Power Electronics

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Lecture - 32

In my last class I have started discussing the push - pull convertor. I told you that push - pull convertor is used for high power applications. For medium power, forward convertor is still attractive. What is the limitation of forward convertor? 1 of the limitations is that the source does not supply power to the load during the time allot for core reset and the flux is either positive or 0, unidirectional excitation.

So, in the BH characteristics, operation is always in the first quadrant. So, we can say that magnetics is not well utilized. How do I improve the utilization? To improve the utilization, I need to reverse the flux in the core. But how should I do that? Because input is DC, it is a DC to DC convertor?

Answer is very simple. If I can increase the flux in the positive direction, somehow I have to reverse the flux and do the same thing in a negative direction. So, what I will do is I will use a center tapped winding. See, I have shown here.

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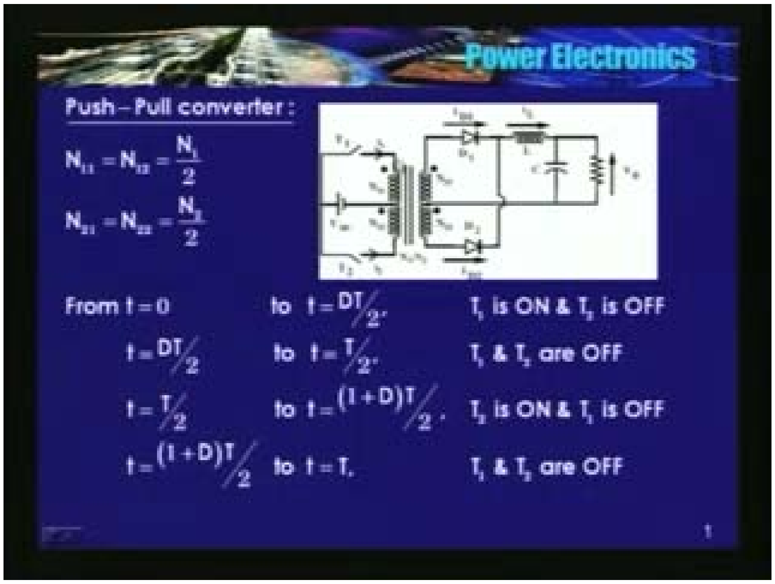

I will use a center tapped winding; see the dotted polarities and I will connect the supply here and 2 switches T_1 and T_2. So, when I close T_1, current enters the dot, so direction of flux, whereas, when I close switch T_2, see, current leaves the dot leaves the dot. So, whatever that happens in N_{11} happens, the just the opposite in N_{12}.

See, positive is applied to the dot. Positive terminal of the battery is applied to the dotted polarity, whereas here; to N_{12}, negative of the battery that is applied. So definitely, direction of flux produced when current i_1 is flowing is opposite to that of the flux produced by i_2. Now, the direction of flux has reversed in the core.

In other words, I can say; it is an AC flux. I have used a transformer. So, voltage induced in the secondary also will be AC. Please, when I am saying AC, it does not mean that it is a sinusoid. It only implies that average value of voltage is 0. That is all, nothing else.

Now, voltage induced in a secondary winding is AC. As I said it is DC to DC convertor, so I have to rectify it. There are various ways to rectify AC voltage. Simplest way is use a center tapped winding and 2 diodes or use a bridge. At that time, I do not require a center tapped winding. The so, the advantages and disadvantages of using a center tapped winding and 2 diodes and using a bridge, I have already discussed in AC to DC conversion. They are still valid here.

Now, let us see how this circuit works? T_1 and T_2 are complementary. Switch signals for T_1 and T_2 should be strictly complementary. What happens if there is a sum overlap, I will discuss sometime later. So, when I close T_1, current enters a dot in the primary in N_{11}. So, current enters the dot, the right direction in the secondary is to leave the dot. So, current leaves N_{21}. In other words, D_1 gets forward biased or D_1 starts conducting.

See, N_{11} and N_{21} is same as the forward convertor operation. Recall a forward convertor operation; I closed T_1, current enters the dot in the secondary, diode also started conducting and power is transferred to the load. So, N_{11} and N_{21} is nothing but a forward connection. So, voltage induced or voltage applied to N_{11} is V_{DC}. So, voltage that is induced in N_{21} depends on the turns ratio.

So, when T_1 is on, what is the voltage that is appearing across T_2 or in other words, what is the voltage rating of T_2? I said primary is a center tapped winding, so N_{11} number of turns in N_{11} winding is same as N_{12}. So, voltage that is appearing across T_2 is twice the V_{DC} twice the V_{DC}. See here, equivalent circuit I have drawn some where here.

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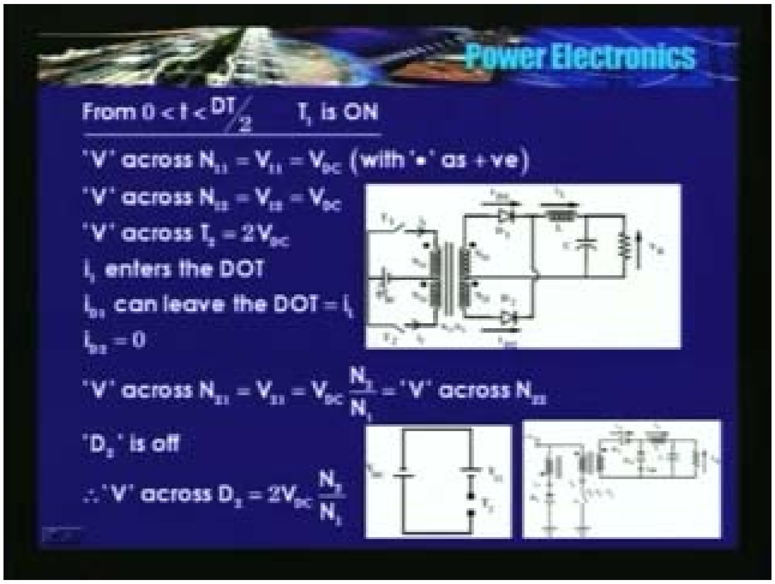

V_{DC} - negative; see, dot is positive, so dot is also positive here. So, V_{11} sorry voltage that is applied to N_{11} is V_{DC}. So N_{12}, voltage induced in N_{12} is also V_{DC}. See V_{12}: that is nothing but V_{DC} itself. So, voltage that is appearing across T_2 is V_{DC} plus V_{12}. That is nothing but twice V_{DC}. So remember, voltage rating in a push - pull convertor; the device that is used in a push - pull convertor is twice the supply voltage.

So, when the primary is energized, in the secondary current flows through D_1. D_2 is off. See, this operation of this part is same as that of a center tapped transformer used in AC to DC conversion. D_2 cannot conduct. Again, voltage rating of V_B, voltage rating of this diode is twice the voltage induced in either in N_{21} or N_{22}.

Now, after sometime T_1 is opened. In fact, T_1 is opened at DT by 2. Now, what happens? Flux in the core should be continuous. When T_1 is closed, primary has the magnetizing current plus the equivalent load current or in other words, I_M plus i_2 prime. So, when I open the switch, I_M should be continuous. So, when I close the switch, current enters the dot.

You recall the operation of forward convertor. See, I have drawn the forward convertor here for convenience. So, in the primary when I close the switch, current enters the dot. So, when I open the switch, the right direction for flux continuity is that current in the tertiary also should enter the dot current in the tertiary should also enter the dot.

Now, come back to push - pull. Magnetizing current should be continuous. So, when I open the switch, what happens in the secondary? I said current was entering the dot when I had closed the switch in the primary. So, the right direction for the flux to be continuous is that current should enter the dot in in any another winding. That can happen in the secondary in N_{22} only. Current can enter N_{22} and leave through D_2. So, if D_2 turns on or if this winding starts carrying the magnetizing current, flux will be continuous. But then there is another problem.

See the secondary; we have a center tapped winding. Current enters the dot in N_{22}. So, the moment D_2 starts conducting in the upper half, even D_1 starts conducting. So therefore, when I open the switch in the primary; till the in the secondary, both D_1 and D_2 starts conducting. So, see the circuit equations are here.

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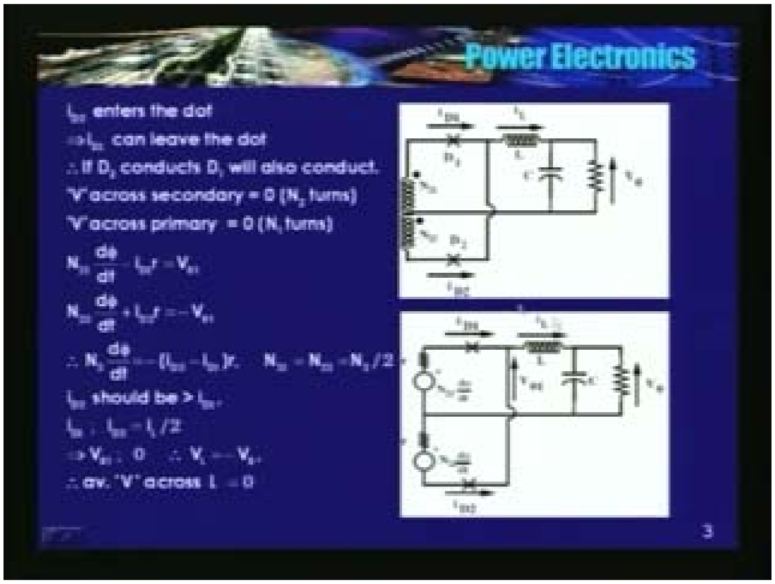

See, dot terminal here, dot here, so voltage induced, so N_{21} d phi by dt is the voltage source with the positive terminal. Similarly, N_2 to d phi by dt, positive here. I am taking a small resistance, winding resistance into account and I will apply KVL. What KVL gives for the upper loop? The KVL is N_{21} d phi by dt minus r into iD_1 should be equal to V_{O1}. In the in the second loop, it is i_{D2} into R plus N_2 to d phi by dt is equal to minus V_{O1} minus V_{O1}.

See the 2 loops. See direction of current and the and the 2 voltage induced voltage sources. So, these are 2 equations. Now, N_{21} is equal to N_{22} that is equal to N_2 by 2. So, I will add them. Add these 2 equations and I will get this equation. We know that when I close the switch in the primary, flux in the core increases. So therefore, when I open the switch, flux in the core should decrease.

I have an equation here; N_2 d phi by dt is equal to minus of iD_2 minus iD_1 into R. In other words, N_2 d phi by dt should be negative. When can it be negative? It can happen only when iD_2 is higher than iD_1 and it is entire magnetizing current is flows through N_{22} and the load current i_L gets divided into 2 parts. Half of the inductor current starts flowing through N_{21} and the remaining half starts flowing through N_{22}.

So, the magnitude of current when you open the switch in N_{21} is i_L by 2, whereas, in N_{22} is i_L by 2 plus the magnetizing current. By the way, magnetizing current is not the same magnitude that was flowing when the switch was closed. In the primary, it is a reflected current. Please, it is a reflected current. So, in fact, iD_2 is higher than iD_1.

Now, when both the switches are conducting, what is the voltage drop across the secondary or what is the voltage across the secondary winding? See, this is the voltage across the secondary winding; N_2 d phi by dt. iD_2 minus iD_1 is nothing but the magnetizing current, equivalent magnetizing current. Winding resistance is very small. So, in other words in other words, voltage across the entire secondary is 0. Voltage across the entire secondary winding is 0. So, the voltage across the entire winding secondary winding is 0; by transformer action, voltage across the primary winding, the induced should also be 0.

In fact, this is an approximate sign; not a semi colon, this is an approximate sign. iD_1 approximately equal to iD_2 is equal to i_L by 2. Now, I have this equation. I will substitute in this, N_{21}.What do I will get? Since winding resistance is very small, I can say that V_{O1} is also 0. I will substitute this, whatever that I get in the last equation, in the first equation and I will solve for V_{O1} and find that V_{O1} is also very small. In fact, it is 0.

So, V_{O1} is nothing but the voltage across N_{21}. If that is 0, the voltage across each half in the primary is also 0. So, this is about the operation of the push - pull convertor. Remember, when I close the switch, only 1 diode is carrying the current. So, when I open the switch, both the windings sorry both the windings in the secondary or in other words both the diodes starts carrying the current.

So, in the process, how do I derive the transfer function for the push - pull convertor? So, when the switch is closed, I said this power circuits looks similar to that of the forward convertor. When I close the switch, both the diodes are conducting. So therefore, V_{O1} is 0. So, if V_{O1} is 0, what KVL gives for this loop? It is nothing but voltage across the inductor is minus V_C. It is V_L is equal to minus V_C. So, by equating the voltage across inductor when the switch is on and when it is off, I can derive a transfer function. See here.

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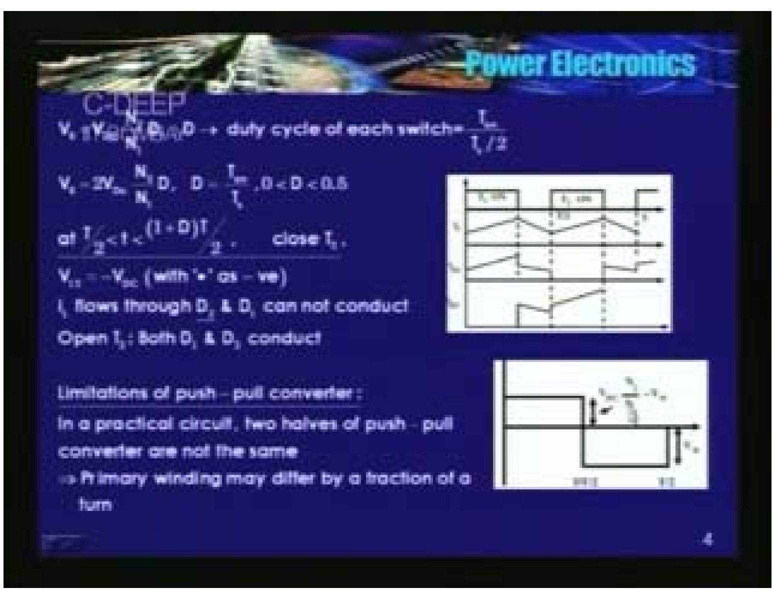

See here, V_{DC} N_2 by N_1 minus V_0 is the voltage across the inductor when the switch is closed, because at one end of the inductor, we have V_C or we have a capacitor with V_0. In other end of the winding is voltage induced in the secondary winding and when the switch is opened, both the diodes starts conducting. So, V_{O1} becomes 0. So, voltage across the inductor is the capacitor voltage itself. That is nothing but V_0. So, this is nothing but, this same waveform we had for a forward convertor forward convertor. But the only difference here is, see, we have DT by 2 and T by 2, wherein forward converter, we had DT and T. I will equate it and I will get a transfer function.

See here, V_{DC} N_2 by N_1 into D where same as same as forward converter where D is a duty cycle of each switch each switch remember, each switch. It is nothing but T_{on} divided by T_S by 2 T_S by 2 duty cycle of each switch. So so instead of using this definition as D, I will use this definition; D is equal to T_{on} by T_S. Then I will get V_0 as this V_0 as this. Twice V_{DC} into N_2 divided by N_1 into D. So, this is the transfer function for a push - pull converter.

I will just show the current wave forms also. See here, load current or iD_2, the same as the inductor current increases linearly when the switch is on. Flux in the primary increases linearly again, may be, starts from 0. At this point, switch is opened. Inductor current starts decreasing. May be, but immediately, see see the current iD_1 and iD_2; iD_1 falls to i_L by 2 and decreases, iD_2 increases from 0 to i_L by 2 plus I_M dash plus I_M dash. So, it continuous still you close T_2 again. So, when you close $T_{2,}$ whatever that happened during T_1 will happen here will happen here.

Now, immediately diode D_1 turns off. Entire i_L entire iL entire iL starts flowing through D_2. In fact, this is i_L. See, there is a jump here there is a jump here. This jump is nothing but i_L by 2 supposing, it may. So, I will not discuss too much about push - pull converter. Compared to fly back and forward, push - pull converter is bit difficult bit difficult. So, I will not go into detail. I will just tell you the limitations of a push - pull converter. What could be the limitations of a push - pull converter?

We have in the primary, a center tapped winding. Whatever that happens when you close T_1, happens just the opposite when I close T_2. To have symmetrical flux waveform or BH loop transition, I need to have identical terms in the primary; in the N_{11} as well as N_{12} turns. See here.

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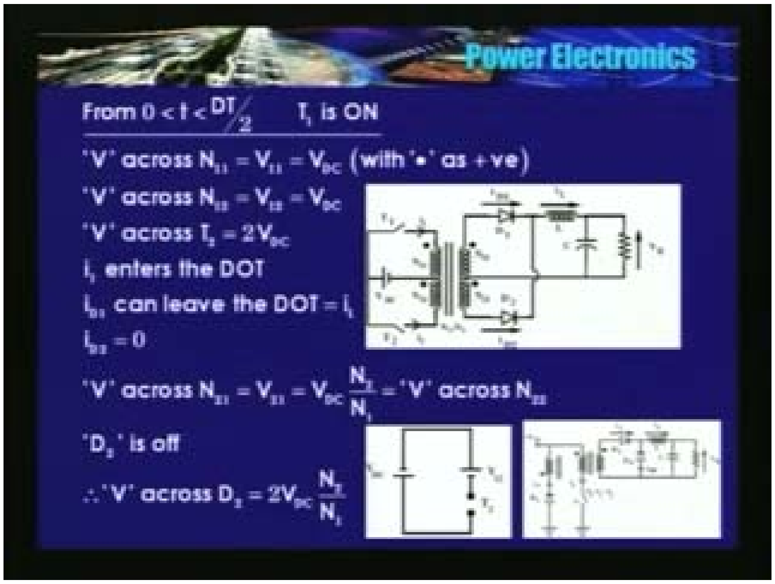

So, number of turns in N_{11} should be same as that of N_{12} and the saturation voltage. In other words, when the device is conducting, the voltage across the device should be the same should be the same. If they are not the same, what will happen? Voltage that is applied to N_{11} may not be the same as N_{12}. So, what happens? The the value of flux that is established in the core when T_1 is on, may not be the same in the negative half in a negative half when you close T_2.

So, in other words, I have a average value of flux in the core. A DC flux exist in the core because I am applying a 2 different voltages for the for the windings or in other words, in a transformer theory in AC excitation, I have a sine wave whose halves are not symmetrical along the x axis. So, so it it remands to a DC flux in the core also DC flux in the core.

So, it may so happen that when I or during over load or sudden change in load, the controller says that increase a value of D. Controller has given a command to increase the value of D, there is a DC flux and it may so happen that core may be driven into saturation. So, protective circuit should be very fast. The moment the circuit identifies a core saturation, immediately it should block the gate pulses for the for the devices. Otherwise, devices will get damage because once the core has saturated, current is limited by the winding resistance.

What is the next limitation? I said, in the beginning the switch signals for T_1 and T_2 are complimentary. In fact, there has to be a dead time. In the sense, you turn off T_1, wait for some time and then you turn on T_2, you cannot. The moment you turn on the, the moment you turn off T_1, you cannot turn on T_2. They cannot be strictly complimented. There has to be a dead time or dead time in the sense, during that time, none other devices in the primary are on. So because, if there is no dead time and both the devices are conducting simultaneously, both the devices are conducting simultaneously, I said number of turns in both the half is the same. I will assume the leakage also to be the same. In other words, self inductance of the upper winding is same as the self inductance of the lower half and that is equal to the mutual.

What will happen now? The flux produced by the upper half opposes the flux produced by the lower half. Net flux in the core is 0 and the current is limited by the winding resistance because there is a cancellation of flux. So, V_{DC} is equal to I into R, R is very small. So, you know, devices may get damaged. So, this is what I have explained here.

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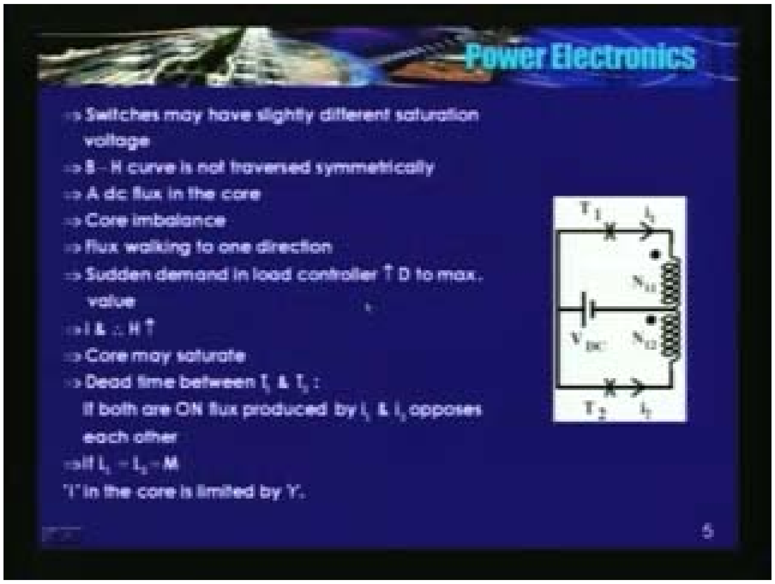

So, this the dead time between T_1 and T_2. If both are on, flux produce by i_1 and i_2, they oppose each other. I am assuming, of course, invariably it is true because I have a perfect winding with with a center tapped here. So, N_{11} is equal to N_{12}. So, I can safely assume that self inductance or L_1 of this is equal to L_2. That is equal to the mutual inductance. Then, the current in the core when both the switches are on, is limited by R. So, we should be extremely careful in designing the gate drive circuit for the push - pull converter.

What could be another limitation or or another limitation could be; voltage rating of each devices is twice the supply voltage, minimum voltage rating. Minimum voltage rating of T_1 and T_2 is twice the supply voltage. So, that is the reason, push - pull converter is generally used for low voltage high current power supplies because voltage rating is higher. As the voltage rating increases, you need to choose a device of higher voltage and it is invariably, our experience is that it is easier to handle a higher current than a higher voltage. So push - pull converter is suitable for or generally used for low voltage high current DC power supplies.

So, that is about the push - pull converter. Over the years, you have seen power conditioning moved from the early stage linear regulators through relatively low frequency pulse width modulated systems to high frequency converters. So, these high frequency converters, pack the same power handling capability of earlier designs into a size which is much smaller than the earlier ones. So, in other words, the size of high frequency power conditioning equipment is much smaller compared to that of our earlier designs.

Take for example; the UPS that is generally used in our homes. How heavy it is, UPS or inverters? Same UPS, we are using in the labs. They are so small. May be, 5.5 KV inverter or 5 KV UPS which is used in the lab, I may be able to hold in my palm. So light, whereas, it will be difficult for me to lift a 0.5 KV UPS which is used in my home.

So, if you see the history of power electronics development, till the 1960s and earlier we had systems with linear regulators, they were highly inefficient, larger in size. But then very simple to design and may be at operators … Then after words, we had systems with switching regulators. They use relatively larger size of L and C. A large number of ICs where required to control these regulators. Now, what is the reason of reducing the size of the the the present day's UPSs to such a smaller size? That is because we have almost a new technology what is known as the resonant power conversion.

Now, before going to resonant power conversion, I just try to tell you what are the disadvantages of the of the control technique that we used so far. Take for example; a boost converter.

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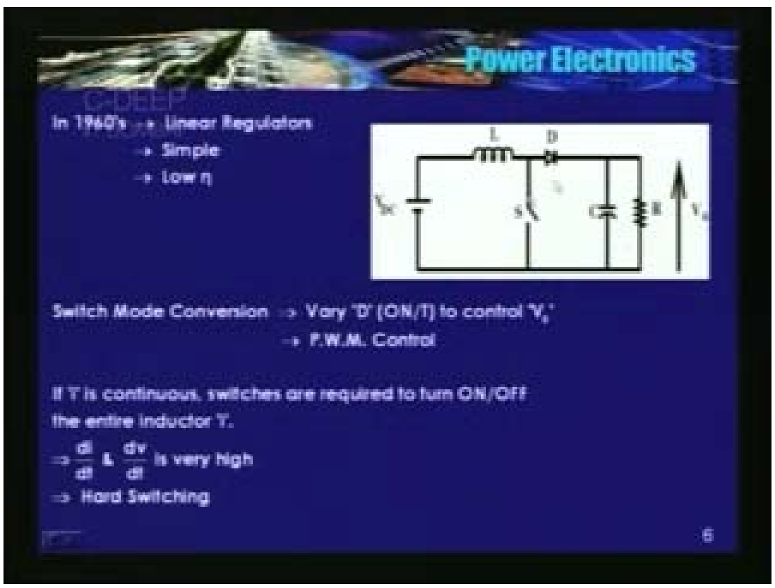

What happens when I close this switch? Whatever that the current that is flowing through L, starts flowing through S. If the current is continuous, instantaneously S has to carry that current and when I turn it off, the current instantaneously becomes 0. In addition to the inductor current, sorry even this diode has to recover and the diode recovery current also starts flowing through S.

So, when I close the switch, di by dt, the rate of change of current that is flowing through S is very high. Also, there is no way I can control the rate of decrease of voltage across the switch. So, basically this type of switching is known as the hard switching. Why it is hard switching? Because, I do not care what is the voltage across the device or what is the current through the device. Whenever whenever it has to be turned on, it is turned on.

So, as a result, the stress on the device, di by dt, it has to carry instantaneously it has to carry the inductor current as well as as well as the diode recovery current. di by dt is very high. See the locus here, the hard switching device.

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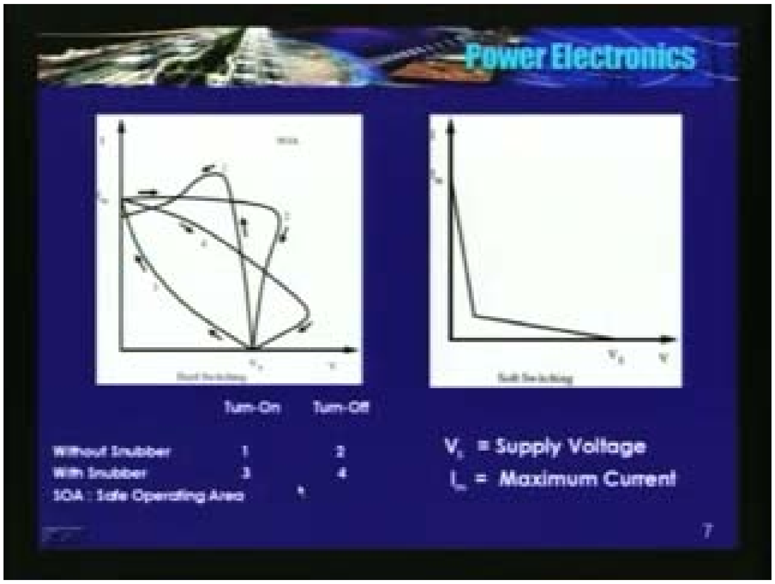

When I turn on, initially just prior to turn on, current is 0. So, it starts increasing. Voltage also starts falling and takes this path. I have explained this while covering the devices. I am just redrawing and when I turn off, this is the path. Now, it is possible to control the rate of rise of current as well as rate of rise of voltage across the device by connecting an external snubber, a passive snubber or lousy snubber. So, this is the path 3. While turn on, while turn off, this is the path.

So, what happens? The instantaneous power loss that was taking place in the device is high. See here is it. I will just show you.

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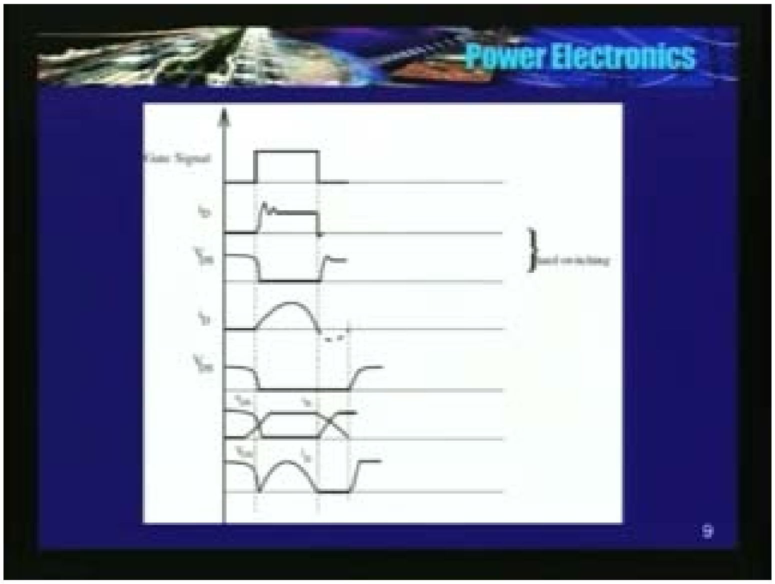

Voltage across the device is falling, current is increasing. So, voltage across the device is quite substantial when it is carrying a relatively higher current. So, instantaneous power loss is high here. We have we could reduce the losses taking place in the device by connecting a snubber. Since I it is a passive snubber or lousy snubber, the losses that are taking place in the device are transferred to an external circuit and they are dissipated there.

So, in other words, we are not able to reduce the switching losses or the inverter losses. By connecting a snubber, we are able to reduce the losses taking place in the device. Inverter efficiency has not changed because losses have not come down. So, the major limitation of a hard switch converter is that device stress is high. di by dt and dv by dt are relatively high. So, what is the reason? So, what is the consequence? As a consequence, the switching frequency has to be reduced. You cannot operate a hard switched converter at a very high frequency.

First of all, the losses taking placing in the inverter are high because it is a hard switch. As I increase the frequency, this loss will also increase. So, overall inverter efficiency comes down. As the losses have increased, I need cool the inverter. So, my cooling requirement or heat sink requirements are increased. So therefore, size also increases, operating temperature has increased. The reliability comes down, di by dt and dv by dt are very high. So, these produce their own magnetic fields. So, there is going to be a electromagnetic interference or EMI problems.

So therefore, the switching frequency of a hard switched inverter cannot be increased above certain range. I you may ask what is that range? I have no answer to that question because it all depends on the voltage rating, the power that is handling and the current. Because, for example, MOSFET or a BJT or an IGBT; basically these are fast devices. But then it does not mean that I can operate IGBT at a very high frequency in a when the input voltage is very high and the power handled is also very.

So, high frequency and the high voltage, high current is just not possible from a single device. In other words, as the power rating increases, I need to come down to the switching frequency. But then I have to reduce the size of the inverter or I have to eliminate all these limitations, EMI. A device cannot produce or affect another equipment which is kept nearby. You have to if you have to sell your product in the international market, there are EMI regulations. So, you may say that I may be I am ready to compromise on efficiency, may be. But then it cannot affect the performance of other equipment which is kept nearby.

How do I eliminate these problems? You can eliminate these problems by switching the device when the voltage across it or when the current that is flowing through it is 0. I will repeat, when the voltage across the device is 0, you turn it on; current starts slowly rising. Voltage across the device is any way 0. So, the power loss that is taking place in the device has come down to 0 approximately or current that is flowing through the device are somehow using the external circuit. I am controlling the di by dt. In other words, the device current that is flowing through the device as soon as I turn on, is always 0. It do not have to carry, instantaneously carry a large current.

Please, try to understand. When I am saying current through the device as soon as I turned on is 0, what I mean is here; see, as soon as I turned on here, the device whatever that current that is flowing through the inductor should flow through S.

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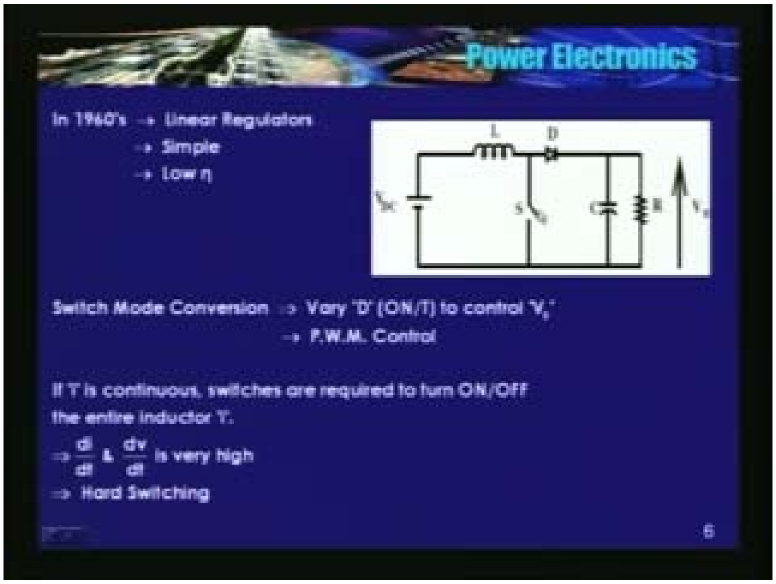

So, instantaneously it will jump to the inductor, the value of the current that is flowing here. In addition, there is a recovery current, diode recovery current. So, instead of having a step jump, what I do is I start increasing slowly from 0.

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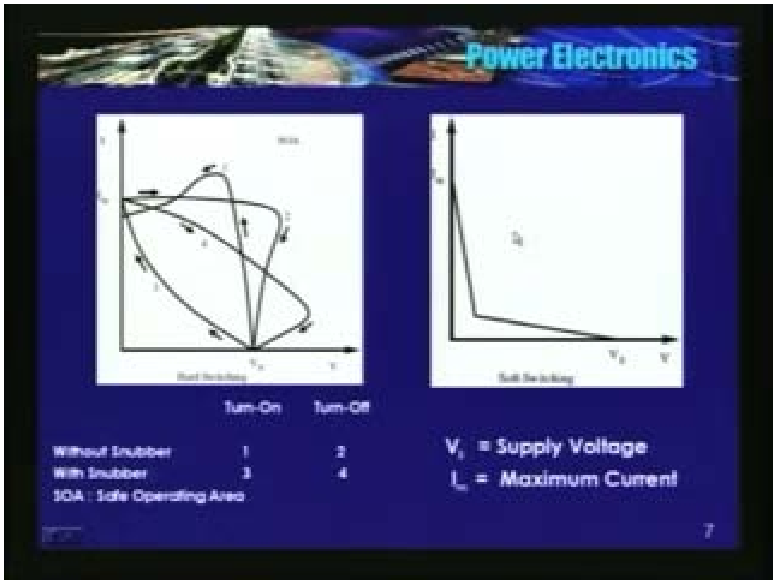

So, these class of inverters or this sort of converters sorry, sorry to use the word inverters. These classes of converters are known as soft switched converters soft switched converters. So, here is the locus. See here, this is the path; current slowly increases, voltage also falls and may be, increases here. Now, it can increase at a faster rate here, no problem because voltage across the device has already become 0, approximately to a very low value. See, the current starts rising very slowly, voltage also falls. So, area under the curve has reduced now, whereas see here, current has substantially has increased, voltage has not fallen much.

So out here, voltage is already fallen to a very low value, now the current increases. Similarly, while turning off, current decreases. I am not allowing the voltage to increase across the device because by connecting some additional components. How? We will see later. Current current decreases but voltage has not increased. Now, the voltage across the device starts increasing. But then at that time current has substantially reduced substantially reduced. So, area under this curve is very small compared to the area under this curve.

So, what are the advantages here? Voltages across the device as well as the current flowing through the device are controlled. They are slowly increasing or decreasing. So, device stress has significantly reduced. The device is switched when the voltage across it is 0 or the current through it is 0. In other words, instantaneously do not need to carry the large current. Practically, switching losses; turn on as well as turn off losses has reduced significantly significantly significantly.

Now, device losses have reduced significantly, stress has reduced significantly. Now, you can increase the switching frequency. Now, if I can switch increase the switching frequency, size comes down. Size of the converter comes down. Inverter efficiency sorry inverter losses have come down, switching losses have come down, my cooling requirement has come down. Size has reduced size has reduced. But then how am I doing all these? How am I ensuring a slow rise in current and a slow slow rise or fall in current and voltage? Because, in this circuit it looks like everything depends on the load and the source. Whatever the current that was flowing through the inductor L when I closed the switch, it has to flow through S. So, I have to do some modification in the existing circuit. But then while making this some modification; the circuit should not lose its basic character.

In other words, the circuit should function as a boost converter or because I have am showing a boost converter for most of the time. I will repeat; for most of the time, circuit should function like a boost converter. This circuit should work like a boost converter. Only when I have turned on or when I have to turn it off, there is a slight modification.

I said I need to use some sort of a resonance technique, soft switching or I have to create some sort of resonance, LC resonance in the circuit. Only when I have a LC resonance, voltage or current starts from 0 in the resonance circuit. So, in addition to the existing components, I have to use separate L and separate C. By the way, what is a resonance frequency of this L and C or in other words, why am I doing or why are we going for the soft switching?

One is I have to increases the switching frequency, therefore I have to reduce the size. Therefore, I can reduced the size. Also, I have to reduce the switching stresses, may be, device stresses. So, to reduce the size of the converter, I have to increase the switching frequency. So, in other words, resonance frequency of this circuit of this LC component should be or will be very high. It could be of the order of say 500 kilo hertz. Again, it depends on the power level, please listen it. This LC resonance circuit, the frequency could be of the order of 500 kilo hertz. Let us see, the resonance frequency is of the order of the 500 kilo hertz, the size of the L and C becomes very small. Size of L and C becomes very small.

Now, I will come back to hard switch converter. Why am I having this as voltage spike or a current overshoot in the circuit? Most of the time the design, if you read the text books, it say a parasitic inductance and parasitic capacitors because of the parasitic inductance, we have a voltage spike. So, the value of this parasitic inductance and capacitance is very small and they effect adversely in hard switch converters.

Now, in soft switch converter, I want a very small L and C to create resonance. Now, I can use the so called parasitic inductance and capacitance for my advantage. See the see the see the beauty of soft switching. All these overshoots are because of the parasitic inductance and capacitance. Now, I can use this parasitic inductance and capacitance for my advantage for soft switching.

By the way, in addition to parasitic L and C, we have to use a small L and C in the resonant converters. I am just trying to highlight is that parasitic tendency can be used effectively in soft switching. So, these are all the advantages of the soft switch converters or the resonant converters resonant converters.

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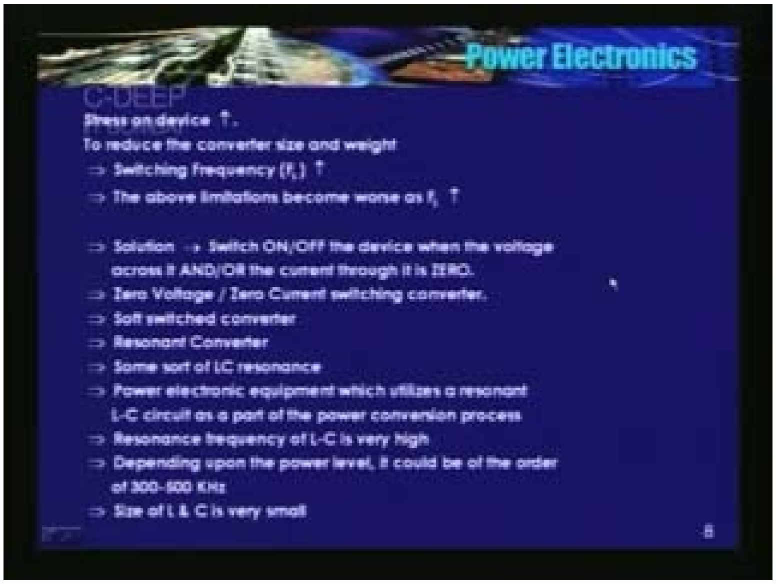

So, if if I switch the device when the voltage across it is 0 volt 0 volts, they are known as 0 voltage switched or ZVS. Instead, if the current through it is 0, they are known at 0 current switched converters. If the voltage across the device is 0, it is known as 0 voltage switched or if the current is 0, it is known as 0 current switched converters. More on this, I will discuss it in next class.

Thank you.