Power Electronics

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Lecture - 36

In my last class we discussed a voltage source inverter feeding various types of loads and we found that if the load power factor is lagging, self commutating devices should be used as the switching elements in the inverter. Self self commutating devices such as MOSFETs, BJT, IGBT or GTO; these are the devices which can be turned off using gate and in case, SCRs are used as switching elements, a separate forced commutating circuitry is required to turn off the conducting thyristor.

I told you that this forced commutating circuitry is nothing but a separate LC circuit. Hence, an inverter made up of thyristors or SCRs becomes a bit bulky. Hence, they are not very popular, whereas, if the load power factor is leading, SCRs can be used as switching elements. In fact, if the load power factor is leading, inverter with the SCRs is very attractive because SCRs are bit rugged, cheap compared to the other devices.

Another observation that we made was if an ideal inverter feeding an ideal inductor, the input source or input voltage source can be a capacitor which is charged to a required value. For part of the cycle, this SCR, this capacitor charger charges or load is supplying back the energy to the capacitor and for some part of the cycle, the capacitor supplies power to the load and over the cycle, the average voltage remains the same.

And in case, if I take the non idealities into account, non idealities of the inverter as well as as well as the inductor; the power input, the real power input to this inverter is very small compared to the output KVAR. Remember the real power input is very small compared to the output KVAR. This real power input is used to overcome the device losses and I square losses that are taking place in the inductor.

By the way, we had used this equipment. In the sense, a bidirectional or converters are using bidirectional devices and a capacitor at the output. We had used it for power factor improvement. See, recall, I have redrawn the circuit here.

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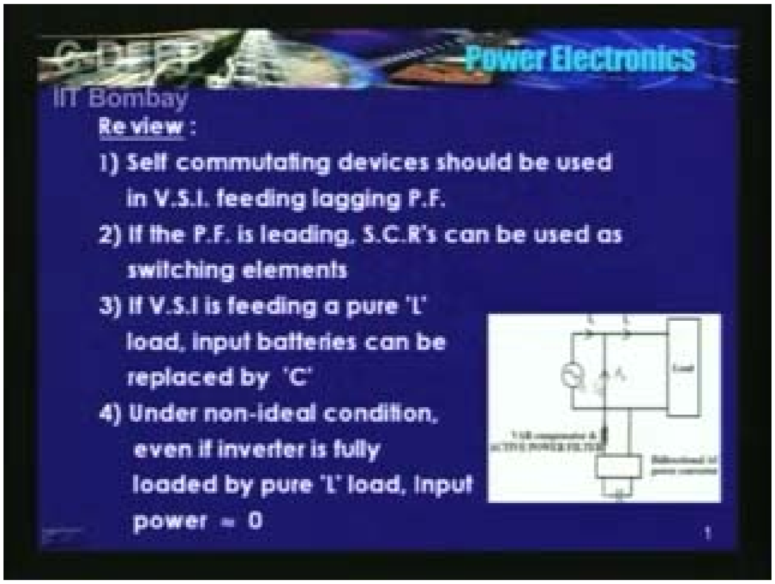

See, here is the circuit; source feeding a lagging load. So, this unit is made up of bidirectional power devices and a capacitor is connected at the output. This is nothing but a voltage source inverter this is a voltage source inverter. I can assume that this input, this is an input and here is the output.

See, in fact, we have derived an equivalent circuit. 2 voltage sources are interconnected by an inductor and we and I wrote the expression for the power transfer that is V_1 V_2 divided by X_S into sine delta. So, when and I told that this voltage at this point is AC, is pulse width modulated waveform.

So, this is again I will repeat, this is a voltage source inverter to the capacitor as the input and the output is available at this point. The real power transferred by the source to this inverter; it is very small, just to overcome the inverter losses and I square R of the inductor and I also told you that this unit can supply both leading as well as lagging current by controlling the magnitude of this voltage, magnitude of the output voltage of this inverter - voltage source inverter. These are very important equipments.

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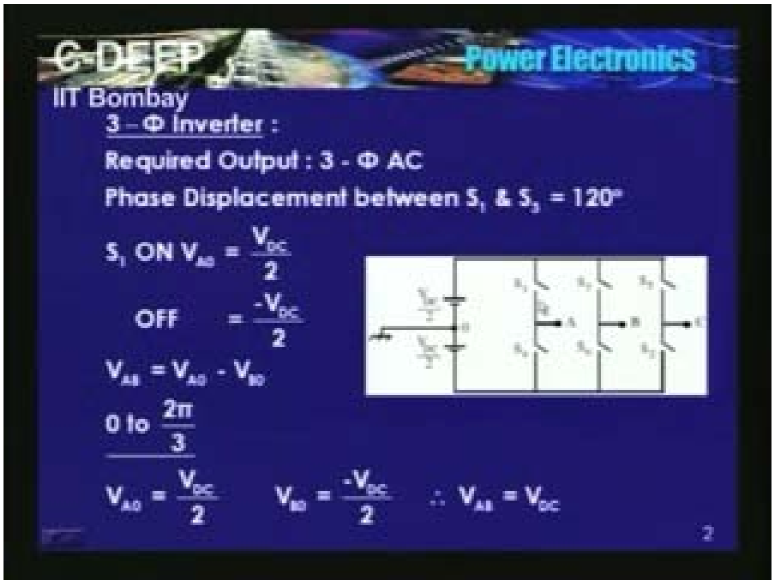

In the last class we had started discussing a 3 phase inverters which has 3 legs or 6 devices. See, here is that. We had taken the centre point of the DC link as the reference point. Sometime later we will find that this not required, remember. We can take the negative DC bus as the reference point.

See, I have shown the switching elements as S_1, S_3, S_5, S_4, S_6 and S_2. I have not shown an anti parallel diode across the switch. So, in any VSI, S_1 implies a controllable device and an anti parallel diode connected across it. I had told you that the switching signals for S_1 and S_4 are complimentary.

Similarly, S_3S_6, S_5S_2; whereas, switching signals for S_1 and S_3, they are displaced by 120 degrees. When these switches are on, the voltage of potential A sorry sorry when these switches are on, potential of A, B and C with respect to O is known. Therefore these voltages, in the sense, V_{A0} V_{B0} V_{C0} are known as pole voltages. I will repeat; V_{A0}, V_{B0}, V_{C0} are pole voltages. The waveform of pole voltages is a square wave of 180 degree duration.

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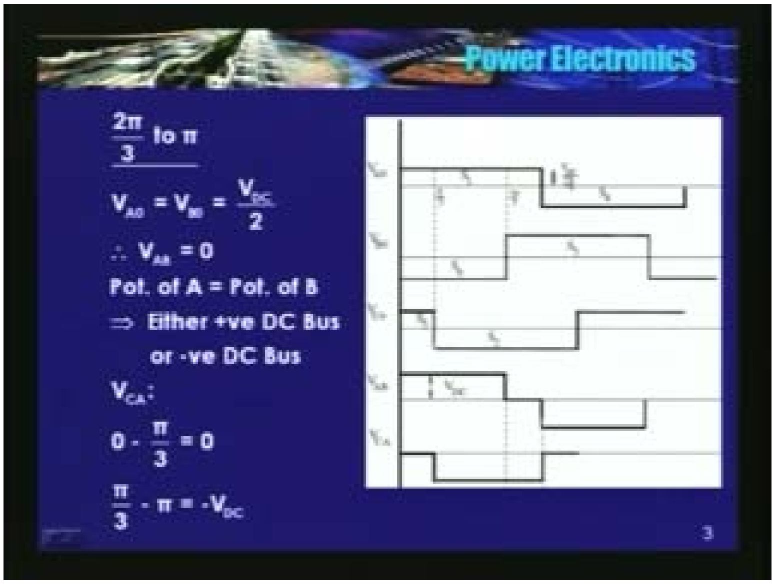

See, V_{A0}, V_{B0}, V_{C0}; all are square waves of V_{DC} by 2 because voltage we have drawn with respect to the centre point of the DC link, whereas, magnitude of line to line voltage V_{AB} or V_{CA} or V_{BC} is the full DC link voltage. I will repeat; magnitude of magnitude of the line to line voltage is equal to the magnitude of the DC link. But the waveform is or in each half cycle, the magnitude is V_{DC} for only 120 degrees. For remaining 60 degrees, it is 0.

See here, V_{AB} is is magnitude of V_{AB} is V_{DC} from 0 to 2 pi by 3 and from 2 pi by 3 to pi radians, V_{AB} is 0. What does it indicate? It indicates that potential of A is equal to potential of B. So, if you see in this figure, I said potential of A is same as potential of B; so, this both the points could be connected to either the positive DC bus or to the negative DC bus.

See, when S_1 and S_3 are on, both S_1 and S_3 are on, V_{AB} is 0. Similarly, when S_4 and S_6 are on, V_{AB} is again 0 because this point gets connected to the negative DC bus, again B also gets connected to the negative DC bus. But then which device is conducting? Whether the controllable switch is carrying the current or the anti parallel diode is carrying the current? That we will see while drawing the current waveform.

See, how do I draw the current waveform? Now, I will assume the load is delta connected, wherein the phase voltage is same as the line voltage. So, if I know the line voltage and if I know the nature of load, it is possible to draw the phase current, remember. So, phase current in a delta connected load is phase voltage divided by the impedance of that branch.

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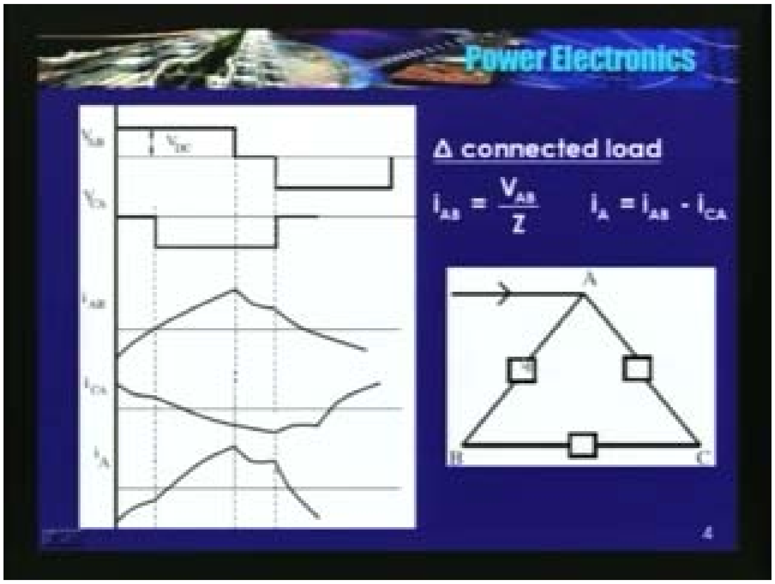

I will assume load to be inductive, RL circuit. So, i_{AB} is V_{AB} divided by Z. Current flowing from A to B, I will repeat; current flowing from A to B is V_{AB} divided by Z. So, at steady state, a positive voltage is applied from 0 to 2 pi by 3. So, current increases. If it was negative, initially, it becomes positive and at 2 pi by 3, B S_3 is turned on. So therefore, V_{AB} becomes 0.

So, for an RL circuit, wherein say, some current is flowing, now voltage is made 0, input voltage is made 0. Therefore, current decays slowly. Voltage is 0, current is positive, so which of the devices are carrying current?

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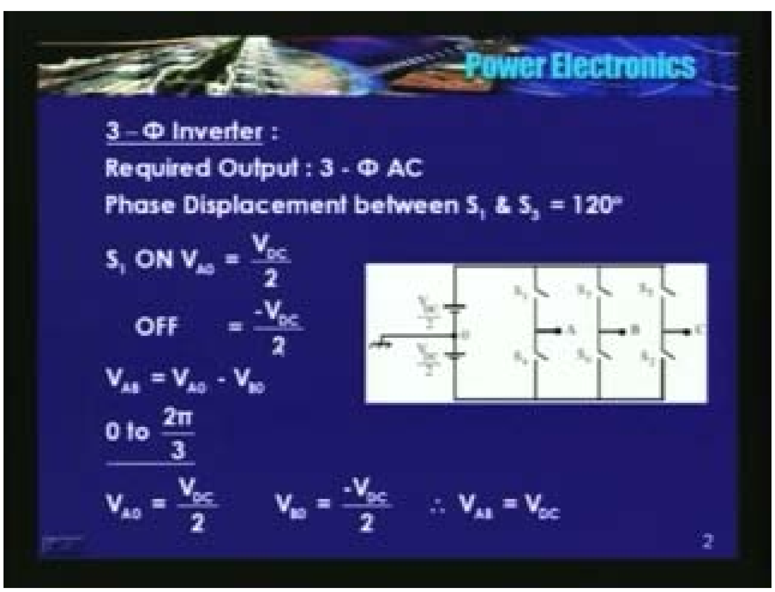

We will go back to the previous circuit; voltage applied is 0, current is positive, current is flowing from A to B. So, current is flowing in this fashion; A, through the load B and back here. So, the controllable switch in S_1 and the freewheeling diode of S_3 are carrying current. See here, current i_{AB} is positive because S_1 and S_3 are turned on, they are conducting. Current is positive, current is flowing from A to B. So, S_1 at the switch, controllable switch, A to B through the load and back. It has to flow in this fashion. So, it is flowing though the anti parallel diode of S_3.

So, knowing the voltage waveform or knowing the switches which are on and the polarities of the current or sorry the sin of the current, if I know the sin of the current; it is possible to determine the devices which are carrying the current. So similarly, from pi to another 120 degrees, current has become negative because a negative voltage is applied. So, this is about i_{AB}.

In delta connected load, in order to draw the line current waveform, I need to know the phase current waveforms of 2 phases or to draw the line current waveform that is flowing through the line A, I need to know i_{AB} and I need to know i_{CA} i_{CA}. Now, i_{CA} I can draw if I know V_{CA} and Z.

See, this is V_{CA} waveform. On the similar lines, I have drawn i_{CA} current waveform. V_{CA} is 0, current decays, V_{CA} is negative, current becomes negative and again become 0, decays, becomes ... Now i_A, I can determine by applying KCL at this point. So, I will get the waveform something like this. I need to just add these 2 waveforms, it is easy.

What observation can I make from this line current waveform? We can see that there are 6 steps in a cycle there are 6 steps in a cycle. I told you that pole voltages V_{A0} V_{B0} V_{C0} are of 180 degree duration and it is an odd function. What is a harmonic spectrum? Harmonic spectrum, it has all odd harmonics.

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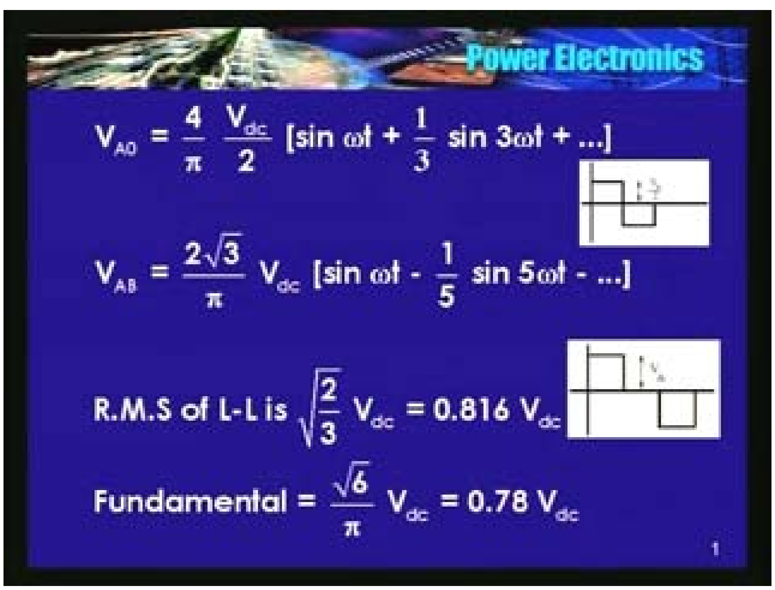

It is given by this expression; see, see 4 by pi V_D by pi is the magnitude, sin omega T 1 plus 1 over 3 is sin 3 omega T so on. Whereas, the line to line voltage waveform has a 0 voltage period for 60 degrees, I will repeat; a line to line voltage waveform has a 0 voltage period of 60 degree duration. So, if I write the Fourier series to this wave form, it looks something like this it looks something like this.

How do I write? One way is I will write V_{A0}. I have written V_{A0} here. Similarly, I will write V_{B0} and I will add V_{A0} minus V_{B0} is V_{AB} or write a Fourier series for this waveform, simple. What observation that we can make from this from these 2 expressions? The pole voltages have all odd harmonics, whereas, line to line voltage waveforms have only 6 and plus or minus 1 harmonics. It has a fundamental and has all 6 and plus or minus 1 harmonics. In other words, fifth, seventh, eleventh, thirteenth so on.

What is the RMS value of the line to line voltage wave form? What is the RMS value? See, it is a square wave for 120 degree duration and for for remaining 60 degrees, it is 0 in the positive half. So, RMS value of this is nothing but square root of 2 pi 3 into the magnitude V_{DC} V_{DC} this should be V_{DC} and what is the fundamental component of this waveform?

See, this is the expression for V_{AB}. So, fundamental component is this component; sin omega T component. So, 2 into root 3 by pi into V_D is the peak of the fundamental component. It is the peak of the fundamental component. So, RMS value of the fundamental component is root 6 by pi. See, 2 root 3 by pi into V_D is the peak of the fundamental peak of the fundamental. RMS value is divided by root 2. So, 0.78 times the DC link voltage V_{DC}.

If I call input voltage as V_{DC}, so it should be V_{DC}. So, this is about a 3 phase inverter which is conducting for 180 degrees. In other words, each device in each leg conducts for 180 degrees, remember. I will repeat; each device in each leg conducts for 180 degrees feeding a delta connected load.

Now, we will replace this delta connected load by a star connected load. For a delta connected load, we need to know the line to line voltage and from there onwards, I can draw the phase current. So, if the current flowing through 2 phases are known, I can determine the line current, whereas, in star connected load, I need to know the phase voltage waveform.

How do I determine the phase voltage waveform for a star connected load? because, if when the inverter devices are on, only pole voltages are known. This pole voltages are nothing but the potential of A or B or C with respect to the center point of the DC link with respect to O or I can also say that when the devices are on, the potential of A, B and C with respect to the negative DC bus is known. But then, how do I get the potential of A, B and C with respect to its neutral N?

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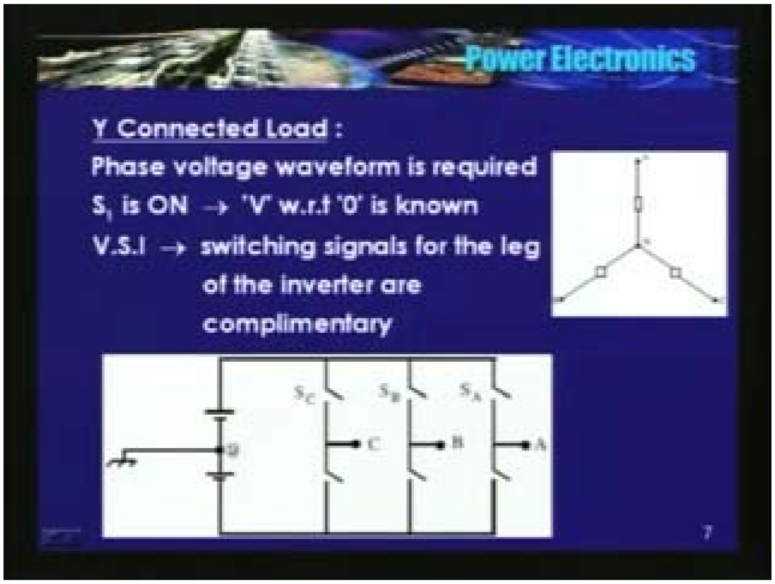

See in this circuit, these are 2 different points. I may be knowing the potential of these points with respect to O or the negative DC bus. But to draw the phase current, I need to know V_{AN} or B_N or C_N. See, this A, B, C are connected to these points. In fact, this point O and point N are open. So, if they are open, you can have any potential between them.

By the way, see, out here, I have drawn, I have mentioned as S_C S_B and S_A. In the previous circuit I have drawn 1 and 4, 3 and 6, 5 and 2. I have, I have I am naming them as S_A S_B S_C, just to determine the potential of A, B and C with respect to N.

See, in a VSI, I told you that the devices are conducting for 180 degrees. In other words, S_A is conducting for 180 degrees. S_A is complementary; the lower device is conducting for 180 degrees. So, at any given time, 1 device in each leg is conducting. I will repeat; at any given time, 1 device in each leg is conducting. So, at any given time, 3 devices are conducting. So, if I know the conducting state of S_A S_B and S_C, I know the conducting state of the remaining 3 switches because they are complementary. So, there are 3 switches which are to be monitored. I do not need to monitor all 6 because they are complementary.

Now, these 3 switches, each one of them can be either on or off. So, how many possible cases are there? I said the switching or the conducting state of either upper 3 switches or lower 3 switches should be known or should be monitored. So, there are 3 switches and each switch can be either on or off. So therefore, there are 8 possible cases 8 possible cases.

So, the binary value, it starts from 000. That means all 3 switches, the upper switches, S_A S_B S_C, I can say they are off. If those 3 are off, the lower 3 will be on to 111. All upper switches are on and lower switches are off. So therefore, from 000 to 111, there are 8 possible states and for each state, we will determine what is the phase voltage V_{AN} V_{BN} and V_{CN}?

I told you, you can have either 000 or 111. What happens when all 3 switches are off? All 3 upper switches are off, that means all 3 lower switches are on. If all 3 lower switches are on, point A, point B and point C, they are connected to the negative DC bus.

See in this circuit, all 3 switches are off. That means these 3 switches are on. If these 3 switches are on; point A is connected here, point B is connected here, point C is connected here. In other words, point A, B, C are at the same potential. So therefore, V_{AB} is equal to V_{BC} is equal to V_{CA} is equal to 0 is equal to 0.

So therefore, this vector 000 is known as a 0 voltage vector because when all upper switches are off, the lower 3 switches are on. At that time, the line to line voltages of all 3 is 0, of all 3 line to line voltages are 0. The whatever that the whatever the current that is flowing through the load freewheels freewheels through a negative DC bus.

Same thing happens when all 3 switches are on, S_A S_B S_C are on. The point A,B,C; now they are connected to the positive DC bus. Therefore, V_{AB} is equal to V_{BC} is equal to V_{CA} is equal to 0. Load freewheels through the positive DC bus. Freewheeling in the sense, whatever the current that was flowing, it continues to flow and path is completed through the positive bus only. Source does not supply any power because all 3 points are connected to this point. Then, what about the remaining 6 states? Let us see, what exactly is the voltage waveform for the remaining 6 vectors?

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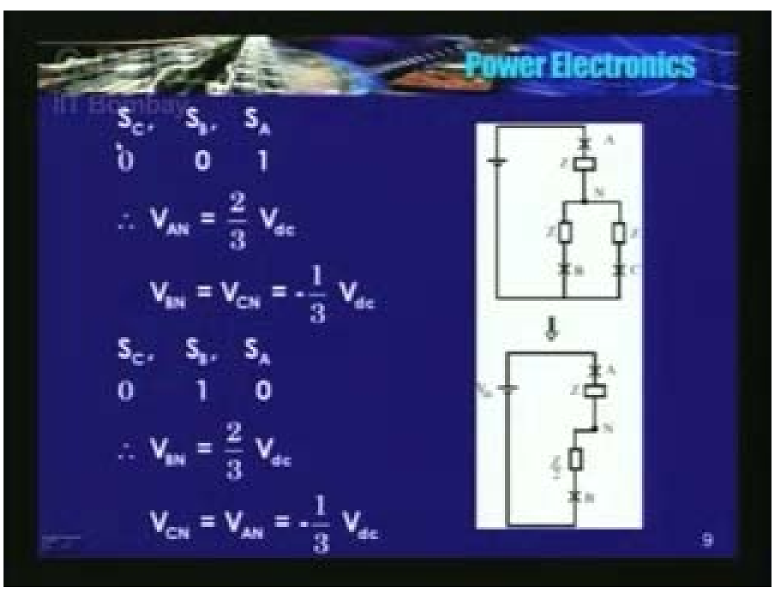

I will take S_A is on, that means upper device in phase A is on, S_B and S_C are 0. So, the vector is 001. So, A is on. So, when A is on, point A gets connected to the positive DC bus. See in this circuit; when this switch is on, point A gets connected to the positive DC bus and when the lower switches are on, B and C points are get connected to they get connected to the negative DC bus. So, this is the equivalent circuit; A to positive DC bus, B and C to negative DC bus and some impedance that is connected between the phase and the neutral ZZZ. I am taking a balance load, so this circuit can be simplified further, A and now B and C are in parallel, same load. So, I will write Z by 2 and this point could be either B or C. Voltage applied is V_{DC}.

So therefore, what is V_{AN}? How do I determine V_{AN}? See, V_{DC} is applied across 1.5 times Z. Z plus Z by 2, 1.5 Z. So, voltage across Z is 3 by 2 times V_{DC} 3 by 2 times V_{DC} and remaining 1 third times the voltage, 1 third times the DC link voltage appears across the load connected to B and C.

Now, point A is at higher potential than N. So, I am calling V_{AN} as positive 2 by 3 V_{DC}, whereas, B is at then B is connected to the negative DC bus. So, V_{BN} is negative V_{BN} is negative. So, V_{BN} is nothing but V_{CN}. See, V_{BN} is same as V_{CN}. So, that is equal to minus 1 third V_{DC}. So, we determine the phase voltages for S_C is equal to 0, S_B is equal to 0 and S_A is equal to 1. On the similar lines, I can determine the phase voltage for S_C is equal to 0, S_B is equal to 1 and S_A is equal to 0. In the sense, only 1 switch in the upper half is on and therefore the 2 half, the remaining 2 phases in the lower half are 1.

So, under this condition, the voltage of the phase in which the upper device is on is 2 by 3 V_{DC} and the phase voltages of the remaining 2 phases in which the lower devices are on is minus 1 third V_{DC}. See this, only S_B is 1, S_A is 0, S_C is also 0. So, we can find that V_{BN} is 2 by 3 V_{DC}. See, we had 001. V_{AN} is 2 by 3 V_{DC}. The voltages or phase voltages of V_N, V_{BN} and V_{CN} is minus 1 third V_{DC}. So here, V_{CN} and V_{AN} is minus 1 third V_{DC}.

Now, what happens to devices of the upper arm … ? See, something like this; S_A is 1, S_B is 1, S_C is equal to 0. So, that means A and B are connected to the positive DC bus and point C is connected to the negative DC bus. So, whatever that happened for 001, its complementary should happen for for 110.

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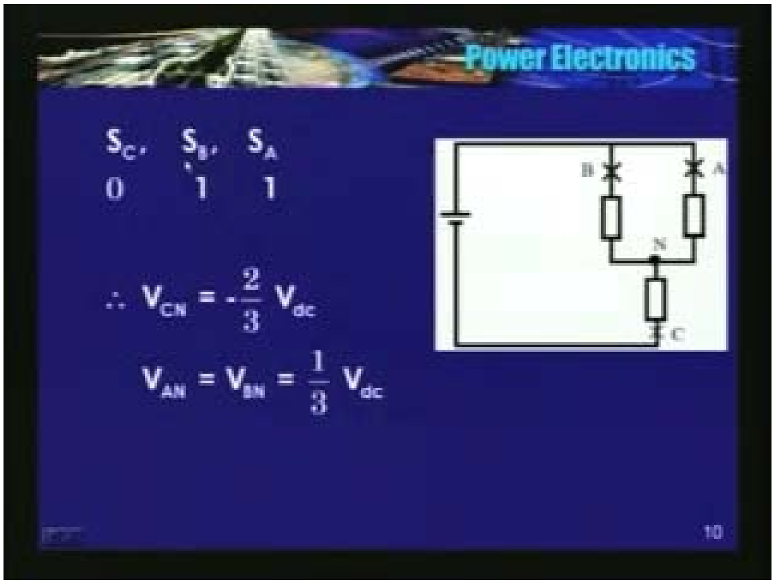

So, when phase, see in this, here; for 001, I have minus 1 third V_{DC}. Now, if I make the complementary of this, I should get just the opposite. See here, for S_A and S_B equal to 1, it will happen that V_{AN} and V_{BN} are 1 third V_{DC} 1 third V_{DC} 1 third V_{DC} and V_{CN} is minus 2 by 3 V_{DC}. So, now I know the phase voltages for each switch combination. Now, we will draw the phase voltage waveform for the entire cycle.

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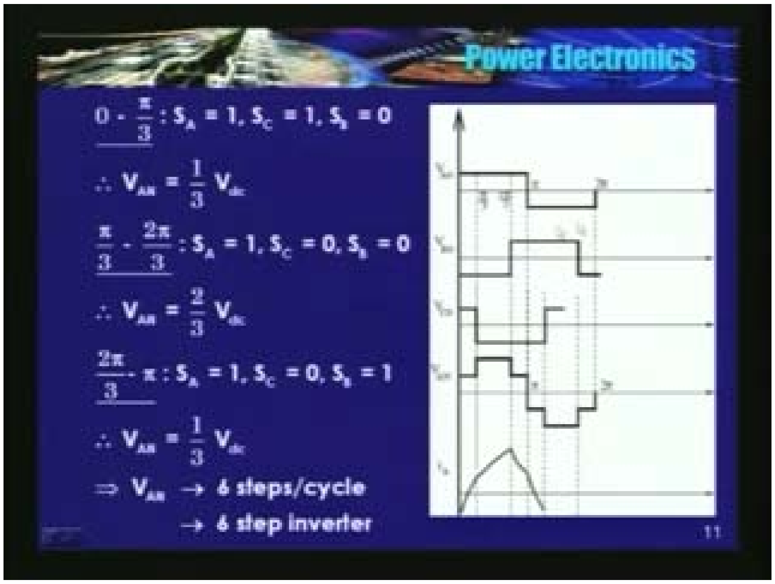

See here, V_{A0} V_{B0} V_{C0}. See, V_{A0} is on for if 0 to pi, V_{B0} becomes V_{DC} by 2 or S S_3 is turned on at 2 pi by 3. So prior to this, S_6 is on. Similarly for C phase. Now you see, from 0 to pi by 3, 0 to pi by 3; you have upper switch on in phase A, lower switch on in phase B, again, upper switch on in phase C. It is something like this; 101. So therefore, V_{AN}, V_{AN} is 1 third V_{DC}. See, we have 2 1s and 1 0, we have 2 1s and 1 0. See in this case, we have 2 1s and 1 0. So the phases which are 1 is 1 third V_{DC} and which are 0, it has minus 2 third V_{DC}. So therefore, V_{AN} is 1 third V_{DC} 1 third V_{DC}.

What happens from pi by 3 to 2? pi by 3, we have V_{A01} or V_{A0} is plus V_{DC} by 2 or S_A is equal to 1 S_A is equal to 1, S_B is equal to 0, S_C is equal to 0. We have something like this; 001. So, the phase voltage V_{AN} is 2 by 3 V_{DC} 2 by 3 V_{DC} and from 2 pi by 3 to pi, we have again 110. So, again phase voltage drops to 1 third V_{DC}. So, this is the positive half. So, we will have similarly in the negative half.

So, how many steps are here? Again, there are 6 steps in a cycle. So, a 3 phase inverter in which each device is conducting for 180 degrees and the load is delta connected. So, there are 6 steps in a cycle in the line current wave. The same inverter, feeding a star connected load, the phase voltage has 6 steps in a cycle. There are 6 steps in a cycle.

Now, following the same procedure that I used to determine the line current waveform; now, here line current is same as the phase current. It is V_{AN} divided by Z V_{AN} divided by Z, I will assume RL load, may be, at steady state you have something like this: increases from positive value sorry increases from negative value, becomes positive. Now, I am applying 2 by 3 $V_{DC.}$ So, rate of rise here is higher than rate of rise of current in this because voltage applied to the load is 1 third $V_{DC,}$ here is 2 third V_{DC}.

So, rate of rise is definitely is higher than that in this case. At this point, again, a 1 third V_{DC} is being applied. So definitely, I need to have a symmetric waveform. So, current decreases and so on. So, again there are 6 steps in that cycle, in a 6 steps in a cycle. So, 3 phase inverter in which each device conducting for pi radians is known as a 6 step inverter, remember.

What is a 6 step inverter? It is a voltage source inverter in which each device is conducting for 180 degrees each device is conducting for 180 degrees. So, if it is a load is a delta connected load, there are 6 steps in cycle in the line current waveform. If the load is a star connected, the phase voltage and the line current has 6 steps per cycle. Hence the name, 6 step inverter.

What is the limitation of a 6 step inverter? What is the harmonic spectrum or what is the predominant harmonics that are present in the 3 phase 3 wire systems? In a 3 phase 3 wire system, the line currents cannot have triple harmonics. I will repeat; in a 3 phase 3 wire system, the line currents cannot have triple harmonics. Therefore, the frequency spectrum is 6 N plus or minus 1 times the fundamental frequency. So, the frequency of the harmonic component that are present is 6 N plus or minus 1 times the fundamental frequency.

I said source is the variable voltage, variable frequency type. In other words, output voltage of the inverter should vary with frequency if the load is AC motor. I can control the frequency by controlling the on time of the device. Till now, I have not discussed as so how to vary this output voltage? I will discuss it after some time. But then the fact remains. That is the magnitude of the output voltage should change with the frequency.

Now, this frequency of the fundamental could be 1 hertz. Say, very low speed of operation. It could be 10 hertz or it could be say, 40 hertz. Of course, above the rated, the magnitude of the voltage will remain constant. So, when the fundamental frequency is 1 hertz, the frequency of the predominant harmonic is 5 hertz, 7 hertz, 11 hertz and 13 hertz. When the frequency of the fundamental is 10 hertz, the frequency of the predominant component is going to be 50 hertz, 70 hertz so on.

So therefore, listen to me carefully; since, the frequency of the fundamental component is itself is changing, the frequency of the predominant harmonic also changes. So, frequency of the predominant harmonic could be 5 hertz or 50 hertz or 250 hertz, depending upon the frequency of the fundamental and this frequency component have its own effect on the load. I am not going to discuss the effect of harmonics on the machine. So, this topic should be handled in drives. The fact is that you have to eliminate this or you have to filter this, the predominant harmonics.

To filter this predominant harmonics, 1 solution is to use a filter. So, when the frequency of the fundamental component is 1 hertz, I need to have a filter which blocks 5 hertz components and 7 hertz components. When the frequency of the predominant components is 10 hertz, I need to have another filter which blocks 50 hertz and 70 hertz and if the frequency of the fundamental components is 40 hertz, I need to have another filter which blocks 200 hertz and 280 hertz, 40 into 7 is 280 280.

So, is rather impossible to design a filter to filter out the predominant harmonics that are present in the line current when the frequency of the fundamental itself is changing. I will repeat; it is rather impossible to filter or it is rather impossible to design a filter which filters the predominant harmonic component that is present in the line current when the frequency of the fundamental itself is changed. So, that is 1 limitation.

Now, let me address another issue in a square wave inverter or a 6 step inverter as to how to control the output voltage? I said frequency can be varied by varying the on time of the device or the device for which or time time for which the device is on. I said if it is if upper device is on for 10 milliseconds, you have a 50 hertz supply. If it is on for 100 milliseconds, I have a 5 hertz supply. How do I vary the output voltage? How do I vary the output voltage? From the various waveforms we have observed that when the device is on, the input voltage appears across the load.

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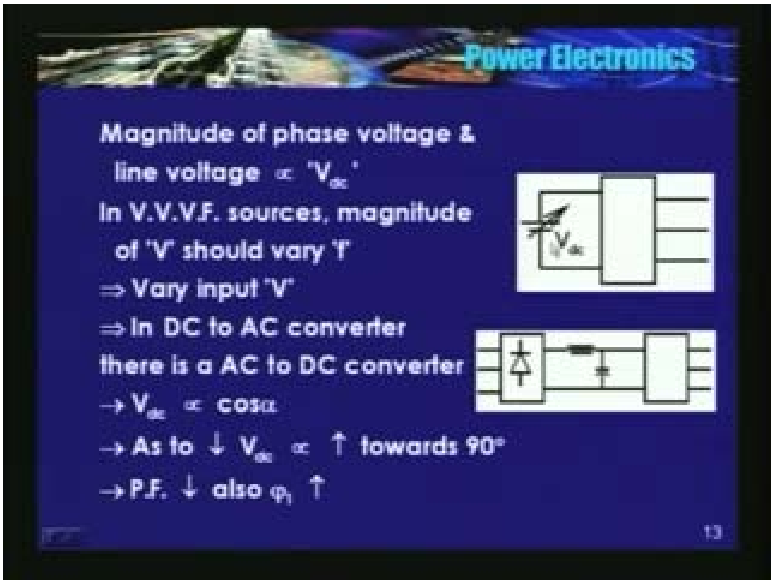

In other words, see the output voltage wave form here; the magnitude of the output voltage is proportional to the input voltage V_{DC} because line to line voltage wave waveform, the peak value is V_{DC} is constant for 2 pi by 3 radians. I can control the frequency. How do I control this magnitude? So, if I have to vary this magnitude of V_{AB}, I have to change the magnitude of V_{DC} itself. So, one has to change the magnitude of V_{DC}. How do I vary this magnitude of V_{DC}?

In my very first in my very first lecture in DC to AC converter, I told you that in an inverter there has to be a AC to DC converter because how do I get a DC power supply of from? Where to get this DC supply? So, the input DC is generally obtained from rectifying the input AC, an inverter or I need to store in a battery. Again that battery has to be charged from AC supply itself. So, assuming that there is an AC to DC converter, the output of the AC to DC converter should be varied.

So, in other words, I need to have a controlled rectification at the source side. Either it could be a 3 phase fully controlled bridge or it could be or single phase fully controlled bridge. I need to have some control over the output voltage. Yes, if I have a if I have a controlled bridge, by introducing phase angle delay, I can reduce or I can control the output, DC output voltage of the bridge, AC to DC converter. As the frequency of the DC to AC converter reduces as the frequency of the DC to AC converter reduces, I need to reduce this V_{DC}. How to reduce this V_{DC} and what are the various issue involved, we will see sometime later.

Thank you.