Power Electronics

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Lecture - 42

In my last class we discussed the power circuit configuration of AC drive. We found that there are 2 stages of power conversion. One is AC to DC conversion and again DC to AC conversion. So, input is fixed frequency, fixed voltage, AC source and the final output is variable frequency, variable voltage source. Invariably, in most of the general purpose AC drives, the AC to DC conversion is realized using an uncontrolled diode bridge because there is economical very rugged. But then the limitations are source current is peaky, so power factor is very poor, also harmonic content is high and if the AC voltage fluctuates, the output of the bridge also will fluctuate.

We know that a voltage source inverter is capable of operating in two quadrants. Current can reverse. It is expected that power will flow from DC to AC side. So, when does there is a reverse power flow from AC to DC or when this load will supply back the power to the DC link? In other words, this induction motor now operates as an induction generator. When does this happen?

We know that induction motor always runs at a speed which is less than slightly less than the synchronous speed. But then to operate as an inverter sorry, to operate the induction motor as a generator, the rotor speed should be higher than the stator frequency or the synchronous speed. The rotor speed should be higher than the synchronous speed, slip should be negative. How can you implement this or how do you operate the induction motor as an induction generator? What is being done is stator frequency is instantaneously reduced.

So, the moment stator frequency is reduced, the speed of the rotating magnetic field produced by this stator also reduces. In other words, synchronous speed comes down or it falls with the stator frequency. Rotor speed cannot change instantaneously, speed rotor speed cannot change instantaneously because of it has its own inertia. So therefore, the rotor speed now is higher than the synchronous speed. So, slip becomes negative, induction motor now works as an induction generator and feeds backs the power back to the DC link.

Now, in the last class we had connected a resistor and a switch in the DC link. We monitored the DC link voltage. As soon as it increases above the certain level, we closed the switch and dissipated that energy. So, in high power drives, it is desirable that this regenerated energy should be fed back to the AC source. So that is a reason the input stage should have bidirectional power flow capability. It should be able to supply as well as DC. Second is it should be able to maintain a constant DC link voltage irrespective of the input AC fluctuation and third one is power factor should be unity. So, these are the desirable features of a high power AC to DC conversion stage.

So, here are the some of the results that you have taken in the laboratory.

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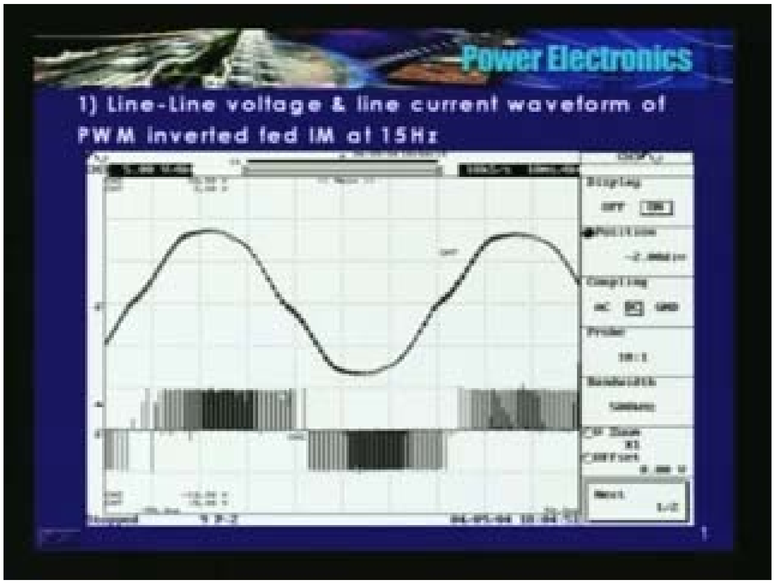

It is a line to line current drawn by the induction motor at 15 hertz, approximately 15 hertz. See, without using an inverter it would not have been possible for us to run the machine at 15 hertz. The frequency of this current waveform drawn by the induction motor is of the order of 15 hertz and this is the line to line voltage waveform; see, it has a large number of pulses. It has a large number of small, small pulses. Current waveform is approximately a sinusoid. This is at 15 hertz.

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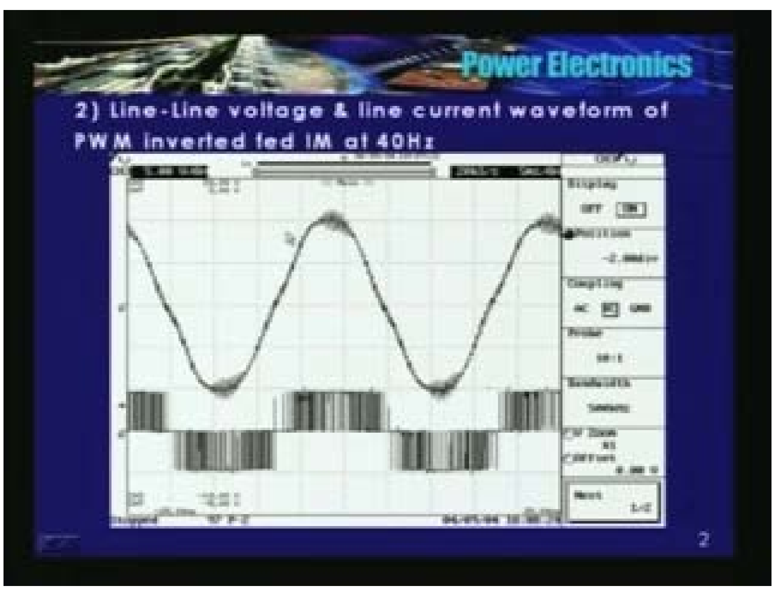

See, this is at 40 hertz again. See, current waveform is sinusoid as a very high frequency ripple.

In other words, a small current varies over a very small band. Of course, this current is not controlled within a hysteresis bands. Though we are applying high frequency pulses, current is still sinusoid. See, I extended this waveform.

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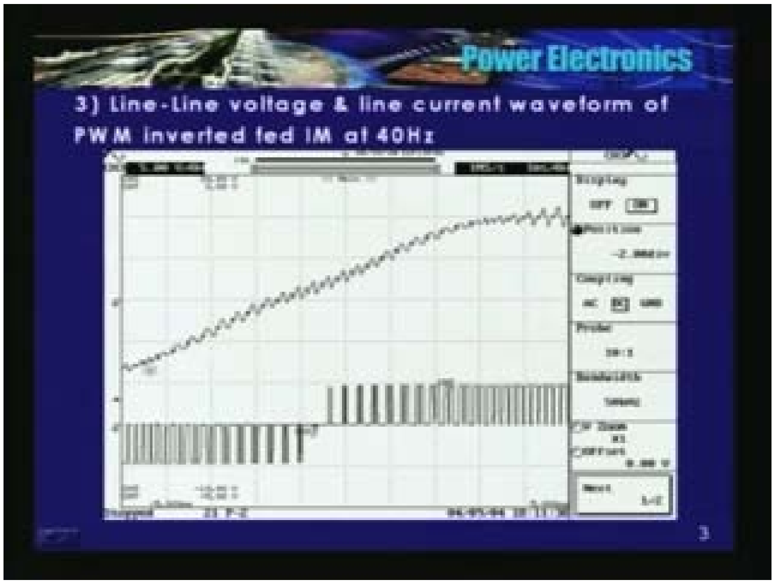

See, it looks like this. See, the wave pulses here, large number of pulses. Transition from 0 to the DC link, the rated value is almost instantaneous almost instantaneous. In other words, dv by dt is very high. Plus dv by dt as well as minus dv by dt is high. See the current waveform, it is almost a sinusoid it is almost a sinusoid.

Now, I have a question. We are feeding now a stepped waveform, current is still a sinusoid? See, machine is designed for a sinusoidal excitation. You are supposed to connect it to a 3 phase sinusoidal voltage source and it draws a sinusoidal current. Now, inverter fed machine line to line voltage waveform has a large number of pulses, dv by dt; positive as well as negative dv by dt is very high, whereas, input if it is fed from a AC source which is sinusoidal, there is voltage changes uniformly.

In other words, there are no transients there. In both the cases current is sinusoid. How can this happen? So looks like for the motor, it does not matter whether it is being fed from a sinusoidal source or at this sort of a waveform wherein, there are large number of pulses and the variations from 0 to the rated voltage is almost instantaneous. In the both the cases, we find that current is sinusoidal.

What is the reason or how can this happen? One conclusion that I can draw is that if I take the Fourier series of this waveform this wave form, it should have a fundamental component whose frequency is same as the frequency of this sin wave. See I will repeat; it should have a fundamental component whose frequency is same as the frequency of the sinusoid and the frequency of other components should be very high. Only then I can have a sinusoidal current.

Since, the frequency of the other component is very high, they get filtered by the stator inductance, leakage inductance.

So therefore, it is not necessary that you should feed a sinusoidal voltage to an induction machine. You can feed any waveform but then it should have a fundamental component and the next immediate component; its frequency should be very high. If you ensure that you will have a sinusoidal current drawn by the machine.

See, sinusoidal current but then but then a large number of pulses large number of pulses. The variation from See, it is clear here; variation from 0 to plus V_{dc} and plus V_{dc} to 0 is almost instantaneous. But then current is still a sinusoid. So, that is about a voltage source inverter.

So, what are the features? Input is a stiff DC source. In the beginning of inverter classes, I told that you can also have a stiff current source. So, that sort of an inverter is known as a current source inverter - CSI - current source inverter. In order to maintain a constant voltage in a VSI we had used a large capacitor. Now, we need to have a constant current. Therefore, we have to use a large inductor in series with the inverter. So that almost a constant and ripple free current is maintained in the DC link.

See, the power circuit configuration here.

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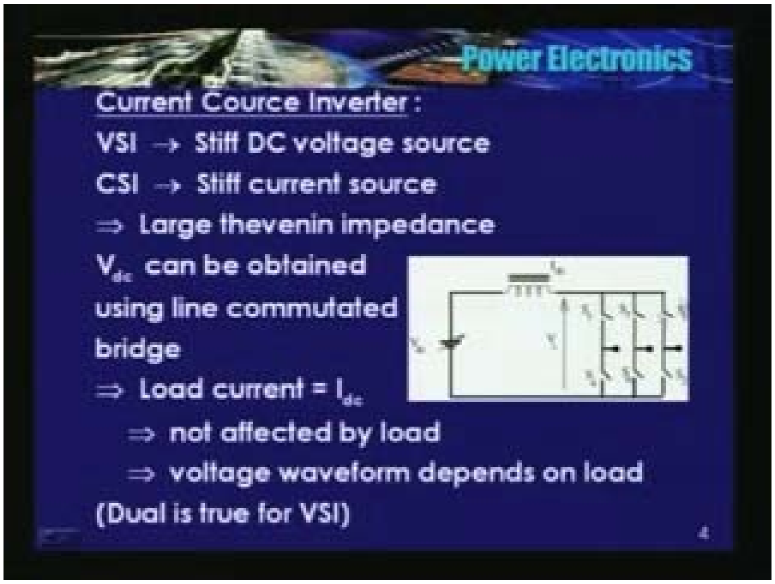

I have just shown 6 switches. The features of these switches, we will see some time later. A large inductor which maintains essentially a constant current here and a variable voltage source V_{dc}. So, I_{dc} can be varied by varying this voltage. How do I get this V_{dc}, a variable voltage, variable DC voltage? By using controlled rectification, remember. Now, I need to have a controlled rectification. In a VSI, current can change instantaneously, current can reverse. In a 2 quadrant operation, current can reverse, voltage will not reverse; voltage cannot reverse or rather in VSI.

Just the opposite is true in the CSI. Since, we are use a large inductor in the DC link, current cannot reverse there. But then voltage reverses.

See here, V_i can reverse. V_i or V_i will reverse polarities. If the polarities of V_i reverses, we need to have the switches which are capable of blocking the reverse voltage, remember. I will repeat; the switches here should be capable of blocking a negative voltage negative voltage. The devices which we use in a VSI cannot be used here. We are connected a freewheeling diode across the controllable switch. So the moment you connect a freewheeling diode across controllable switch, it cannot block a negative voltage. So, this S_1 to S_6, either they should be SCR's or GTO's which are capable of which are capable of blocking the reverse voltage.

Now, if you want to use IGBT or BJT there, you need to connect a diode in series in the switch like in this fashion. See here.

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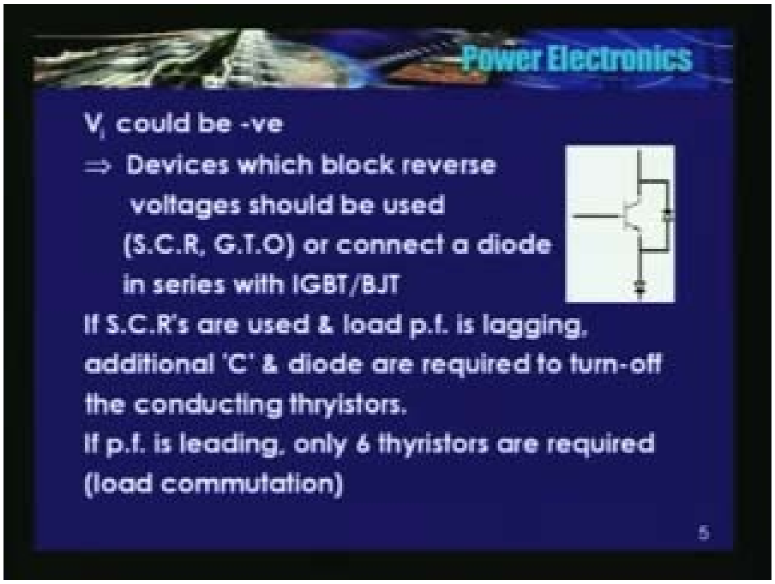

Now, the switch can block the negative voltage. It can pass the current, unidirectional current. Now, diode can block the negative voltage. So, you can use these switches in a CSI. I told that SCR's can be used. If SCR's are used and a load power factor is lagging, we need to use additional capacitors and diode to turn off the SCR's. I told you in a VSI, we had used L and C. Separate L and C we had used.

So, in a CSI if the load power factor is lagging and the devices are SCRs, we need to forcibly turn them off. So generally, capacitors and diodes are used and if the power factor is leading, only just 6 thyristors are sufficient. If the power factor is leading, I said this sort of a commutation is known as load commutation; current becomes 0 first and then voltage becomes 0. So, thyristors turn off on their own because current has becomes 0 and it has reversed something known as a load commutation.

So, in the load commutated inverter fed drive, there are only 6 thyristors only just 6 thyristors in a DC. So please recall, may be while doing the inverters, initial portion; I said load commutated inverter fed synchronous motor drive synchronous motor drive. A load commutated inverter fed synchronous motor drive is nothing but a current source inverter. Current source inverter with 6 SCRs feeding a synchronous machine or synchronous motor with wherein the power factor is leading power factor is leading. They is a very attractive is very attractive.

Now, what is the difference between a VSI operation and a CSI operation? In a VSI, at any given time 3 devices are operating. One switch in each leg is operated. So, you may have a condition of wherein all upper 3 switches are on or all lower 3 switches are on. The freewheeling through the positive DC bus or freewheeling through the negative DC bus. There is no problem at all; even if the load is inductive. It is not necessary that one of the switches in upper half or lower half should be on.

It is not a essential condition at all because there are freewheeling diodes across the switches. So, they provide a path for the continuity of current load current and we had used pulse width modulation to control the output voltage of a VSI. We had used PWM to control the output voltage of a VSI and depending upon the power level the switching frequency also varies and you could have of the order of say 10 kilo hertz or so. So, if someone says the switching frequency of a VSI is 10 kilo hertz; it is fine, it is possible.

How about in a CSI? At any given time only 2 devices are on or only 2 phases are conducting. One in the upper half, one in the lower half because DC in the DC link there is a large inductor. You cannot break an inductive circuit. So, at any given time DC link through the inverter circuit should be completed, remember.

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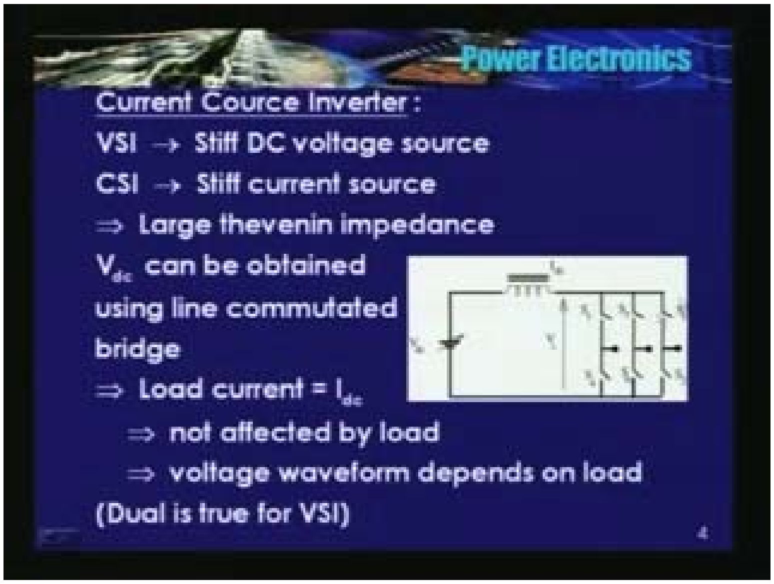

See in this, this current you cannot break it. You have to provide a path you have to provide a path by one at least 1 switch in the upper, 1 switch in the lower should be on. So, at any given time 1 switch in the upper half and 1 switch in the lower half were on. In other words, 1 phase is open, 1 phase is open. See, this sort of operation we had seen in 3 phase AC to DC conversion. Almost the same thing; at any given time, 1 in the upper, 1 in the lower device is conducting. 3 phase AC to DC converter because same principle. There also we had a load which is which is equivalent to a current source type. We had connected see assume that this I am connecting to a 3 phase AC source. We had connected a DC link inductor to smoothen the filter out the current and this I can represent it or this can be equivalent to the back emf of DC machine.

Of course, the direction of current of these devices should be in the opposite. So one more, the same operation we have here; at any given time at any given time only 2 devices are conducting, one phase is open. What about the voltage waveform across the load? Current is independent. Whatever the current that is flowing in the DC link will flow through the load. See only 1 switch is open and 1 switch is opened in the both halves. Whatever the current that is flowing in the DC link will flow through the load and back but depending upon the load, waveform changes.

In other words, terminal voltage waveform is determined by the response of the load to the applied current. I will explain to you some time later. I will show you some of the waveforms. I will repeat; the terminal voltage waveform across the of the load is determined by the response of the load or depends upon what sort of a load it is feeding and …

Now, take for example; a 3 phase current source inverter.

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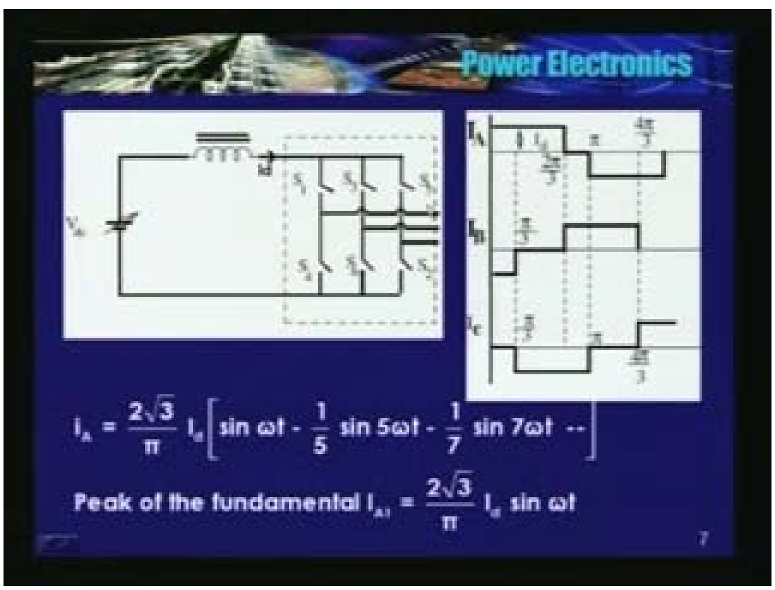

Again, I am not using I am assuming S_1 to S_6 as switches. Though so called as self commutating switches may be GTOs because if you are using thyristors and the power factor is lagging, you have to use separate cn diodes. So, I am not going to discuss that aspect, so called the commutation aspect. I am taking these 6 switches which are capable of commutating or capable of turning off using gate or it is possible to turn these devices off using the gate signal.

I said any 2 devices are on and each device conducts for 120 degrees. Same thing, whatever that happened in 3 phase AC to DC conversion. Each device conducts for 120 degrees and for 60 degrees, 1 phase is open. See here, i_A. In other words, S_1 is conducting for 2 pi by 3 radians, 120 degrees. Whatever the current that is flowing in the DC link flows out of the terminal A. From 2 pi by 3 to pi S_1 is also off, S_4 is also off. At pi again, S_4 is turned off. In the B phase; when S_1 turns off, S_3 should be turned on because this path should be completed I_d, there has to be a path for I_d. S_1 turned off, S_3 turned on and it remained on for another 120 degrees.

So, if S_1 is S_3 turns on here, definitely that phase is off for 60 degrees and here S_6 is on. See, at this point S_3 or S_6 turned off, at this point S_6 turned off. In the upper half, S_1 is on. So, one device has to turn on in the lower half, S_4 cannot because S_4 turns on see at pi. So, at this point S_2 turned on. So if you see, at any given time say from 0 to pi by 3, 6 and 1, 6 and 1. From pi by 3 to 2 pi by 3; 1 and here 2 and from 2 pi by 3 to pi, this is 3 and this is 2 and so on so on. Almost the same current waveform we had in 3 phase AC to DC conversion.

So, we had assumed that DC link current is constant and ripple free. So, phase current or line current that is flowing out is also also constant and ripple free. What is a harmonic spectrum? See, we had a line to line voltage waveform in a VSI, almost the same. For 2 pi by 3, it is V_{dc}; from 2 pi by 3 to pi, it is 0 and again from pi to another 120 degrees, it is minus V_{dc}. Line to line voltage waveform in a 6 step inverter wherein each device conducts for 180 degree, we have something like this.

What is the harmonic spectrum or what is the Fourier series that we wrote? It is here. Harmonic spectrum is 6 and plus or minus 1; fundamental, fundamental component - fifth and seventh again eleven and thirteen so on. So, peak of the fundamental is the fundamental component, I_d sine omega t.

Now the question that is asked; I said current when T_1 where S_1 is turned off, current becomes instantaneously 0 in that phase and entire DC link current starts flowing through S_3. See here, S_1 turned off instantaneously and S_3 turned on instantaneously. S_1 turned off, S_3 turned on. So, what is di by dt here and what is di by dt here? di by dt is infinity, rate of change of current. So, if there is an inductor in the load, can you have this sort of a waveform? See, for 2 pi by 3 to pi there is no current that is flowing in that phase no current is flowing in that phase.

Now see, there is an if suppose there is an inductor inductive load connected here, this current constant current was flowing. At this point, S_1 is opened, S_4 is also S_4 is opened and it will be closed after 60 degrees. So, what happens what happens or if there is an inductive load, what sort of a voltage waveform will be there or the question is can you realize this sort of a current waveform if there is an inductor if there is an inductor?

Answer is no answer is no because it will create a large voltage spike large voltage spike. So, in other words, change over from 1 to 3 should be slow to limit the di by dt. In other words, see here, this current should gradually fall gradually fall and this current should be gradually rise gradually rise so that it should be able to contain or it should be able to limit the di by dt because if you have this sort of waveform, di by dt is going to be infinity. That will create a large voltage spike.

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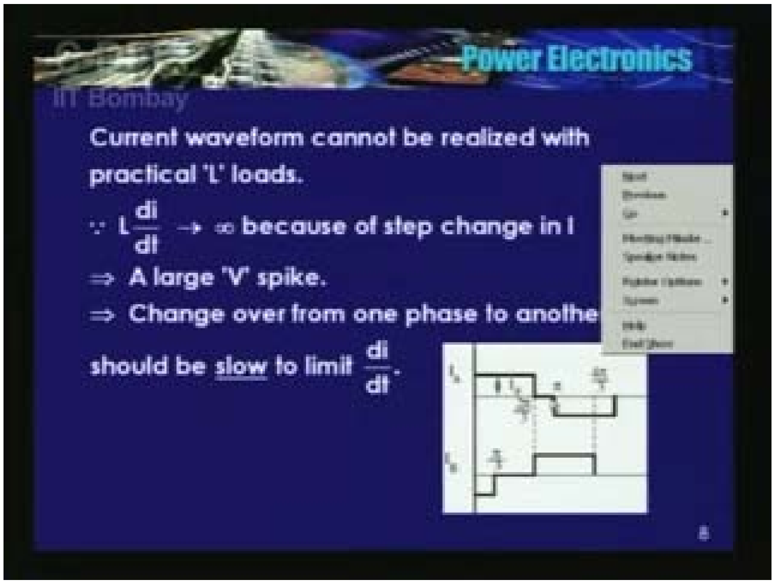

What did happened in voltage source inverter? In fact, we had used a very fast devices very fast devices. We wanted an almost instantaneous change over from one device to another device, load may be inductive. Why here we need to have a gradual fall and gradual rise? Reason is very simple. There, there are the freewheeling diodes taking care of this inductive energy. There are no freewheeling diodes here there are no freewheeling diodes. So, this are the difference. You cannot have this fast rise this fast rise and this fast fall. Its change over should be as should be slow to limit the di by dt.

See here, inductive load in a VSI. You could have an inductive load.

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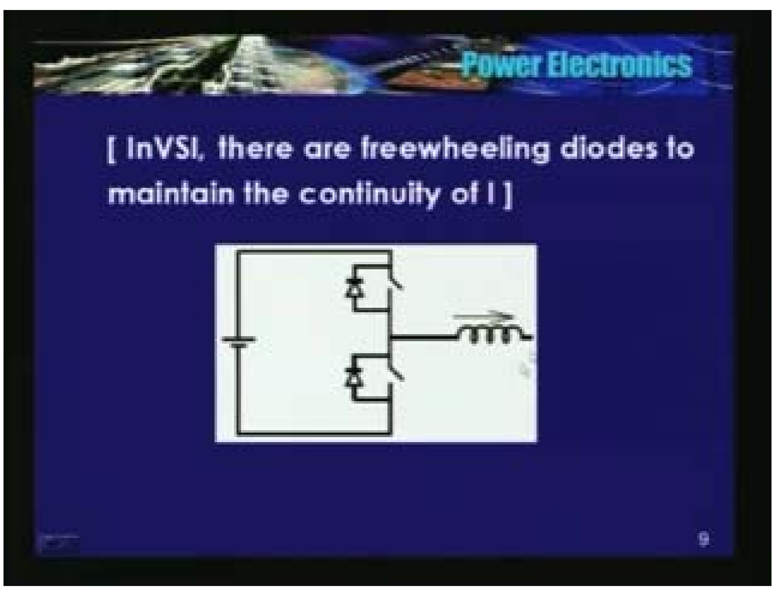

I am not saying that we are changing the current in an inductance instantaneously by opening or change by opening the switch. In fact, we wanted a very fast switches here very fast switches. The moment I opened the switch; I do not need to close this, current will start flowing through this diode current will start flowing through this diode. That maintains a continuity in a VSI.

So, L di by dt is spike depends on the leakage inductance. I said in a CSI terminal voltage waveform is governed by the load. Whatever the current that is flowing through the DC link will continue to flow through the load. Now, load voltage waveform depends on the type of load. I just explain here.

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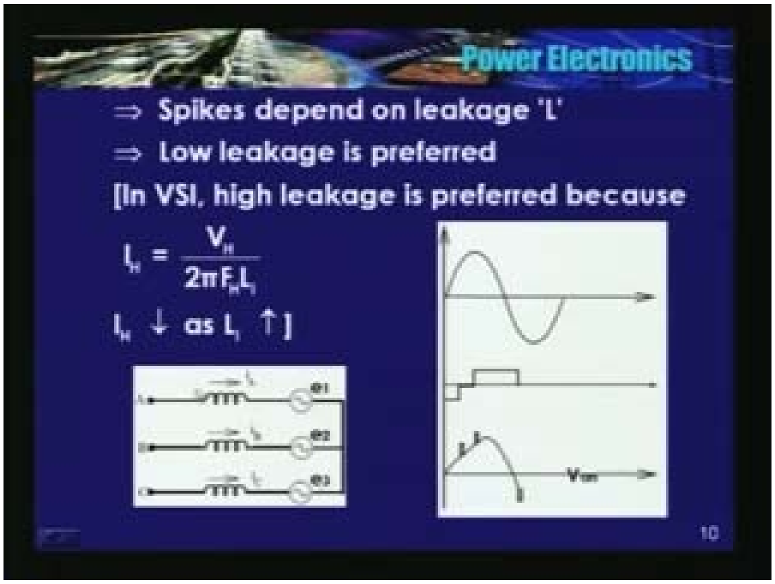

See, assume that you have a back emf and inductance in series, resistance I am neglecting; something similar to an induction machine similar to induction machine. Back emf means inducting machine. I am assuming e_1 e_2 e_3 to be sinusoidal. Now see, this is one of the phase current waveforms, a line current waveform i_A; assume that it is i_A. It was negative, became 0, for 60 degrees it remained 0 and again a positive current. So, there is a positive L di by dt again there is a positive L di by dt.

So, what is the voltage here? e_1 plus so there is a L di by dt here and L di by dt here; there is no L di by dt here, it is 0. So, there is going to be a spike in these two points. So, this the how do I reduce this spike? One is to have a gradual transfer. Of course, if it is slow, it affects the power transfer. So, another way to decrease the magnitude of the voltage spike is to have a low leakage. So, if the machine is being fed by a current source inverter, it is desirable to have low leakage or machine with low leakage is desirable. Just the opposite is true in a VSI. Why? See, what is the expression for the harmonic current?

See, here is the expression. The magnitude of harmonic current of a given frequency is equal to the magnitude of that harmonic, magnitude of that particular harmonic divided by the impedance offered to that harmonic. I am neglecting the resistance now. So, I_H current decreases as L_1 increases. See here, so I_H decreases as L_1 increases for a given harmonic voltage. Whereas so therefore, higher leakage is desirable if the machine is being fed from a voltage source inverter and in case if it is being fed from a current source inverter, low leakage machine is desirable. Is that okay?

See, in this current source inverter where induction motor is generally used for high power applications. CSI motor is invariably used for high power applications because one of the advantages is circuit is very rugged. So in case, S_1 and S_4, they conduct in the same time; nothing is going to happen because we have a large inductor in the DC link. It has an inherent short circuit protection, whereas, in a voltage source inverter, you just cannot afford to have a short circuit in the DC link. So, you cannot allow S_1 and S_4 to conduct at the same time. So, that is the reason we use a really a fast devices there. Here, slow devices or slow devices can be used.

Another advantage of current source inverter is that all 4 quadrant operation is possible or in other words, it is easier to have 4 quadrant operation in a CSI fed drive. How is that possible?

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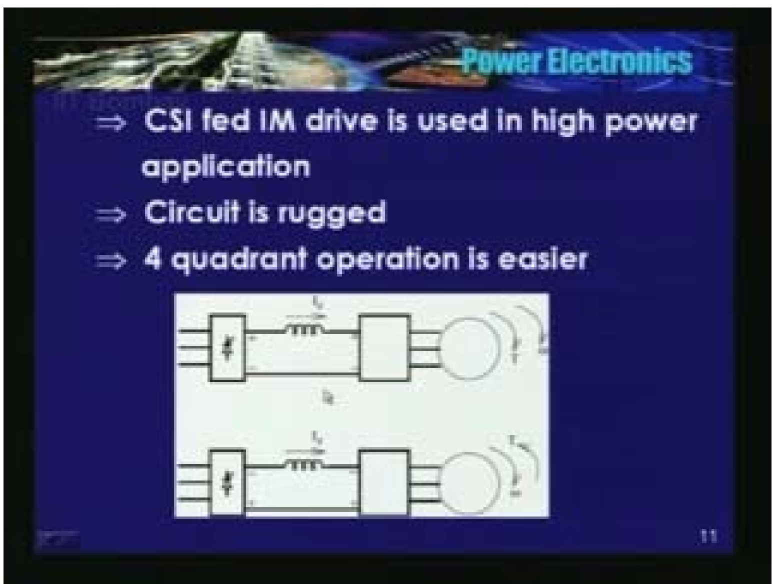

See here; a large inductor, AC to DC conversion, so we need to have a variable voltage here, a regulated variable voltage here which you can realize it using controlled rectification, 3 legged inverter feeding a machine. So, at any given time, operation is in the first quadrant. T is also in this direction, omega … with plus minus plus minus.

Now, input voltage is positive, current is also positive. Source is supplying power to the inverter and to the load. I have told you that this voltage changes or polarities of this voltage will change in a CSI. Now, we want to go to second quadrant or fourth, depends on which one you have taken; T along X axis or Y axis, it does not matter.

So, what do I need to do? I have to inter change the polarities here by changing or increasing alpha above 90. I can still of course, current direction is the same, you cannot reverse the direction of current. Same thing, just the opposite, dual is true in now VSI; voltage polarity cannot be reversed. Current is still flowing in this direction. See, the polarities of V_{dc} and V_{in}, voltage inverter, torque and omega. Operation has changed, has gone to somewhere, second as if gone to another quadrant.

So, may be regenerative breaking, speed will fall. So, as the speed falls or near the 0 speed, you want the motor to rotate in a reverse direction; you interchange sequence of the SCR or device triggering. When you interchange the sequence of triggering pattern, indirectly you are interchanging the phase sequence. So, if you change the phase sequence, machine will try to operate in a in a reverse direction.

Now, you are in the third quadrant, the so called the reverse motoring or may be from there you go to another quadrant; either second or fourth. It depends on depends on how you came from first to third. So, in other words, regenerative breaking or all four quadrant operation in a CSI phase drive, it is very simple to implement. We have just controlled AC to DC rectifier and here again an inverter, whereas in a VSI, we wanted or we used bidirectional power converter bidirectional power converter to feed back the power that is received from the load to the source. We used a bidirectional power converter. The device is a capable of carrying the current in both direction, whereas here, we are using just 6 thyristor in the AC side. So, these are the advantages of a current source inverter.

Of course, it is current source CSI inverter is quite vast. But then the voltage source inverters are more popular. Popularity wise VSI is far ahead than a CSI because there are large number of low power drives. There is know I have not gone into analysis of the CSI using SCRs, the so called commutation circuitry. Of course, I have not done even for a voltage source inverter. There also I had assumed assume a self commutating devices. Even in a voltage source inverter, we had used self commutated devices. But then I cannot use this same devices in a CSI, I need to modify them. But in case if you use SCRs, you need to forcibly commutate them. So, that is about the inverters as a whole.

What did you do in the whole inverter chapter? We started up with the basic building block of half bridge inverter. Then we went to full bridge, single phase, 4 devices. From there 3 phase VSI. We discussed 180 degree conduction, square wave operation. There are harmonic problem. Then after that we used various pulse width modulated techniques, PWM techniques to control the output voltage and we found that suitably if you turn the turn the devices on and off, you can eliminate certain harmonics. In the conventional inverter, wherein only 6 device are used, there are only 2 levels in the pole voltage waveform; either 0 to plus V_{dc} or minus V_{dc} to minus V_{dc} by 2 to plus V_{dc} by 2 depending upon which point you have taken as a reference. The pole voltage, there are only 2 levels; hence the name, 2 level inverter.

So, I have told you that as the power level increases, switching frequency should come down. So, instead of using pulse width modulation, I said we can have more number of levels in the pole voltage thereby synthesizing approximately sine wave. So, this sort of inverters are known as multi level inverters. The pole voltage has more than 2 levels. I said these are popular in high power applications.

From there onwards we started discussing a current source inverter, CSI fed inverter. I may not have gone into detail but I will try to tell you the operation of the inverter. DC link current waveform or DC link current is maintained constant, load voltage waveform now depends on the type of load. I told you that transfer from one device to another device should be slow to limit the di by dt and 4 quadrant operation is easier to implement and these drives are used or CSI used for high power applications.

So, line current waveform in a CSI is a square wave of 120 degree duration. So, there are 6 and plus or minus 1 harmonics then fifth, seventh, eleventh, thirteenth. What do we do in VSI to eliminate the harmonics? We had used pulse width modulation. So similarly, can we use pulse width modulation to eliminate this current harmonics? Answer is no, In other words, pulse width modulation is not very popular in CSI.

See, because first of all, we had we have used slow devices. I said in order to limit a di by dt spike, the current transfer from one device to another device should be slow. So, if I am using pulse width modulation that means I need to turn off S_1 and S_3 simultaneously. The problem may get aggravated.

So, PWM is not very popular in CSI fed drives and another main difference in a CSI and VSI is that you need to have closed loop operation in CSI operation. Closed loop in the sense, we need to monitor some output quantities, may be speed we need to monitor and depending upon the required speed you may have to set some current in the DC link.

See arbitrarily, you just cannot have some current in the DC link because that current is flowing in the machine and it is going to produce some torque. Where where does the machine operate now? or the electromagnetic torque and the load torque intersect each other is the operating point. See, we have no idea about the load requirement and just setting of some current in the DC link, you may have some sort of an unstable operation. So, you can set a DC link current based on the load requirement.

So, in other words you in other words a closed loop operation is a must in a CSI fed drive which is not required in a voltage source fed voltage source inverter fed induction machine. So, with that we have come to an end of inverter chapters. I will just try to give you know a over view of inverter chapter. It is a vast subject by itself.

For first course in power electronics, this should be sufficient. If you are interested more, I will encourage you to go back to the library and read. So therefore, we have covered 3 important chapters in power electronics. What are they? The first one is AC to DC conversion, we call them as rectifiers; then DC to DC conversion. So, depending upon the power level, we said choppers or switch mode power supplies and the third one is DC to AC converters.

So, what about the last one in the power electronics chapters? That is input is AC, output is also AC. Again, there are 2 different classes; the first one being both frequency as well as magnitude variable. See, I have a converter here, input is AC, output is also AC. There is no conversion from AC to DC and DC to AC; direct AC to AC conversion.

So, first class is input is fixed frequency, fixed voltage, AC. Output is both voltage as well as frequency variable; direct conversion direct conversion and second one is frequency constant, magnitude variable. The second class of inverters the equipment which belong to the second group, they are known as phase regulators or phase controllers or AC voltage regulators. We will study this class of controllers in detail. By the way where are they used? There is a fixed voltage as well as frequency source and we want frequency constant, voltage magnitude of voltage variable. Where could this equipment be used?

One general purpose application is fan regulators fan regulators. What are they doing there? In order to vary the speed of the fan by changing the knob of the regulator, what exactly we are doing? We are applying reduced voltage to the machine or to the fan motor. Frequency is being untouched, frequency remains the same remains the same.

So, similarly in a temperature controller, suppose you want to control the temperature, vary the temperature with just changing the knob, what exactly we are doing? We are applying a reduced voltage to a load. Lighting intensity controller: there is a knob, we are turning a knob to reduce the intensity of the bulb, what are we doing there? Same thing: frequency constant, varying the magnitude of voltage that is being applied to the load. The the principle of operation of this circuits we will study in the next class.

Thank you.