch, inductor current flows through $D_{1,}$ diode DB, load and $D_{2,}$ back in the positive half. In the negative half, D_3 and D_4 will conduct and then what is the difference? There is no difference in the working principle of the circuit. Only difference is that now, inductor is in the AC side, current that it is carrying is alternating. If I put the inductor on the DC side, it is a full wave rectified current.

So therefore, you are not utilizing the iron very efficiently because only half of the BH loop you are utilizing. Current increasing, decreasing, it is always positive. BH loop or BH, if I plot B verses H, we are always in the first quadrant, whereas, in the second case when the inductor is in the AC side, we are using the both halves. In other words, a better utilization of iron is possible. So, that is only the advantage, may be.

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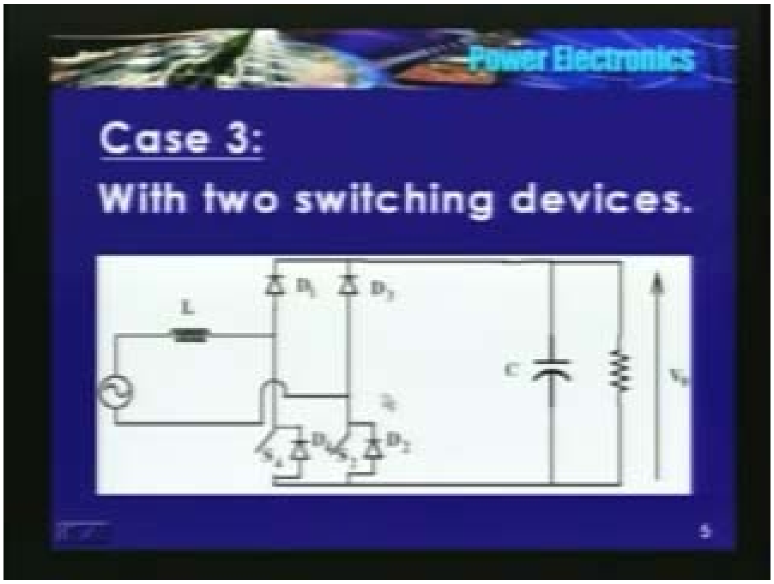

We will see the next circuit, same, in the sense, recall our AC to DC conversion. Initially, we had all 4 diodes and a switch. Now, we replace 2 diodes by 2 self commutating switches; S_2 S_4. D_1 and D_3 are the diodes. How does this circuit work? Same, in the positive half, I will close S_4 only. So, what will happen? Source, inductor, there is a short here and D_2.

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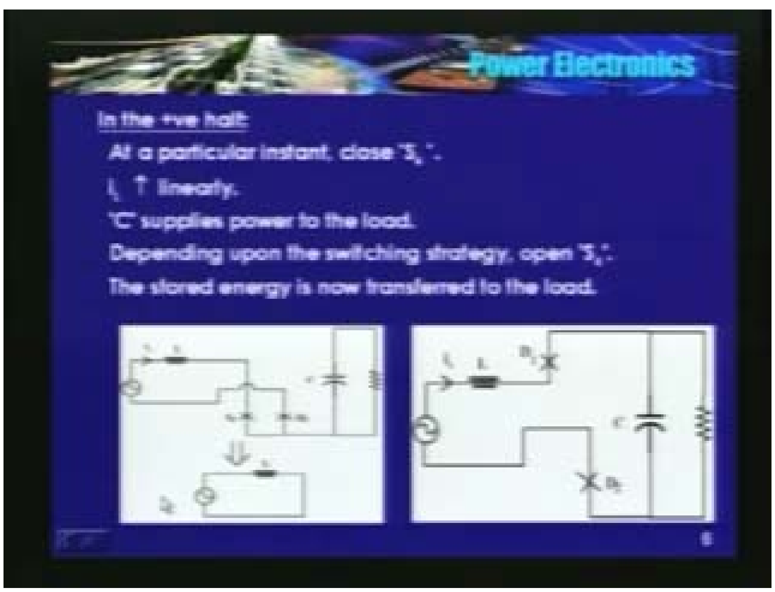

So, here is the equivalent circuit L, S_4, $D_{2.}$ So, in other words, inductor is short circuited, V_i, this voltage is proportional to the instantaneous value of V_i. It could be negative also in this case. Capacitor is supplying power, the conditions are the same, output voltage should be higher than the peak of the input. After sometime, depending upon the control strategy whether it is a fixed duty cycle or a current control or any other control strategy, when I open S, what will happen? Inductor current was flowing in this direction when I close this switch. It will try to flow through D_1. D_1, capacitor, load, back to source to D_2, this is the circuit.

Stored energy in the inductor is transferred to the output. So, operation is the same. So, in the second half or in the negative half, I will close S_2. So, current will flow, now potential of B is higher than A in the negative half. Flow through S_2, D_4, L, back to source. S_2, D_4, inductor, back to source, this is the equivalent circuit.

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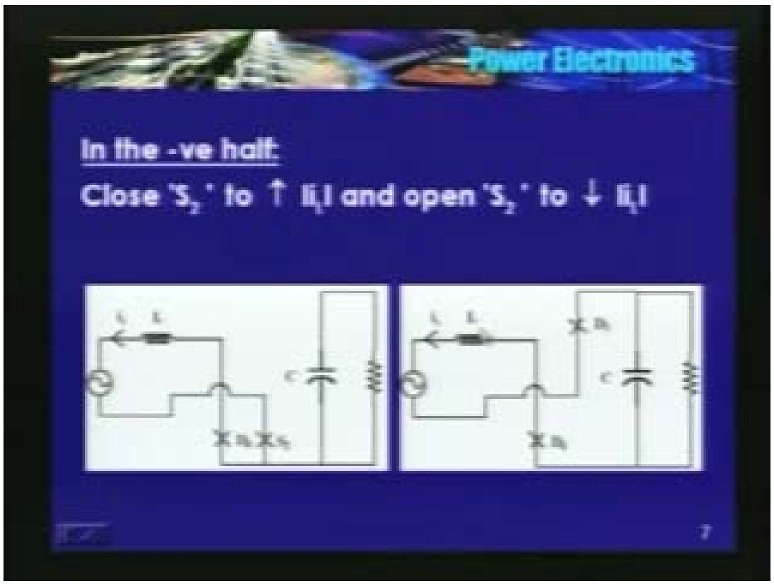

When I open the switch, S_2, current was flowing in this direction. So, what will happen? You have opened the switch, so there is a diode in the upper half, D_3, load, D_4, back to source. Source, D_3, load, D_4, back to source, same thing, same principal, I_L decreases, provided, value of V_m is less than V_0 or V_i is less than V_0. When I open the switch, current decreases, principal of the operation is the same.

I have a question to ask. What sort of a waveform will you absorb at the input side of the bridge? What sort of waveform? At one side, you have pure sinusoid. You are assuming that source is an ideal sinusoid, an inductor and we are connecting to a bridge. What sort of a wave form will I get when S_4 S_2 are continuously switched? Will it be a sinusoid or will it be a step wave?

See, in the previous transference, when I closed in the positive half, of course, input is still a sinusoid. Voltage across AB or V_{AB} is 0. This is A, this is B, V_{AB} is 0. See, S_4 and D_2 are conducting. This is V, this is point A, this is point B. So, they are connected to together, there is a short circuit. So, V_{AB} is 0 and when I open the switch, this is A point, this is B. B is at the negative potential of the capacitor voltage and D_1 or point A is at the positive. So, V_{AB} is a capacitor voltage, V_0, remember. So, when I close S_4, V_{AB} is 0 and when I open S_4, V_{AB} is V_0. So therefore, do not say that voltage across V_{AB} is also a sinusoid.

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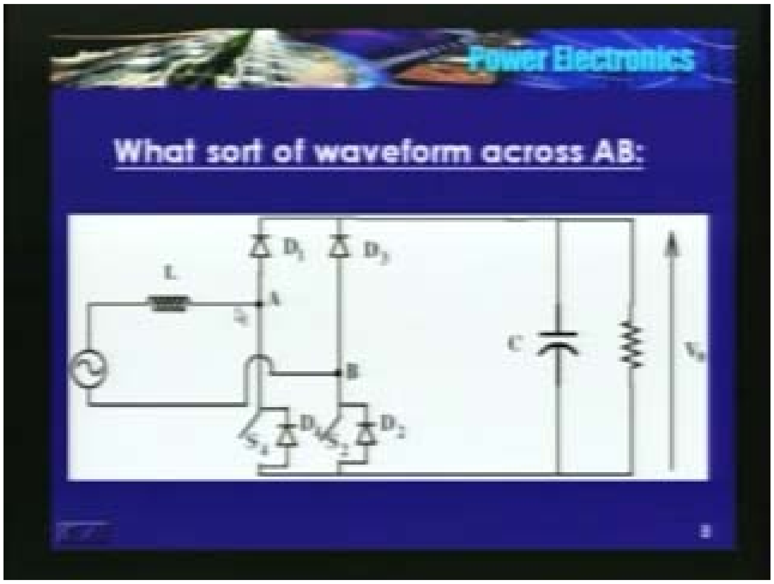

No, voltage across the points AB or voltage across this inductor at this point is a stepped wave. In the positive half when I close S_4, it is 0 and when I open S_4, it is V_0. So, I get a pulses, series of pulses. Switch on, switch off, switch on, switch off. Similarly, in the negative half, remember, I will use this waveform sometime later.

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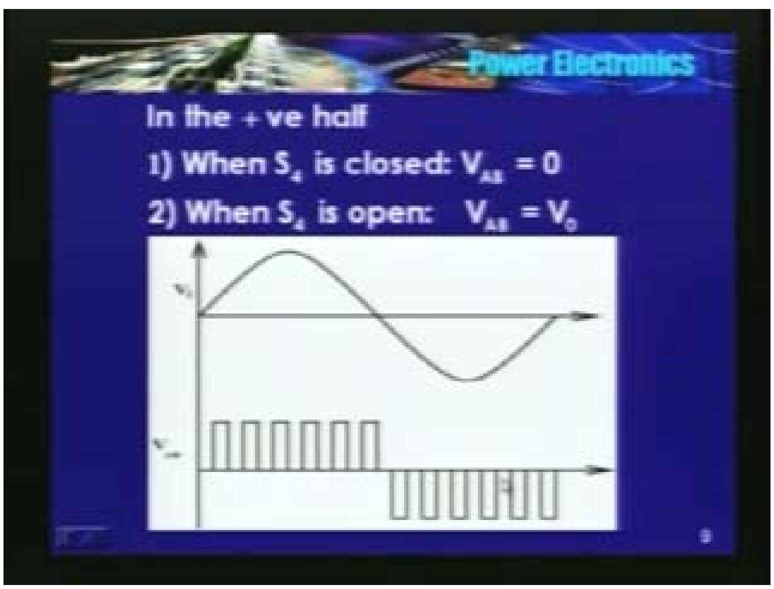

Voltage across AB or voltage at the other terminals of the inductor is not a sinusoid. Input is a sinusoid, other side is not a sinusoid. Similar to the line commutated convertor that we studied, uncontrolled bridge, then we studied half controlled bridge, both are single quadrant, current is also positive, unidirectional, voltage also unidirectional. Then we replaced all 4 diodes in an uncontrolled bridge by 4 SCR's then we found that voltage polarities of V_0 can change. Therefore, we called it as a 2 quadrant converter. Similar operation should be possible even in devices with self commutating devices, bridge with self commutating devices.

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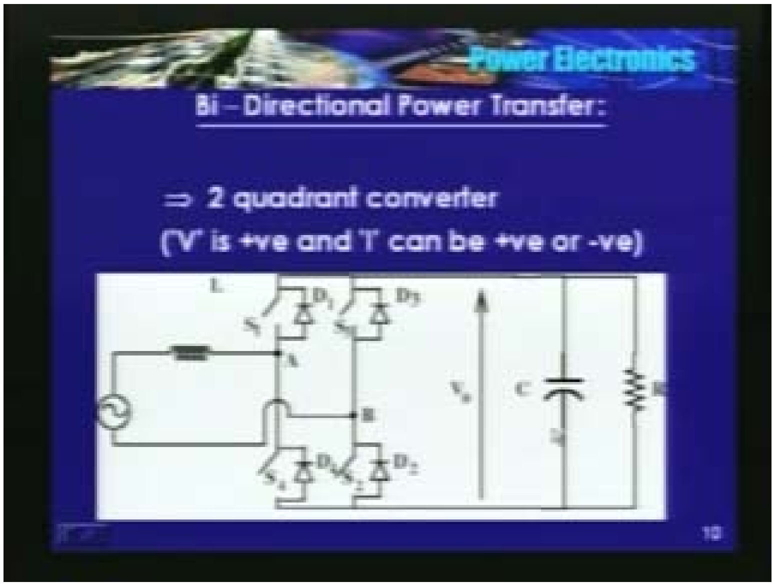

See in this bridge, we have all 4 self commutating switches. We have connected a capacitor here. Therefore, polarities of V_0 cannot change. Can i change in this link? Yes, i can change because see, current can flow through this diodes back and capacitor. 1 direction of current and current can also reverse and it can flow through either S_3 like this or S_4. Similarly, there are paths down also. By the way, I hope all of you know if it is like this and if I close the switch, current flows in this direction, remember.

See, S_4 if I close like this, current will flow in this fashion, down, downwards. Here also current is downwards. In case, if I have this point here, in this fashion, if I show it in this fashion, when I close it, current will go up, current will flow in this direction, So, there is a sign convention.

So therefore, this bridge V_0 cannot change its polarities. We have large capacitor here, whereas, current can change. I can have a bi directional current, hence the name, 2 quadrant convertor. Same thing, in a fully control bridge, voltage can change, current cannot change, whereas here, current can change, voltage cannot change. Let see how it works?

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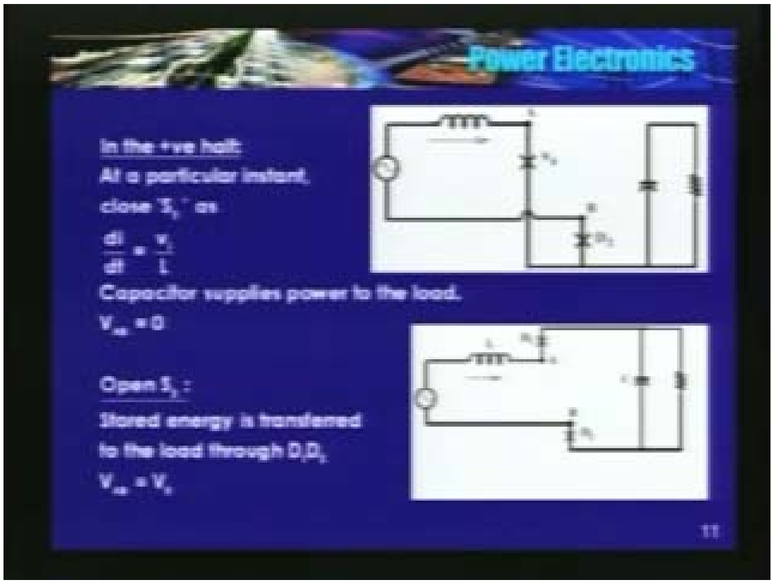

First cycle, case 1, first cycle, positive half, depending upon the control strategy you close S $_4$, S_4 only. So, what happens? See in this bridge, I close S_4 only. Current will flow through S_4, D_2 back as in the previous case. Capacitor supplies power to the load. So, the equivalent circuit is here, S_4, D_2 back, the capacitor. di by dt is V_i by L. V_i is an instantaneous value of the input voltage and what is V_{AB}? It is 0, V_{AB} is 0 because it is short circuited.
After sometime, again depending upon the control strategy, open S_4. Do not need to do anything to S_1. We know that inductor current should be continuous. It was flowing in this fashion but then there is upwards, there is D_1. So, current will flow through D_1.

So, even if you try to close S_1 here, sorry even if I close S_1 here, current was flowing in this direction, even if I close S_1, current will not flow through S_1. Current will flow through D_1. D_1, capacitor, D_2, back to the source.

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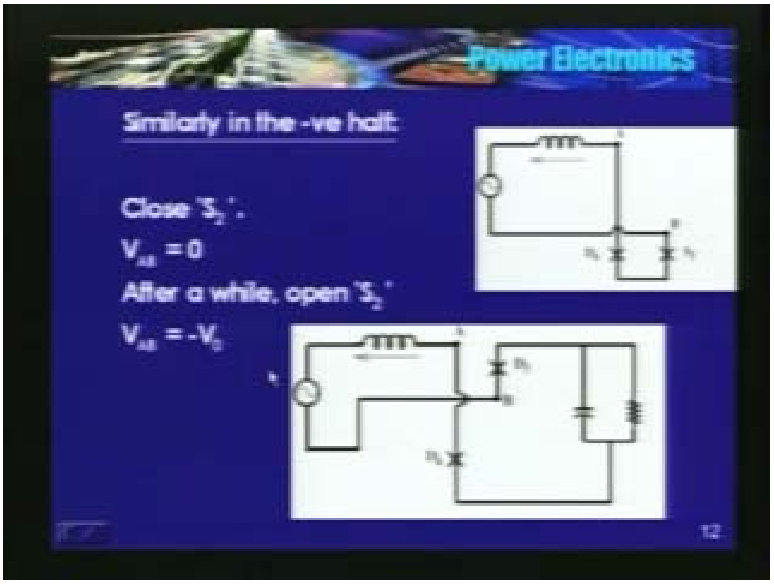

So, even the same thing in this second half; close S_2 only, circuit will be completed through S_2, D_4, inductor. Open S_2, current goes flowing in this direction, flow through D_3, load and back. Here, V_{AB} is 0, whereas here, V_{AB} is minus V_0 in the negative half. A is connected here, B is connected there, this point. So, V_{AB} is negative, whereas, in the previous case, in the positive half V_{AB} is nothing but V_0 itself. So, case 1, in the positive half, we controlled S_4 and in the negative half, we controlled S_2.

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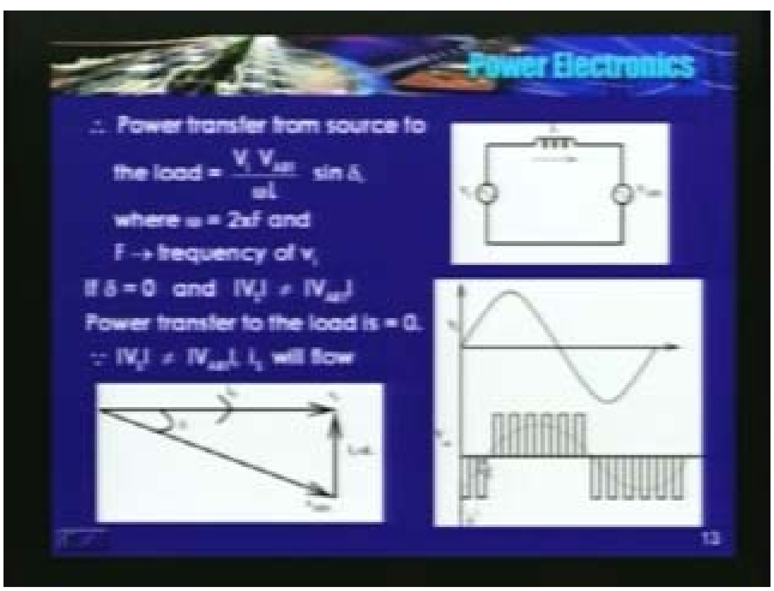

So, the waveform is 0 when the switch is on and when the switch is off, it is V_0. By the way, this pulse is the width of the pulse depends on again the control strategy. If it is a current control, may be pulse width will be continuously change.

So, I will draw an equivalent circuit. This is the input voltage, inductor and at this point, we found that voltage wave form is a stepped wave. Definitely, it will have a fundamental component whose frequency is same as the supply frequency and a higher frequency component. See, let me recall. If the input is sinusoid, current is the sinusoid. We have assumed that current is approximately sinusoid and has a high frequency component. So, this voltage also should be a sinusoid having high frequency component.

So, for analysis for pulse, I will just use the fundamental component which is the sinusoid. So, I have a very interesting case here. Input voltage V_i sinusoid, V_{AB1} is again a sinusoid connected by an inductor L. Now, what is the power that is transferred from source A to B? Or, if there is a V_i or there is a V_{AB}, I have 2 voltage sources are connected by an inductor.

So, expression for power is given by V_1V_2 divided by Xs into sin delta, remember. I think, you might have derived this expression in synchronize machine. We have a generator and we have grid interconnected by an inductor. We said that power transfer to the grid is V_1V_2 divided by Xs into sin delta where delta is angle between V_1 and $V_{2.}$

So similarly, here, power that is transferred from V_i, the source V_i to the load, it is V_i V_{AB} sin of the angle between V_i and V_{AB} divided by X or omega L. That is this expression, V_i into V_{AB} divided by omega L into sin delta. Omega is 2 pi F, F is the frequency of V_i, the fundamental frequency, 50 hertz.

So depending upon the power rating or depending upon the power requirement, I need to change the delta. I need to just change this delta. As delta increases across 90 degree, power transport also increases. Now, what if I made delta is equal to 0? An ideal condition, consider my inverter is a lossless and I have a capacitor at the output. If I make delta is equal to 0, the power expression says that power transferred from the source to the load is 0.

So therefore, definitely there has to be no load also in the output. I have neglected the losses in the converter. In other words, converter is ideal, efficiency is 100% but then power transfered may be 0. But then if the magnitude of V_i and V_{AB}, if they are not the same, current has to flow and current will flow.

I will repeat; I have made delta is equal to 0. In other words, V_i and V_{AB} are in phase. If they are in phase and magnitudes are also same then there is no current through the inductor because both the potential or both points are at the same potential. They are in phase but then the magnitudes are not the same. There has to be some current flowing through the inductor and current will flow. What sort of a current? What is the angle between now the inductor current and the supply voltage?

See the vector diagram for a finite delta is here, V_i and I want the source power factor should be unity. So, V_i I_S, V_i into I_s into cos of the angle between V and I_s is the power transfer that is nothing but V into I_{rms} value of both this … but then that power same as V_i V_{AB} divided by omega L into sin delta.

So, I need to have some angle between the positive 0 crossing of the input voltage and the positive 0 crossing of V_{AB}, voltage at this point. So, as you increase this delta, power transferred from source to the load increases. So, for this circuit, this is the vector diagram. So, V_{AB} plus I_s into omega L is Vi. Now, if I make delta is equal to 0 and $V_{i,}$, the magnitude of V_i is not the same at V_{AB} and delta is equal to 0, they are in phase, 0 crossing of V_i matches with the 0 crossing of V_{AB}. Magnitudes are not the same, they are in phase. Some current has to flow. What sort of current now?

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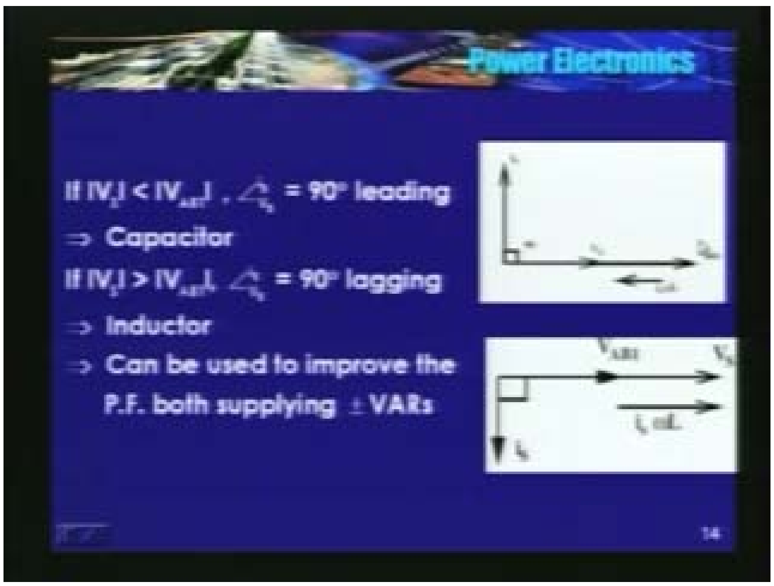

In case, take for example if the magnitude of V_s is less than the magnitude of $V_{AB,}$ I have not told you how to change the magnitude of V_{AB}. Now, assume that magnitude of V_{AB} is higher than $V_{s.}$ but I told you that magnitude of V_0, the output voltage should be higher than the peak value of V_m that I have told you. So, in this vector diagram, magnitude of V_s is less than magnitude of $V_{AB.}$ So therefore, voltage drop across the inductor should be in this direction. So difference between V_s and V_{AB} should be I_s into omega L. If this is the voltage drop across the inductor, current should lag this vector by 90 degrees. So, current vector will be in this direction.

So, now what is the angle between the source voltage and the source current? It is 90 degrees and source current is leading the source voltage by 90 degrees. So, this is nothing but source feeding a capacitor or a capacitor is connected across the source. Capacitor current is leading the voltage by 90 degrees.

Take second case, magnitude of V_{AB} is less than the source voltage. So, this should be I_s into omega L. If this is the voltage across the inductor, current vector, current flowing through should be lagging this vector by 90 degrees. So, this is I_s vector. Now, we will find that angle between I_s and V_s is 90 degrees and I_s is lagging V_s by 90. So, this is nothing but an inductor.

So, we found that if magnitude of V_{AB} is higher than V_s and they are in phase, source does not supply any power to the converter and the current drawn by the converter is leading by 90 degrees. In other words, we are connecting a capacitor across the load, across the source.

In the second case, if the magnitude of V_{AB} is less than the source voltage, angle between the source voltage and source current is 90 degrees. Source does not supply any power to the load because we can prove it, V_s into I_s cos of the angle between them is the active power transfer to the load. In this case it becomes, angle is 90, therefore, it is 0 and we found that angle between the current and the source voltage is 90 degrees lagging. It is equivalent to an inductor is connected across the source or source is feeding an inductor.

So, we discussed 3 cases; the first case is I can have a unity power factor operation. The source voltage and source current are in phase. The second is angle between the source voltage and source current can be 90 degrees leading and third is 90 degrees lagging. So, all 3 possible cases we discussed. One is if I can have unity power factor operation, it becomes a purely resistive load. If the angle between them, source and source voltage and source current is 90 degree lagging then it becomes a purely an inductive load and if the source current is leading in the source voltage by 90 degrees, it becomes source feeding, a purely capacitive load. So, unity power factor operation, plus or minus 90 degree operation are possible. What are the uses in power system? We will see in our next lecture.

Thank you.