Power Electronics

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Lecture - 35

In my last class I discussed about the features of DC to AC converters. So, one of the feature of DC to AC converter is that both output voltage and frequency should remain constant. There are another class of DC to AC converters, wherein both output voltage and frequency should change till the output voltage is equal to the rated value and from there onwards, it should be able to keep this voltage constant and increase the frequency. So, these are the basic 2 types of inverters are quite popular.

There are basically 2 different possible constructions in inverters. One is a voltage source inverter, wherein input is a stiff voltage source. The thevenin equivalent impedance is approximately equal to 0. So, input is strictly a voltage source. Therefore, the polarities of this voltage source cannot change. But then but then current should be able to reverse or this inverter handles unidirectional voltage and bidirectional current.

So, the type of switches that are used in a VSI should be able to carry this bidirectional current. In other words, you need to connect a diode across the controllable switch. So, another feature of a voltage source inverter is that the switching signals for the one leg of the inverter are complementary. See, I mean, see, this is one leg of inverter; these 2 are controllable switches and these 2 are anti parallel diodes.

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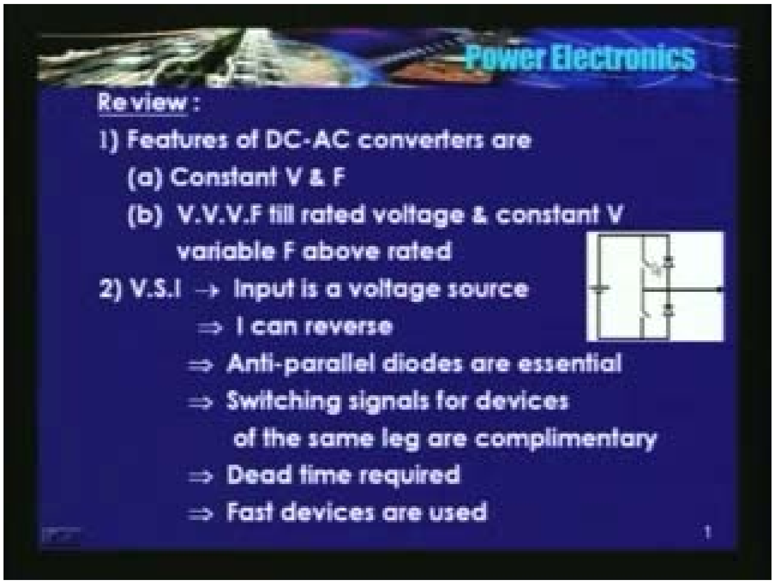

The positive direction of current or positive current can flow through this device and negative current can flow through this device. I said gate signals for these 2 switches should be complementary. Since, the thevenin impedance is very small, it is very difficult to protect these devices against shoot through faults. Shoot through in the sense, both devices are accidentally conducting. So, if both devices are carrying current, a large current will flow. So, in order to protect these 2 devices against shoot through faults, a small dead time is provided between the gate signals of these 2. In the sense, this device is turned off and after sometime this device is turned on.

Another requirement in a voltage source inverter is that these 2 devices should be able to turn off very fast or in other words, these are fast devices because if there is a shoot through fault, I have to withdraw the gate signal and and thereby, I should be able to protect them. So, if they are slow; input is a stiff voltage source, has practically 0 impedance, series impedance, so, a large current will flow and damage the devices. If the devices are fast, there is some hope in protecting this inverter.

So therefore, one of the requirements of a voltage source inverter is that you need to have a fast device and second one is a current source inverter.

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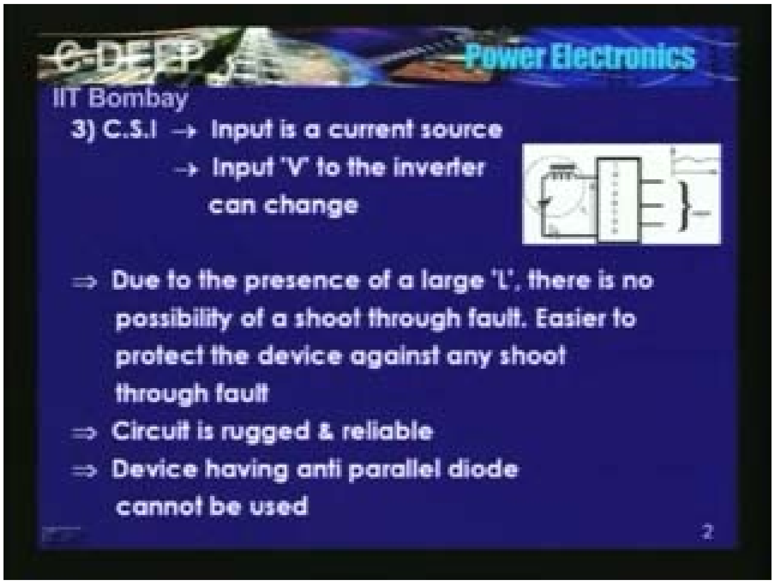

A large inductor is connected in series with the input variable DC source. Why this is variable? We will see sometime later and this is the inverter. There is a large inductor connected in series here. So, current cannot change its direction. But then input voltage to the inverter can change its polarities. So therefore, it is not possible to use the devices having anti parallel diodes because if there is an anti parallel diode, those voltages, those devices cannot block voltage in the reverse fashion, remember. If there is a device with an anti parallel diode, that device cannot block the voltage in the reverse direction. So, in a CSI inverter, the devices having anti parallel diodes cannot be used cannot be used not possible to use.

So, another feature of CSI is that a large inductor is connected in series. So, circuit is very rugged and reliable. Why it is rugged and reliable? Assume that there is a shoot through fault here. Shoot through in the sense, one leg accidentally turning on. Since there is a large inductor, current cannot change very fast and now it is possible to protect this inverter against shoot through faults by withdrawing the gate signals which is a bit rather difficult in a voltage source inverter because input impedance is practically 0.

Here, there is a large inductor. Current cannot change instantaneously, current has to change slowly. So, the moment I moment the moment the shoot through is detected, you withdraw the gate signals. So, devices are turned off. So, it is possible to protect a current source inverter against shoot through faults which is not the case in a voltage source inverter.

We also discussed in the last class about a half bridge voltage source inverter. The input voltage, the magnitude of the input voltage is V_{DC}. We had V_{DC} by 2, V_{DC} by 2, a center point we took as a reference point, but then output voltage, the magnitude is V_{DC} by 2. See in this figure, input is V_{DC}, output is a square wave with half V_{DC}. Output voltage waveform is a square wave with half V_{DC}, so it has all the odd harmonics; third, fifth, seventh, ninth, eleventh so on and the total harmonic distortion is of the order of 48%.

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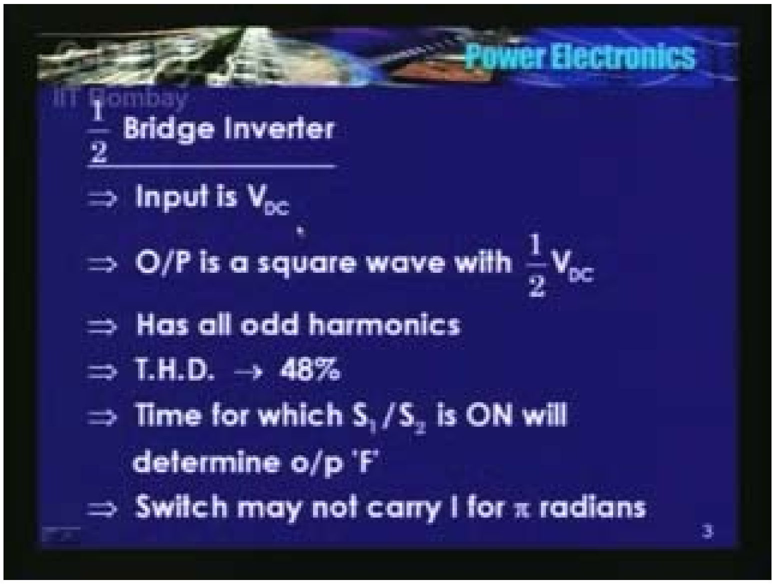

See in this figure, we had calculated in AC to DC conversion, we had a source current is approximately a square wave. We assumed that load current is constant and ripple free. Therefore, source current became a square wave and we derived the total harmonic distortion and we found that this value is of the order of 48%.

So remember, the output voltage in a in a half bridge inverter, voltage source inverter has 48% harmonic content. We also found that output the frequency of the output voltage can be varied by varying the on time of each device. So, as of now, we found a way to vary the frequency of the output voltage. You keep you keep the device on for say, 10 milliseconds, 1 device. So, total period becomes 20 milliseconds. So, I have a 50 hertz supply. So, we know how to vary the frequency of the output voltage waveform. So, far we have not discussed discussed as to how to vary the magnitude of the output voltage. As of now, whatever is the input voltage in this case, though I have a V_{DC} by 2 and a V_{DC} by 2; in fact, the total is V_{DC}, I have a V_{DC} by 2 and a minus V_{DC} by 2.

In the last class we also found that just because a device is kept on for 10 milliseconds or T by 2 seconds, it does not mean that the device, the controllable device is carrying the current, no. It may so happen that the diode which is connected across the device may be conducting. So, we found that if this controllable device is a SCR, gate pulses should be present till the current through it is higher than the latching. So, you need to have a broad pulses if if the device, controllable device are SCR's.

Now, we will discuss the inverter feeding, half bridge inverter feeding, a purely inductive load. Please try to listen to me because this is a very important feature of a voltage source inverter. This feature is extensively used in in power factor correction. May be, after discussing this I will go back to AC to DC converter. We had already discussed that that power circuit configuration. So, try to understand this principle.

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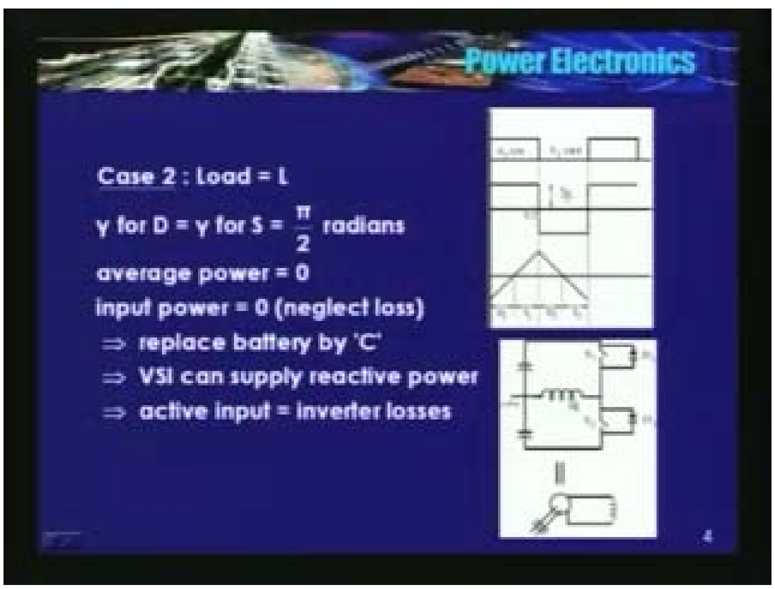

Same circuit configuration; I have connected an ideal inductor here, we have V_{DC} by 2, V_{DC} by 2, 2 switches - S_1 is on for T by 2 period and it is off for another T by 2 period, S_1 and S_2 are complementary. So, voltage across the inductor is V_{DC} by 2 and minus V_{DC} by 2. So therefore, from 0 to T by 2, voltage applied to the inductor is constant and is equal to V_{DC} by 2. Therefore, current in the inductor increases linearly, L di by dt is equal to V. Since, V is constant, I increases linearly.

So, at steady state at steady state you will find that this period or period for which D_1 conducts is T by 4 cycles. See, in the in the positive half, current increases linearly and in negative half, current should decrease linearly. Now, average power, average input power should be 0 because I have an ideal inductor ideal inductor and I have considered or I have assumed that devices are also ideal; remember, devices are ideal, inductor is ideal.

So, power transferred from the source to the inductor, average power average power should be 0. Average power transferred to the inductor should be 0. Average this is the input voltage, this is the current, so upper half area, this area should be equal to this area. So, if this is T by 2, this should be T by 4 - T by 4, T by 4, T by 4, T by 4 at steady state. It should be symmetrical.

So, what you can infer? Average power supplied to this load is 0. If the devices are ideal, input power to this inverter feeding in a purely inductive load is 0. I will repeat; I have assumed ideal inductor, inverter devices are ideal. Ideal inductor, average power input is 0. Ideal devices, there are no switching losses or inverter efficiency is 100%. Therefore, input power to the inverter is 0, average input power is 0. So, if the input average power is 0, I can remove the input batteries, remember, I can remove the input batteries and I can connect 2 capacitors.

Why 2 capacitors? Because each 2 capacitors each of V_{DC} by 2 and V_{DC} by 2. Because, at steady state, average power transferred by this capacitor is going to be 0. So, I need to charge this capacitor only once and I will connect it the, connect it to this inverter. For sometime, see during this period, see, voltage is positive, current is negative. Therefore, power transferred to the load is negative.

In other words, load is supplying power back to the source. See here, voltage positive, current negative, power input to the load is negative. So, what does it mean? Load is supplying power back to the source. So, in this region, source is charging and in this region; see, voltage positive, current positive. So, power input is positive. So, source is discharging. Again, source is charging and source is discharging in this period. So, you can replace these 2 batteries by capacitors. You charge the capacitor once and forget about it.

Of course, this is an ideal case. If I take the non idealities into account - what are the non idealities? Inductor having a small resistance - and the device losses which are again very small, the source has to supply a very small amount of active power a very small amount of active power. That power is dissipated as heat in the resistor, in the inductor and some is dissipated as heat in switching losses, inverter losses.

So, if the inverter is loaded, fully loaded by an inductive load, the active power input to this inverter is very small very small. This active power is used to overcome the losses in the inverter and I square losses that are taking place in an inductor. So remember, if the inverter is fully loaded by a purely inductive load, the input active power is very small very small.

See, this is almost same as almost same as a generator supplying a purely inductive load a generator supplying a purely inductive load. What is the active power transfer to the load? It is approximately 0. So, if I neglect the generator loses, I square R winding loses or something, what do I need to do? I have to just rotate the rotor in the magnetic field, that is all and this input is approximately 0. I have to just rotate the conductor or I have to just rotate the rotor in that magnetic field. Input is practically 0 or turbine input is 0 because active power transferred to the load is 0. So, input is output plus losses. If I neglect the losses, input is also 0. But then but then there has to be are there is current flowing in the load, so there has to be voltage induced. I have to rotate or the rotor has to be rotated in that magnetic field that is all. Active power input is practically 0, almost the same.

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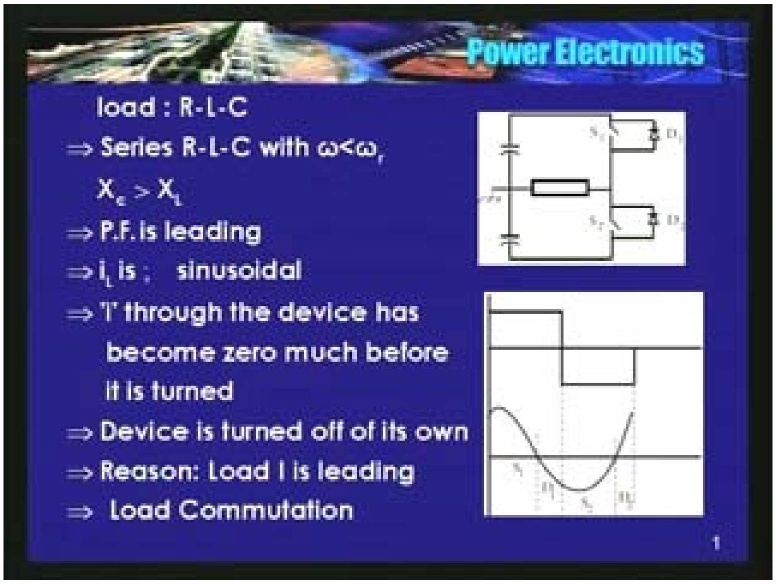

So, what is the third case? Third case is a RLC load, inverter feeding a RLC load or the frequency of operation or the frequency of supply applied to this load is less than the resonant frequency. Remember, in a series RLC, the frequency of the voltage applied to the RLC circuit is less than the resonant frequency. Power factor of the circuit is leading power factor of the circuit is leading because magnitude of X_C is higher than magnitude of X_L.

So, in a series RLC RLC circuit with X_C higher than X_L, current flowing through a load could be a damped sine wave current flowing through a load could be a damped sine wave as shown in this figure. So, at steady state you may have a current flowing in this fashion. Now, just see what happens here. Device is or S_1 is turned on for T by 2 radians. Current is leading, so current has become 0. See here, current has become 0 at this point and after that S_1 is turned off. See, S_1 is turned off at this point or gate signal to S_1 is withdrawn at this point and S_2 is turned on.

Since, the power factor is leading, current has already become 0 much before the voltage has reversed its polarities. So, positive voltage, positive current, positive voltage, positive current, so S_1; the controllable switch is carrying the current. See, positive voltage, negative current in this region, positive voltage, negative current. It can it can happen only when D_1 is carrying the current. It can happen only when D_1 is the D_1 is carrying current. This is D_1; positive voltage, negative current.

Similarly here, negative voltage, negative current from this point to this point. Current is being carried or flowing through or current is flowing through this controllable switch S_2. Negative voltage, positive current, negative voltage, positive current, current is flowing through D_2 D_2. This should be D_2 this should be D_2, this should be D_1.

So, see the difference here; S_1 conducts first, afterwards the diode connected across it starts conducting, then S_2 starts conducting, the diode connected across it starts conducting, just the opposite. If the load is inductive, see here, D_1 starts conducting first, then switch 1 S_1; D_2 started conducting first, S_2 starts conducting later. So what is the advantage of this sort of a system - an inverter feeding, a leading load or inverter feeding a load with leading power factor?

See, I observed; much before the device is turned off, I remember, much before the voltage has reversed the polarities, current through the controllable switch has become 0 and it has started flowing through its anti parallel diode. Remember, the device has turned off of its own. Gate signal may be present gate signal may be present but then current is not flowing through it. It has it was flowing, it became 0 and it has started flowing through anti parallel direction.

In other words, device has turned off of its own. Why? That is because of load is a load power factor is leading. So, this sort of a turn off process is known as load commutation. I will repeat; load commutation, why? Load current has become 0 much before voltage has changed its polarity. In other words, the controllable switch has or the current through the controllable switch as become 0 much before the gate signal has withdrawn. So, this is known as the load commutation.

So therefore, if the inverter devices are SCR's, what will happen in this case? Before discussing this, if the inverter devices are SCR and if it is feeding a feeding a inductive load, what will happen? See, we all know SCR can be turned on using a gate. But then SCR cannot be turned off using a gate signal. If I withdraw a gate signal after the current is higher in the latching, SCR will not turn off. I can turn off the SCR only by reducing the current flowing through it to a low value which is less than the holding current. In other words, current through the device should be less than the holding. How do we do in AC to DC converter? See, see here, I will just recall.

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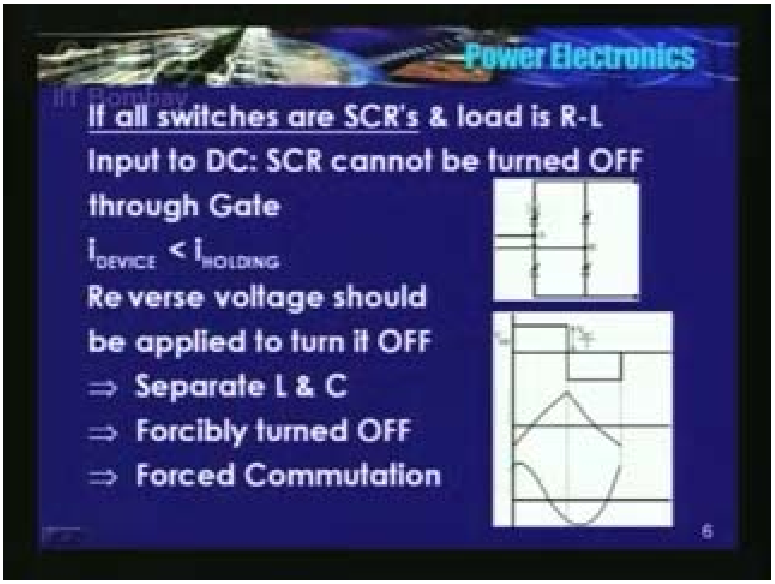

See a fully controlled bridge. In the positive half, at alpha we triggered T_1 T_2. In the negative half, T_3 T_4 were triggered. So, in the negative half, potential of B is higher than potential of A. So, when T_3 is triggered, the input voltage appears across T_1, in the reverse fashion. See, B gets connected here. So, a negative input voltage appears across the thyristor and thyristor turns off. What did we call this process, turn off process? We called it as line commutation. Why did we call line commutation? Line voltage is used to turn off the thyristor.

The previous case; load power factor is leading, current has become 0, so SCR has turned off of its own SCR has turned off its own. That sort of turn off process is known as load commutation. Now, what if the load is lagging, a RL load? See here, the waveform; voltage waveform, current, See, at this point, it is desired to turn off the upper thyristor and turn on the lower thyristor. At this instance you find that current is, of course, this magnitude of current is determined by the load, a positive current is flowing through the load. In other words, this current is being carried or is flowing through this thyristor.

Then, how do I turn off the thyristor? Unless until I turn off the upper thyristor, I cannot turn on the lower thyristor; but current is significant large current is flowing through the SCR, it cannot turn off its own. What should I do? See here, I have to turn off the conducting thyristor and I have to turn on the lower thyristor. It does not matter; the even if I turn on the lower thyristor, current may not flow through it. But then diode starts if the diode connected across it starts carrying the current, fine, fair enough. But then I have to turn off the conducting thyristor at this point. Current is finite, how do I do?

You can do or thyristor can be turned off by applying a reverse voltage across it. Somehow, we have to apply a reverse voltage across the thyristor. Somehow, a reverse voltage has to be applied across the thyristor, externally. This generally is done using a separate L and C circuit. I repeat; somehow a separate voltage has to be applied across the conducting thyristor in the reverse direction or you have to reverse bias the thyristor for sometime by applying a reverse voltage. How to do?

Generally, it is done using separate L and C circuit. So, this sort of a turn off process is known as forced commutation. Why forced commutation? We are forcibly turning off the thyristor by applying a separate voltage across it. Hence the name, forced commutation. So, we have studied line commutation, load commutation and forced commutation.

In a forced commutated inverter, apart from the devices; device in the sense, controllable switch as well as freewheeling diode, there are additional L and C elements are required. This additional L and C elements are used to turn off the thyristor forcibly. Therefore, the size of the inverter, for all inverter becomes really big. The inverter is bulky and it is noisy also because of L and C elements.

Therefore, the present day inverters, they do not use thyristors. So, most of the inverters, they use self commutating device self commutating devices and in case, thyristors are used in the inverter; they should be fast enough. In other words, inverter grade thyristors are required because reason is simple, the same thing because input impedance is practically 0. For a shoot through fault, you have to in order to protect the inverter against shoot through faults, device should be fast enough.

So, there are 2 types of SCR's. One is the converter grade SCR and another one is inverter grade SCR. So, in a VSI, incase thyristors are to be used; so, one has to be going for inverter grade SCR's. Invariably, these inverters are on their way out. They are almost all the inverters are with self commutating devices. Having said that: so, there is an exception.

I told you if the load power factor is leading, you do not require separate L and C. The thyristor turns off its own. See, while covering the devices; I have told you that thyristor are bit rugged, more rugged compared to other controllable devices. Thyristor is more rugged compare to IGBT, BJT or other devices. Or the cost of thyristor of the same voltage and current rating is much less compared to the other self commutating devices.

The problem with SCR is that I cannot turn it off using gate. But here is a load, wherein the power factor is leading. So, I do not require additional L and C to turn it off. If that is the case, using thyristors, it is a really an attractive proposition. See, I will repeat; if the load power factor is leading, you do not require additional L and C. I require just the thyristors and along with the anti parallel diodes, may be. This inverter is really attractive compared to other inverters or its counterpart. But then you require a load the leading power factor. So, which load has a leading power factor?

Recall your machines theory or whatever that you have studied in machines course. You have been told that synchronous machine or synchronous motor; if you are over excite it, power factor becomes leading. Therefore, an over excited synchronous motor which is being fed from a thyristor inverter is very attractive is very attractive. It is still, may be being used. This combination is called as or known as load commutated inverter fed synchronous motor. I will repeat; load commutated inverter fed synchronous motor.

The inverter configuration is really simple; only 6 switches 6 switches, very rugged and cost is less. I said load is a synchronous motor. Our teacher who taught machines has told that synchronous machines are invariably used in high power applications high power applications. So, as the power rating increases, the cost of semi conduct devices, the cost of self commutating devices also increases. So, if I can use SCR, nothing like it nothing like it. So, that is the reason, load commutated inverter fed synchronous motor is still being used still being used and load commutated inverter using SCR's is very attractive. I do not think I do not think, the inverter with other devices can compete with load commutated inverter using the SCR's.

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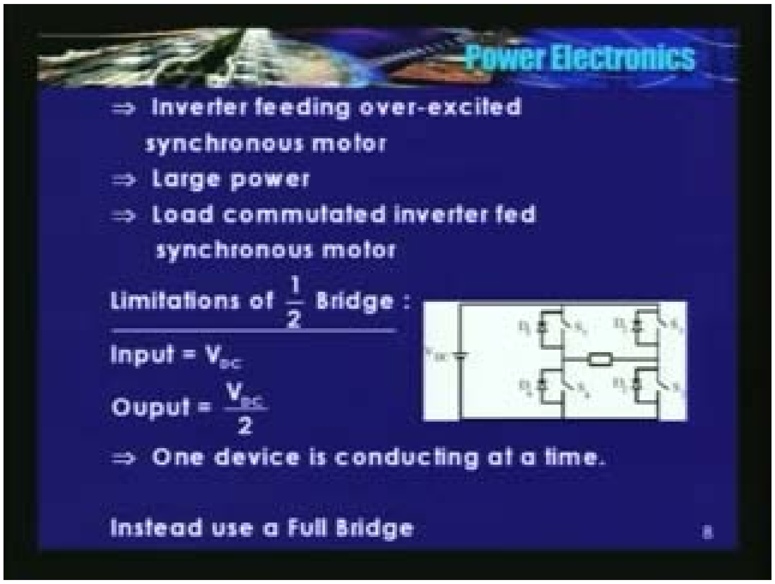

Now, let us continue, what is the limitation of half bridge inverter? Now, forget about the load. Input, I had V_{DC} but then output I have a square wave of half V_{DC} by half V_{DC}. Only one device is conducting at a time. So, if there is a half bridge, there has to be a full bridge. So, here is a configuration; so, 4 devices along with the freewheeling diodes, the load is connected between these 3 devices, see here, and the input V_{DC}. See, I do not require or the center point of the DC bus is not required. Center point of DC is not required, the center point is not required. How does it work?

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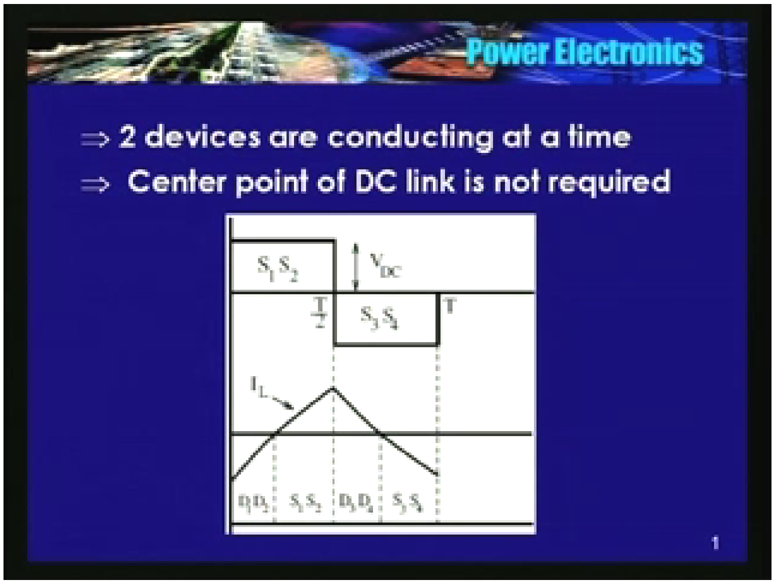

2 devices are conducting at a time; see in this, S_1 and S_2 are turned on. What happens? V_{DC}, S_1, load, S_2, back here. V_{DC}, S_1, load, S_2, back here. Voltage applied to the load is V_{DC}. After sometime or T by 2 seconds, open S_1 and S_2, close S_3 S_4: V_{DC}, S_3, load, S_4, back. So, minus V_{DC} is being applied to the load. So, S_1S_2, S_3S_4; T by 2, T or pi by pi radians and this is 2 pi, pi n 2 pi radians. Voltage is positive, current is negative because I have assumed a RL load RL load.

At steady state, you have a current waveform something like this, current wave form something like this - positive voltage, negative current. So, in this circuit if you see, positive voltage can happen only when this point is connected here and this point is connected here. Negative current, current is flowing back to the source. So, it can happen only when D_2 and D_1 are conducting it can happen only when D_2 D_1 are conducting.

So see here, in this region positive voltage, negative current, D_1 and D_2 are conducting: positive voltage, positive current, S_1 S_2 and so on. So, principle of operation of half bridge and full bridge is almost the same; except in full bridge, 2 devices are conducting at a time, voltage applied is V_{DC}. I have input is also V_{DC}, output also V_{DC}. So, this is about the single phase inverter.

I have not discussed so far, how to as to how to vary the output voltage? We will see sometime later. Now, we will see or discuss the operation of 3 phase inverter. I said 3 phase inverter; so, you require 3 phase voltages – A, B, C, 3 phase voltages.

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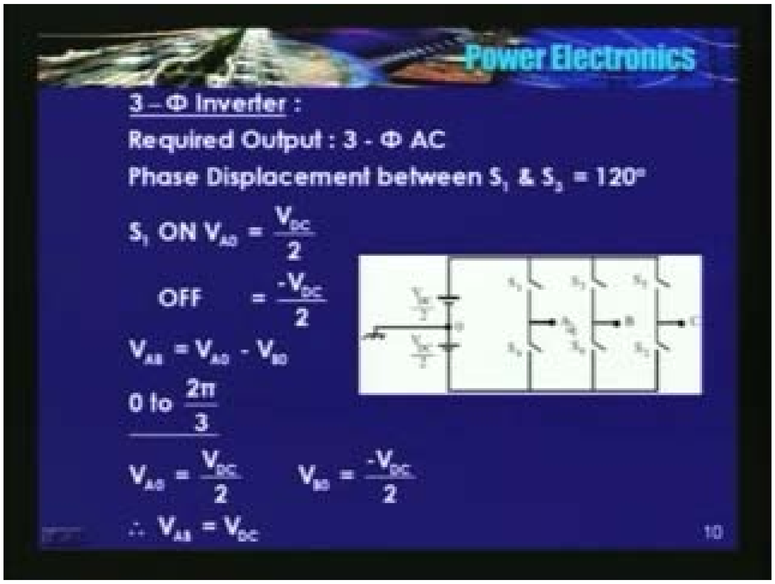

They should have a phase displacement of 120 degrees. So, what I have done here? I have used 3 half bridges. That is the reason I called you, half bridge as a basic block. In an H bridge or full bridge; there are 2 legs, here there are 3 legs. As of now, listen to me, as of now, I have used the center point of the DC link. Look at this; I have taken this as the reference. After sometime we will find that this is not required. You can take the negative bus as the reference.

I will repeat; you can take negative bus as the reference. For convenience I have taken this as a reference point. Operation is the same: for T by 2 period, S_1 is closed and for the remaining T by 2 S_4 is closed. So, when will you close S_3? S_3 is closed after 120 degrees closing S_1 because phase displacement between them should be 120 and again 120 here.

When S_1 is on, voltage potential of A with respect to O is V_{DC} by 2. When S_1 is on, V_{A0} when S_1 is on V_{A0} is V_{DC} by 2 and when S_1 is off, I am just saying S_1 is off, that does not it implies that S_4 is on, V_{A0} is minus V_{DC} by 2. Similarly I have V_{BO} and you can have V_{CO}. But then now, I am more interested in line to line voltages. What is V_{AB} or what is V_{BC}? V_{AB} is nothing but V_{A0} minus V_{B0}, V_{AB} is V_{A0} minus V_{B0}. Remember this expression. I will show you the waveforms here.

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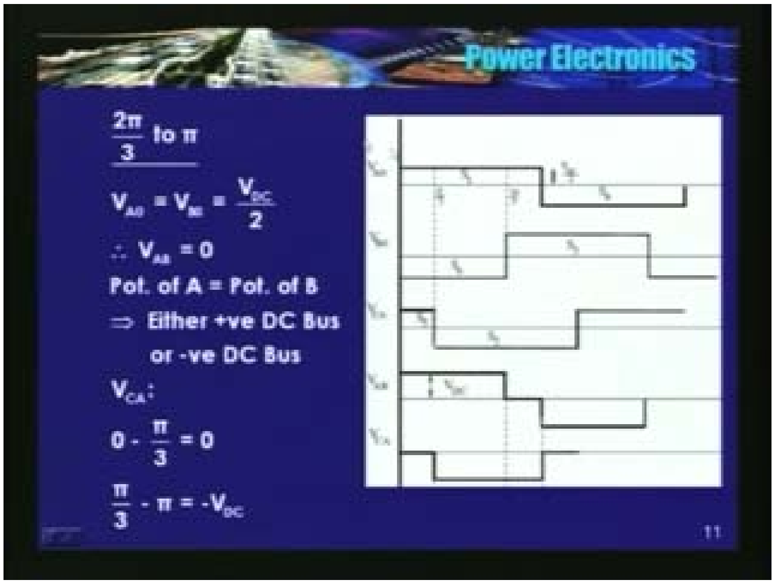

See here, V_{A0} for pi radians is V_{DC} by 2. For the remaining pi radians, it is another V_{DC} by 2. S_1 on, S_4 on; after 2 pi by 3 radians, S_3 is turned on S_3 is turned on. See, this is 120 degrees, so S_3 is turned on here. So, if S_3 becomes on here, S_6 should become off because S_3 and S_6 are complementary. So, if this is the on period of S_3, it implies that this should be off period for S_3. So, in this period, S_6 is on.

So similarly, V_{C0} is S_5 is on, 0 to pi by 3 radians and S_2 is on here, in this zone. Now, what is V_{AG} V_{AB}? V_{AB} is V_{A0} minus V_{B0}. So, from 0 to 2 pi by 3, V_{A0} is V_{DC} by 2, V_{B0} is minus V_{DC} by 2. So, therefore V_{AB} is V_{DC}, remember. V_{A0} minus V_{B0} but V_{B0} itself is negative, so V_{A0} is V_{DC}. From 2 pi by 3 to pi radians, both V_{A0} and V_{B0} are positive so and they are equal. So, V_{A0} minus V_{B0} is 0. So, from 2 pi by 3 to pi, it is 0 and of course, this is a negative half with V_{DC}.

What happens to V_{CA}? V_{CA} is nothing but V_{A0} minus V_{C0}. From 0 to pi by 3, V_{A0} and V_{C0} are positive. Magnitude is the same, so, V_{CA} is negative and from pi by 3 to pi, V_{CA} is V_{DC}, minus V_{DC}. So, I have drawn line voltages of V_{AB} and V_{CA}.

Similarly, we can draw V_{BC} also, same philosophy. In my next class we will consider various loads, 3 phase inverter feeding at delta connected load and a star connected load. We will draw the current waveforms and we will see what are the limitations of this inverter? In the sense, wherein, wherein, each device is conducting for 180 degrees or pi radians. So, I will stop here.

Thank you.