Power Electronics

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Lecture - 34

In my last class we have started discussing about the one of the very important topics in power electronics known as the inverters. Input is DC, output is AC. I am calling output is AC because the average value of the output voltage is 0. It need not be a pure sinusoid as said. It may be very important topic in power electronics, but then till now, we are not we are not very much convinced regarding the use of such an equipment because power that is generated is AC. Here is an equipment which converts DC to AC.

I told you that in any DC to AC conversion or DC to AC equipment, power electronic equipment, there has to be an AC to DC converter which converts input AC to DC and DC this DC forms an input to input to to the DC to AC converter. In the process, we found that or we have seen an equipment, wherein, input is a 12 volt DC and output is 230 volt 50 hertz AC. This is nothing but sometimes we call it as a UPS - uninterrupted power supply or we also call it as an inverter.

Then we started discussing about the theory of a 3 phase induction machine and we found that if the machine is driving a constant torque load, the input to the machine remains approximately constant and it is independent of speed of operation. So, as the speed decreases, S times the input is dissipated as heat. So therefore, even for fan type of loads, if you want to vary the speed over a wide range, it is always advantageous to vary the synchronous speed itself. These observations, we had made in the last class.

Then we started discussing about an equivalent circuit for an induction machine and I told you that if the power rating of the machine is high or if a high power motors, the values of series parameters; the winding resistance as well as the leakage flux is relatively low. So, we can shift the magnetizing branch to the source side, provided, the frequency of operation is fairly high. In the sense, if the operating frequency range is around say, 30 to 50 hertz or so, you can call or we can say that E_1, the voltage across the magnetizing branch is approximately equal to the supply voltage itself.

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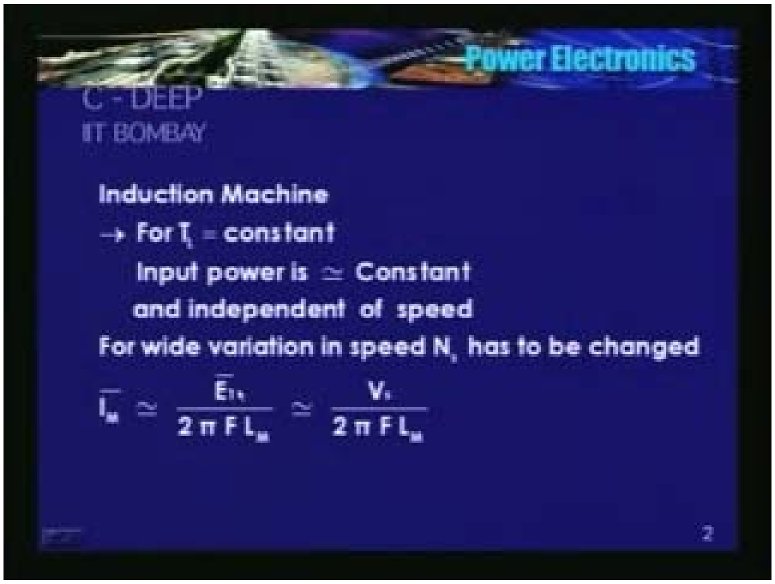

So therefore, see in this equation, magnetizing current is given by E_1 divided by 2 pi F into L_M. Actually, it is not approximate, this is equal. I_M is equal to please, this is equal to E_1 divided by 2 pi F into L_M which is approximately equal to V_S divided by 2 pi F into L_M.

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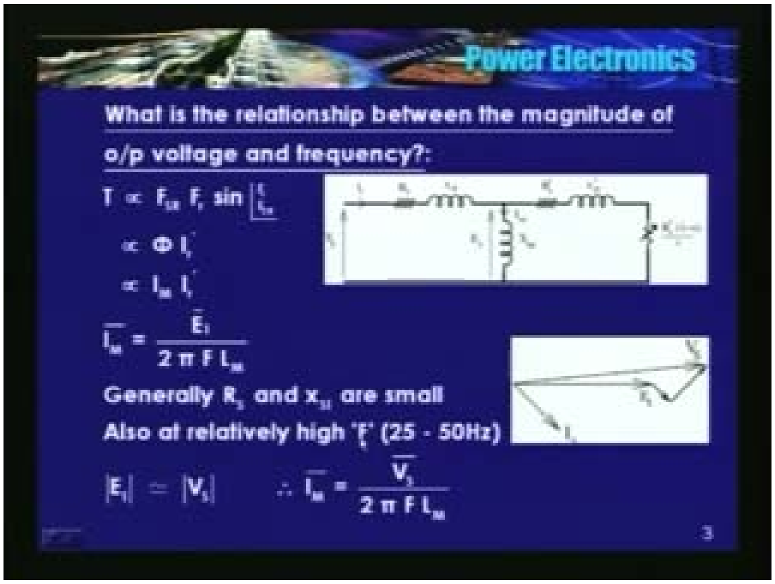

Where, see, this is the equivalent circuit we had discussed and this is the equation we had derived. So, we also discussed about one of the possible cases in which we kept V_S constant and we tried to reduce frequency. Since, we are decreasing the frequency, synchronous speed will fall. V_S is held constant, F reduces; therefore, the magnetizing current increases. Therefore, the equation says that if the magnetizing current increases, flux also increases. This is what the equation says. But then in the machine, we all know that they are operated at the knee point. I mean; knee point in the sense, the point at which the saturation begins to start. So, I_M is no longer linearly varies with flux or flux does not change linearly with I_M.

Machine is starts getting saturated. Therefore, source current will become peaky. So, the moment source current becomes peaky, harmonics are introduced. Power factor also falls and core losses are going to increase. So, we have concluded that keeping V_S constant may be, at its rated value and decreasing F is not a solution.

So, what could be the second option? Second option is we will keep V_S constant at its rated value and increase F above the rated. The previous case what we did? We kept V_S constant and tried to reduce the frequency below the rated, not possible. The second case, we will keep V_S constant at its rated value and will try to increase F, to increase N_S. What the equation says?

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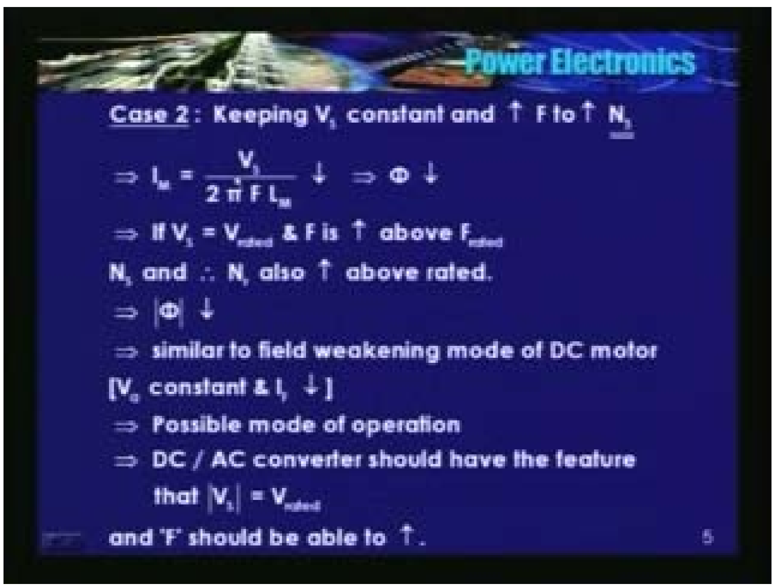

I_M is given by V_S divided by 2 pi F into L_M. V_S constant, F increases. Therefore, I_M reduces. If I_M reduces, flux also reduces. Maybe, this linear, the relationship between I_M and phi may be approximately linear because beyond the knee point, it is non linear, below the knee point relationship between BH curve is almost linear.

See, for all for all practical purposes, even a 3 phase induction motor is a constant speed motor because reduction in speed with load is not much. Say for an example, a good induction machine; no load speed for a 4 pole 50 hertz motor, no load speed could be of the order of 1485 rpm or so. Synchronous speed is 1 twentieth by p, it is 1500 rpm. F is 50, P is 4. So, N_r at no load could be of the order of 1485 and on full load, it could be of the order of 1460 or so.

So, reduction in speed from full load to reduction in speed from no load to full load is of the order of say, 20 to 25 rpm and the base value is 1500 rpm, the synchronous speed. Therefore, for all practical purposes induction motor is also considered to be a constant speed motor. Coming back to the theory, I said V is kept at V rated. I am increasing the frequency above the rated, therefore synchronous speed which is approximately equal to or may be slightly higher than their speed of rotation of motor also increases above the rated.

In other words, machine is now running at a speed which is higher than the rated. Air gap flux has reduced because I_M has reduced. I_M is equal to V_S divided by 2 pi into 2 pi F into L_M. Flux has reduced and speed of rotation has increased.

Now, let me recall a theory on DC machines. What did we do to increase the speed above the rated? We did we kept the armature voltage constant and we tried to reduce the flux by reducing the voltage applied to the field winding and we called it as a field weakening mode of operation. See, in a DC motor speed control, separately excited DC motor speed control, armature voltage is held constant and we tried to reduce the flux by reducing the voltage applied to field winding and we called this mode as operation as field weakening mode.

Since, speed is inversely proportional to flux; speed started increasing above the rated. The same operation is taking place in this case. Speed of rotation is above the rated and air gap flux is fallen. So, this mode of operation is similar to field weakening mode of DC machine. It may not be directly changing the voltage applied to the field. Of course here, xm, those points are not available outside, whereas, in DC motor, we could have independent control of the flux.

So, I can make another conclusion that is; a DC to AC converter should be able to provide a constant voltage and the frequency should be able to increase. I will repeat; magnitude of output voltage should be held constant, I should be able to keep it constant and we should be able to increase the frequency above the rated. We do not want to keep the voltage constant and decrease the frequency; that operation is ruled out. But we should be able to keep the voltage constant and to increase the frequency to increase the speed of rotation. So, this is another feature a DC to AC converter should have.

Now, let me take it to the third case. What did we do in the first case? We kept V constant, tried to reduce F. In the second case, we kept V constant and increased the frequency. Yes, it could it is one of the possible modes of operation. Now, what will we do is we will keep V and F constant.

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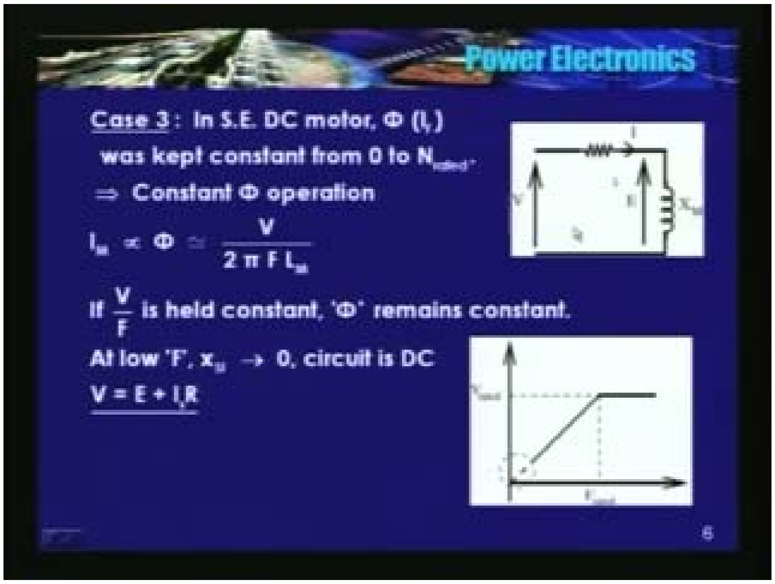

In other words, we will try to reduce V as well as F. See in this equation, I_M is proportional to flux and this is approximately equal to V, the supply voltage. May be, in the previous equivalent circuit I must have called it as V_S divided by 2 pi F into L_M. So, if I keep V by F constant if I keep V by F constant, the flux will remain constant flux will remain constant. Of course, you may say that increase V above the rated. It is not a good engineering practice. The maximum voltage that I can apply to the machine is its rated.

So, you can apply a reduced voltage to the motor. That is why I said we will keep V by F constant and will try to reduce V in such a way that V by F ratio remains constant. So, as F reduces, 120 F by p which is nothing but synchronous speed also reduces. Therefore, another feature of a DC to AC converter is that it is possible to keep D by F ratio constant till the rated. So, from low speed of operation, I am calling low speed, why? I will tell you later. From low speed of operation or from low frequency to 50 hertz which is the rated frequency, it should be able to keep V by F ratio constant.

In other words, V by F relationship should be linear. So, this mode is similar to similar to constant torque of operation in DC motor or how do we how do we reduce the speed of operation of DC machine? We have kept I_F constant we have kept I_F constant and we tried to reduce the armature voltage. Omega is directly proportional to the applied voltage to the armature. So, we have kept flux constant and will try to reduce the armature voltage. Therefore, speed reduces.

Same thing is happening even here. I will keep V by F constant, flux remains constant. F is reduced, F reduces; therefore N_S, the synchronous speed reduces. N_r should be less than N_S. So, N_r also reduces. Same operation same operation, the constant flux operation in a DC machine which is similar to this operation in an inverter fed induction machine.

By the way, why did I say that low frequency? Why not 0 frequency or 0.1 hertz or 0.2 hertz? Why did I say from low frequency to 50 hertz V by F relationship is linear? Why not down to very very low frequency? Now, I will take back to the equivalent circuit of induction machine. See, I have just drawn the stator side. I have not shown you the rotor side and I have not shown you or in this circuit leakage reactance is missing. Why it is missing? It is very much there. Why it is missing?

I said, frequency has reduced, frequency of operation has reduced. At 50 hertz rated frequency itself the values of these series parameters; winding resistance, leakage reactance. I said they are low at 50 hertz. Another close frequency, say around 10 hertz or so, the value of X_L has reduced to 0.2, corresponds to its rated. So, at 50 hertz it is low. Now, the frequency operation, say around 10 hertz or 5 hertz, there is a proportionate decrease in the magnitude of XSL. So, I can safely neglect the leakage reactants.

I said frequency of operation has come down frequency of operation has come down here, in this of this circuit. It could be of the order of 5 hertz, 2 hertz or 3 hertz or whatever. When I am saying that it is a low frequency AC, I can use a direct DC circuit analysis here. So, a 2 hertz is nothing but a DC itself.

Please try to understand. A 2 hertz AC, I can say, safely say it is nothing but DC. So, I can directly write here magnitudes, I do not need to take phasors into account. V is equal to E plus I_S into … So, I can directly add the magnitudes, if if it is an AC circuit analysis, I need to use phasors. The moment I use a phasors addition, if the power factor is lagging, then I can say that B is approximately equal to E for low values of RS. Now, but then if I am using directly if I am adding directly the magnitudes, now it may so happen that there will be a significant difference in the magnitude of E and V.

Now see, E is E is V minus I_S into R, direct magnitude subtraction magnitude direct substitute. So, what is to be done is or what is done is at low frequency you need to compensate for I_S R_S drop you need to compensate for I_S R_S drop. In other words, this is no longer linear this is no longer linear. That is why I have shown you as doted. Actually, it has a across starting from here. It is like this. Anyway that this generally, this should be discussed in drives but this you may be bit curious to know why it is not linear till the origin. So, I just discussed. It is a non linear function at low frequencies.

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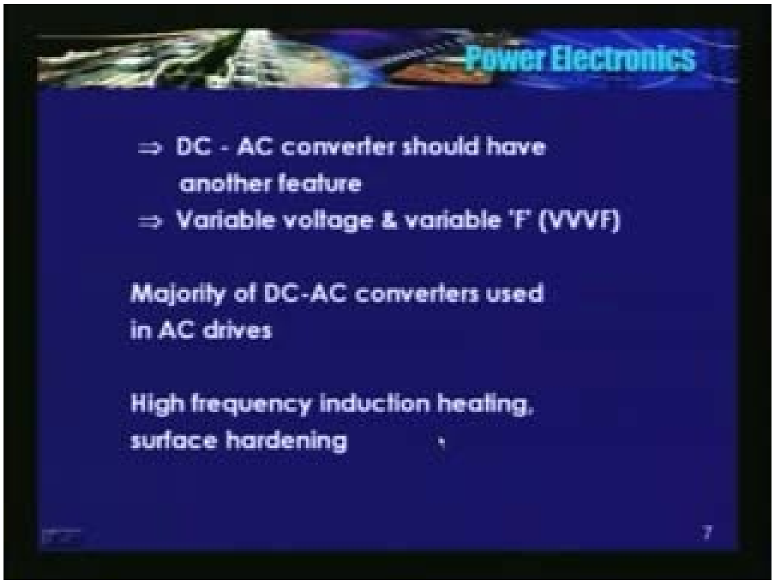

Anyway, so these are the conclusions that I can make. A DC to AC converter should have another feature, that feature is; till the base speed or from very low speed to the rated speed, both, magnitude of the voltage as well as the frequency should be variable. So that may be, V by F remains constant. So therefore, a DC to AC inverter or converter should have 2 features. One is it should be a variable voltage variable frequency source, remember. It should be a variable voltage variable frequency source till the base speed, from 0 to base speed and from above the base the base speed, constant magnitude of voltage and frequency should be able to vary or it should be able to vary the frequency of operation above the base speed keeping the magnitude of voltage constant.

So, these are the 2 important features a DC to AC converter should have or the DC to AC converter used in drives or AC drives or DC to AC converter used to vary the speed of rotation of AC machines, a very important applications. Let me tell you one thing, majority of DC to AC converter or majority of inverters are used in AC drives. They are used to vary the speed of rotation of the induction machine, majority and remaining significant application is UPS - uninterrupted power supplies and another application is high frequency induction heating high frequency induction heating. Let us see sometime later.

So, we have discussed the need for DC to AC converter. Having discussed this, now we will start discussing about the various ways to get AC supply from DC supply. Basically, there are 2 types of inverters 2 types of inverters. The first one is if the input to the inverter is held constant, input voltage is held constant, see I will repeat, if the input voltage to the inverter is held constant, in other words, input to the inverter is a voltage source, we call it as a voltage source inverter. See in this figure.

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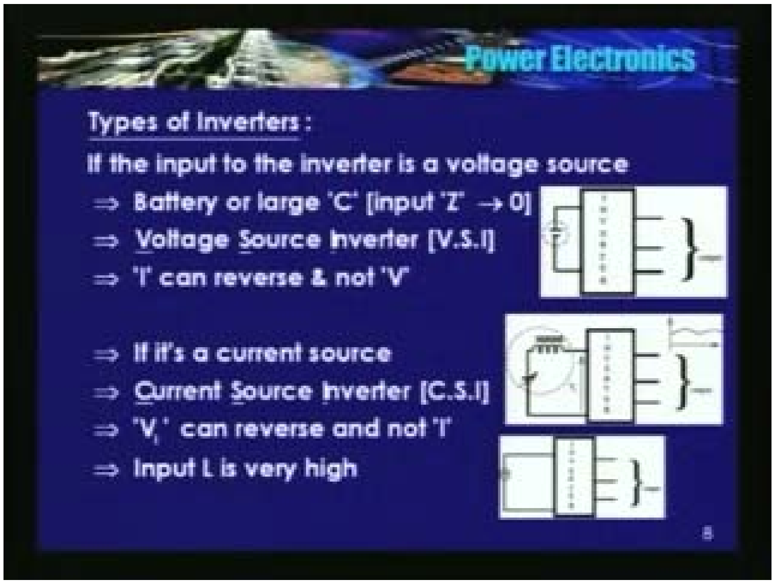

So, this is the inverter, input is I marked it as a voltage source or a battery or a battery. So, the moment I say it is a battery, I can represent it as a voltage source. Almost as an ideal voltage source. Magnitude of voltage is independent of the current that is supplying. So, in other words, the input impedance or the the thevenin impedance is very small. The thevenin impedance of a voltage source inverter is very small, any voltage source. So therefore, you should be extremely careful in operating this inverter.

So, I will repeat; thevenin impedance is very small thevenin impedance is very small. Input is a voltage source, therefore, voltage cannot reverse or polarity of this voltage source cannot reverse. But then current should be able to reverse, remember. So, voltage source a voltage source can supply or sink any amount of current. So, even in a VSI inverter, voltage source inverter, in a VSI, current should be able to reverse or current does reverse in a VSI current does reverse in a VSI. Voltage polarities cannot reverse here.

I have shown you 3 lines indicating a 3 phase inverter. You can have a single phase inverter also. I said input is a voltage source. I can have a current source also. So, I have a variable DC here, source and a large inductor is connected in series to the inverter. So, a voltage source in series with the large inductor can be represented by a current source. See, this we did in DC to DC conversion.

I said input stage of a chuk converter. We had a voltage source and an inductor. So, I said we can represent that combination by a current source. So, it is it is could be represented by almost an ideal current source. Since there is a large inductor here, current cannot change its direction current cannot change the direction here. But we know that voltage across a current source can be either positive or negative: just the opposite in a VSI, voltage source inverter.

Here current can reverse, not voltage, whereas, in a current source inverter, input voltage to the inverter input voltage to the inverter out here can reverse but not the current but not the current. In other words, input impedance or if I have to represent by this way, a thevenin equivalent, I have a current source and large large inductance here.

So remember, there are 2 types. One is a voltage source inverter, current can reverse and not the voltage and we have a current source inverter; this voltage can reverse, input voltage to the inverter can reverse and not the current. The advantages of voltage source inverter over current source inverter or or the difference between the voltage source inverter and a current source inverter, we will discuss in detail after discussing the various topologies of VSI as well as CSI. Here now, we will discuss the various circuit configuration of a voltage source inverter or VSI VSI.

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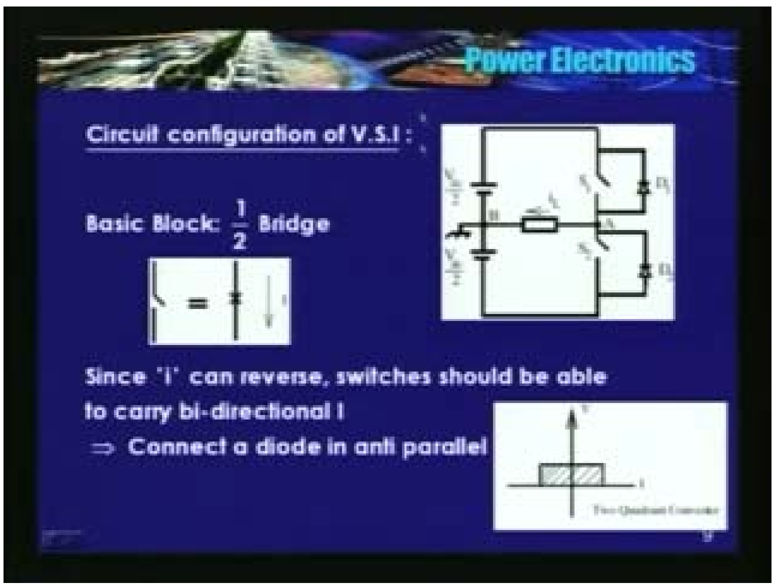

A half bridge configuration, half bridge, a basic building block. We have a center tapped DC source, V_{DC} by 2, V_{DC} by 2, 2 switches S_1 and S_2 and load is connected between the centre point of the voltage source and the centre point of these 2 devices. I will just repeat; I might have done this in AC to DC conversion and I represent a switch in this fashion. When I close the switch, current flows in this fashion, current flows in this fashion.

Voltage source inverter, VSI, polarities of input voltage source cannot reverse. Current should be able to reverse. So therefore, there is a switch here. If I close this, current flows in this direction. Current should be able to reverse, current should be able to flow into the source or back into the source. So, I need to connect an anti parallel diode across the switch, a D_1 across S_1, similarly D_2 across S_2.

So, positive current, if if by term these are the positive current the switch carries, a negative current the diode carries. I said, you need to connect an external diode across S_1. In fact, all the semi conductor devices say for that matter IGBT, a BJT, they do have internal diode connected across. So, you do not need to connect a separate diode across the switch or if you … I said voltage is always positive, polarities cannot reverse, current can reverse; positive current negative current. So, in a VI plane, operation is on 2 quadrants; positive voltage, positive current and negative current. So therefore, a VSI, a voltage source inverter is also known as a 2 quadrant converter. 2 quadrant, voltage positive, current could be positive or negative.

What is another feature of of VSI? The switching signals for S_1 and S_2, they are always complimentary. S_1 and S_2 are, they are complimentary. So, if S_1 is on, S_2 should be off S_2 should be off.

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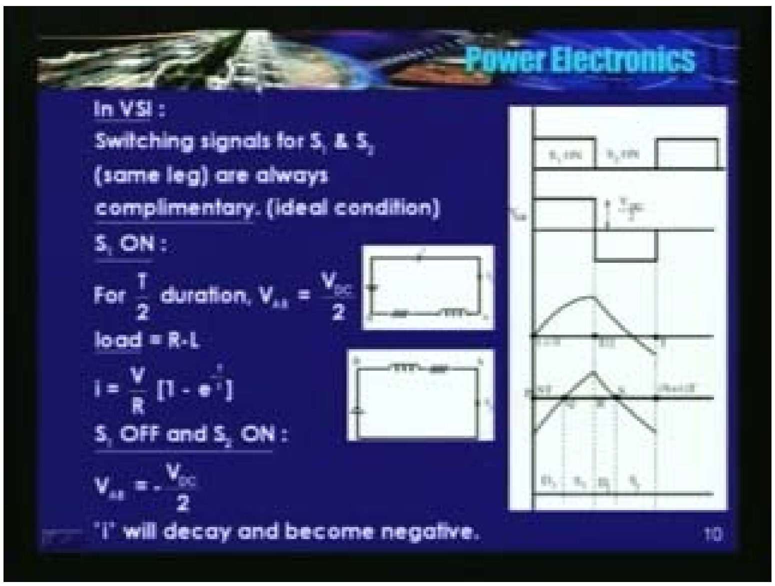

So, how does the circuit works? S_1 is on for T by 2 period, S_1 is turned off and S_2 is turned on for the remaining T by 2 period. So, when S_1 is on, what is the equivalent circuit? See in this figure, when S_1 is on, point A gets connected to the positive of the battery point A gets connected to positive of the battery. So, this is the equivalent circuit. Voltage applied to the load is positive V_{DC} by 2 because with respect to B, point A is at higher potential. Let us assume that load is RL. So, equation for i is V by R into 1 minus e to the power T by tau.

So therefore, for the first cycle for the first cycle T is equal to 0. Current starts from 0, increases linearly and becomes explanation depending upon tau and T. It reaches some value and at this point, T by 2, you open the switch S_1 and close S_2. So, when you close S_2, this is the equivalent circuit. See in this, when I open S_1, close S_2, point A gets connected to negative of the battery negative of the battery.

So, in other words, point B is at a higher potential compared to point A. This is the equivalent circuit. But then when opening S_1 and closing S_2, at that time current is finite. Now, the current will decay and it will reverse. So, at steady state if I have to draw the current wave form, it may look like this. So, when I am closing S_1 current is negative. It increases, becomes positive and attains a positive value. After sometime when you open S_1 and close S_2, it starts decreasing, becomes 0 and becomes negative and this cycle repeats.

Now, what are the observations that you can make from this waveform? I said S_1 is turned on at this point, may be at N_T. N is it could be anything, a positive voltage is applied but current is negative, from P to Q current is negative. Voltage applied to the load is positive. Which device is carrying current now? See here, positive voltage but then negative current from P to Q current is negative.

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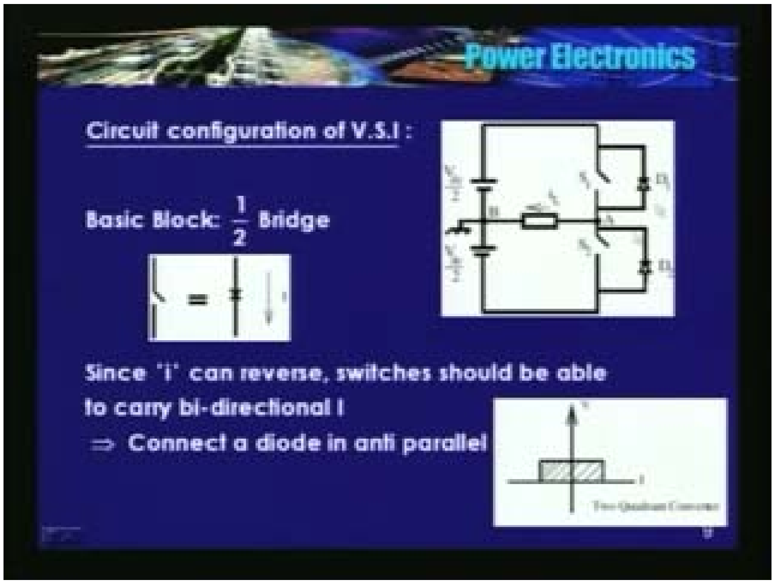

See in this circuit, I can apply positive voltage to the load only when this point is connected to this point. A positive voltage is applied to the load only when point A gets connected to positive of the battery. That can happen when S_1 is on or D_1 is on. Remember, potential of this is same as potential of this when S_1 is on or D_1 is on.

I have assumed a positive value of current. In the sense, positive direction is positive direction of current is when it is flowing from A to B. When the current flows from A to B, it is known as it is assumed to be positive. But then we found that positive voltage is applied to the load but then from P to Q current is negative current is negative. So, in this circuit current is flowing from B to A, B to A and this point is connected to this point. So, it can happen only when D_1 is conducting.

So therefore, though you have closed the switch at NT, that switch will not carry current immediately. It all depends on the circuit parameters. Therefore, from P to Q for RL load, D_1 is conducting even though you have closed the switch S_1.So, because of this the gating requirement changes gating requirement changes.

See, assume that assume that switches are made up of thyristors. Let us assume because thyristor is also there are controllable devices. So, it is possible, in principle I can use SCR's and we all know that a sharp pulse will turn on the thyristor. So, steady state NT, I want to trigger S T_1 or thyristor 1. A sharp pulse is applied, thyristor will not turn on at all thyristor will not turn on at all because current is negative. It is flowing through flowing through the diode that is connected in parallel through the device. Current starts flowing through the device or S: only after Q, only after Q, only after Q.

Say from Q to R, Q to R voltage is positive, current is also positive. From Q to R, voltage positive, current positive. So therefore, it can happen only if S_1 is carrying the current because positive voltage, this point should be connected here, current also flowing in this direction, so S_1 is carrying current.

So, in other words, if S_1 is realized by thyristor, you need to have a gate pulse beyond Q beyond Q because gate pulse should be present till the current through the device is higher than the latching. That is what you had been told. So, a gate pulse should be present beyond Q. Now, what happens from R to S R to S? Voltage applied to the load is negative voltage applied to the load is negative. But then current is positive current is positive.

See in this circuit, voltage applied to the load is negative. In other words, A should be connected to this point A should be connected to this point. Current is positive, current is flowing from A to B A to B but then this point should be connected here. It can happen only when D_2 is conducting D_2 is conducting because when D_2 conducts, potential of this is same as this. But then current is flowing in this fashion in this fashion.

So therefore, from R to S, D_2 is carrying the current. From S_2 to the end of that cycle, S_2 is conducting because the voltage applied is negative, current is also negative. So, you can conclude that even though you have turned on the device, if the load is RL, it may not be carrying that current it may not be carrying the current, remember. In a VSI, just because the device is turned on, it does not mean that the device is carrying the current. It may so happen that the diode that is connected across the device may be carrying the current.

What is other observation that you can make from this operation? S_1 is on for T by 2 and S_2 is on is for remaining T by 2 duration. So, time for which S_1 or S_2 is on will determine the frequency of the output voltage. I will repeat; the time for which S_1 or S_2 or 1 will determine the frequency of the output voltage.

Say for example, if S_1 is on for 10 milliseconds and S_2 is on for another 10 milliseconds, the entire period is 20 milliseconds. That is nothing but I have a 50 herds AC supply. It may be a square wave in this case. But I am calling it AC because average value is 0. Instead, if S_1 is on for 50 milliseconds and S_2 is on for another 50 millisecond, so entire period is 100 milliseconds. So, you have a 10 hertz AC supply. So therefore, the times for which S1 or S2 are on will determine the frequency of the output voltage.

Now, what is another observation that I can make? I said S_1 and S_2 are complementary. In other words, switching signals for S_1 and S_2 are complimentary. Basically, it is an ideal situation. Let me tell you one thing, it is an ideal situation. What happens, if they are truly complimentary what happens?

I said, each a device has its own time or takes its own time to attain a blocking mode. Just because, a BJT or an IGBT; if you withdraw the gate pulses, it does not mean that device has attained a fully blocking mode or device has completely turned off. What what may happen is, you have withdrawn the gate pulses for S_1 and you have applied a gate pulses for S_2 simultaneously and it is if both of them conduct, there is going to be a short circuit across the DC bus.

See here, S_1 was on; you have withdrawn the gate pulse. But then it was not completely turned off and you are applied T_2, it started conducting. Now, there is going to be a shoot through. In other words, there is a short circuit here there is a short circuit here. Input is an ideal voltage source, thevenin the impedance is approximately 0. So, a large current will flow and will may damage the devices.

So that is why reason, you should be extremely careful in operating a voltage source inverter. 2 devices should not be on at any given time or these 2 devices should not be on at any given time. In other words, there should be some delay between the gate signals applied to S_1 and S_2. I will show you in this figure.

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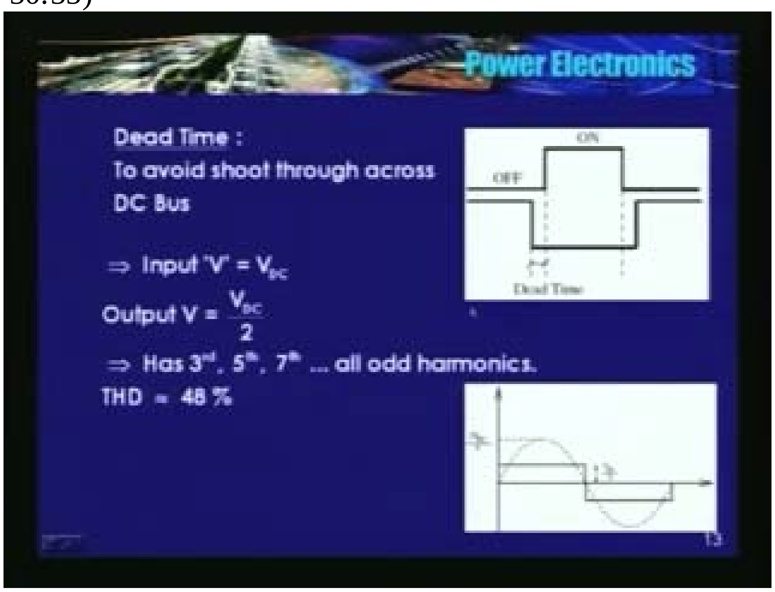

See here, there is something known as the dead time something known as a dead time. Assume that this is for S_1 and this is for S_2. See, S_1 is turned off, S_1 is turned off and for sometime both devices are off. S_1 is turned off here and after sometime S_2 is turned on. After sometime it is turned on.

In other words, in this during this period, both S_1 as well as S_2 are off. Both S_1 and S_2 are off. Same thing is true here; both S_1 and S_2 are off. See, S_2 turned off, after sometime S_1 is turned on. So, for sometimes, both devices are off. Now, you must think that both the devices are off, load is RL, inductive circuit; when the inductive circuit gets open or the current becomes 0 instantaneously? No, answer is no.

Then what happens? Both the devices are off. Remember, there is a diode connected across each device there is a diode connected across each device and current cannot change instantaneously in inductor. So, in this circuit, so if S_1 is turned on and if the current is flowing from A to B, you opened S_1, immediately D_2 starts carrying that current immediately D_2 starts carrying the current in this circuit. Current was flowing from A to B, you opened it, you closed, this current will start from A to B.

So, another important point or that to be remembered is there should be a delay or there should be a dead time between the gating signals of S_1 and S_2. In that dead time, none other devices are on. Second point that is to be remembered is; a voltage source inverter is also known as a 2 quadrant inverter. Current can reverse not the voltage not the voltage and third point having turned on the device, that that device may not be carrying the current. The diode which is connected across it may be connected conducting.

Output voltage wave form is a square wave and I called it as a DC to AC inverter because average value is 0. We are interested in only in a sinusoidal component whose frequency is equal to the frequency of the square wave itself. So, if I take the harmonic or if I write the harmonic series or a Fourier series of this, it has all the odd harmonics. It is an odd function odd function.

So, there is a third harmonic, fifth, seventh, ninth, eleventh including the fundamental including the fundamental, this is the fundamental. If V_{DC} by 2 is the magnitude of the square wave, this will be 2 V_{DC} by pi is the magnitude of the fundamentals. It has a higher frequency third, fifth, seventh and ninth so on, higher frequency components. Magnitude of the square wave is V_{DC} by 2. But then what is the input voltage? We had a centre tapped DC source with V_{DC} by 2 and V_{DC} by 2. So remember, input to the half bridge inverter is V_{DC} but then output voltage is; V_{DC} by 2 in the positive half, minus V_{DC} by 2 in the negative half. Input we have a V_{DC} source, output it is V_{DC} by 2 and V_{DC} by 2. So, that is about half bridge inverter, more about it we will study in the next class.

Thank you.