Power Electronics

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Lecture - 25

Last class we discussed the operation of a buck converter and the boost converter. We derived the transfer function for buck as well as boost converters. For a buck converter, the transfer function is or V_0 is D into V_{DC}, provided, current is continuous. In other words, inductor current I_L is continuous. Output voltage is given by D into V_{DC}. It is independent of the load current, independent of the load or inductor current.

We found that if the load resistance increases above a critical value, current may become discontinuous and if the current is discontinuous, the voltage is no longer equal to D into V_{DC}. It is equal to D V_{DC} divided by beta where beta is the instant, current becomes 0. It is greater than D but then less than 1. Therefore, the output voltage is higher than higher than D into $V_{DC.}$

The second observation was the ripple in the output voltage as well as the ripple in the inductor current. Current increases when the switch is closed and current decreases when the switch is opened. The ripple in the inductor current as well as the ripple in the output voltage is a function of D that is maximum when D is equal to 0.5 for a buck converter. We have derived this in the last class. About the boost converter, ideal boost voltage tends to infinity when D is equal to 1. For a non ideal boost, output voltage tends to 0 as D tends to 1. Why?

In an ideal boost, while deriving the transform function we had assumed that V_0 is constant and ripple free. This may be true or this will be true for low values of D. As you increase the value of D towards 1, most the time capacitor is supplying power to the load. So therefore, capacitor voltage will decrease, will decrease and, and at the input side, inductor is almost permanently connected to a DC. So, it will saturate, current will be very high, V_{DC} by R. So, either the source or inductor or a switch will fail and output voltage will become 0.

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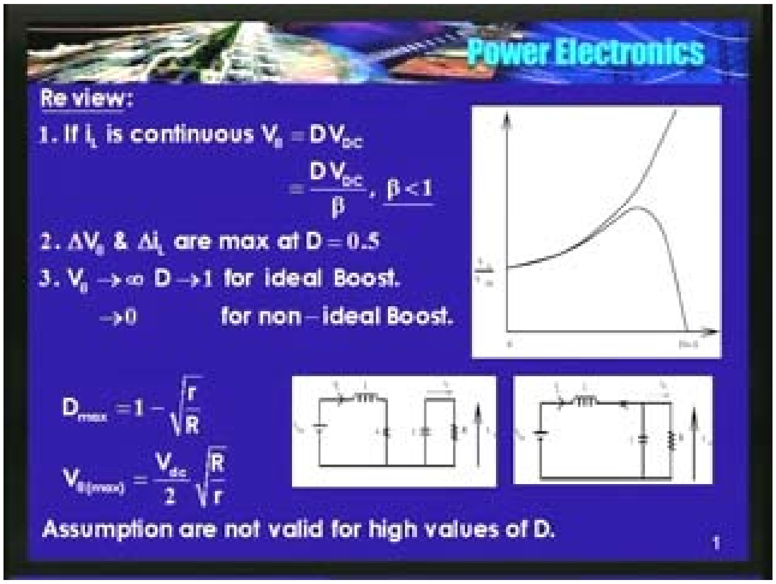

See in this equation, in this circuit, this is when the switch is closed, capacitor is supplying power. If most of the times switch is closed, capacitor will continue to supply power to the load. So, it will discharge. I cannot assume that this voltage will remain constant. Eventually, it will become 0 when S is equal to 1. Of course, you cannot achieve that condition because something else will happen here.

So, output voltage is approximately equal to V_{DC}. If I consider the value of the resistance of the inductor, it increases till D is equal to D_{max} and it is given by 1 minus square root of r by R. This r is the internal resistance of the inductor and capital R is the load resistance and this maximum voltage is given by this equation. So, it is a strong function of the internal resistance of the inductor.

So generally, the thumb rule is V_0 divided by V_{DC}, could be of the order of 7 to 10, a good inductor. I told you how to get, how to design, a design and fabricate a good inductor using a litz wire or using a thin conductors, large number of thin conductors twisting together and using a ferrite core. In the process D, in the process Q, the quality factor of the inductor improves. So, if I use a good quality of good quality inductor, maximum value of V_0 to V_{DC} could be of the order of 7 to 10, 7 to 10.

Now, the filtering requirement for the buck converter as well as the boost converter, what is the source current wave form in a buck converter? If the current is continuous when I close the switch, whatever the current that was flowing through the diode, starts flowing through the switch or from flowing through the source.

So, instantaneously source has to supply the current that was flowing through the inductor and when I open the switch, the current becomes 0. So, instantaneously there is a rise and instantaneously there is a fall. So, current changes abruptly in a buck converter, the source current. So definitely, you require the filter at the input side. What happens in a boost converter?

The boost converter, the source is always present even during powering as well as, as well as or even when the switch is closed and when the switch is opened and the switch is closed also source is there in the circuit and even when I open the switch, source is there in the circuit. Here current increases and in this case, current decreases, current decreases.

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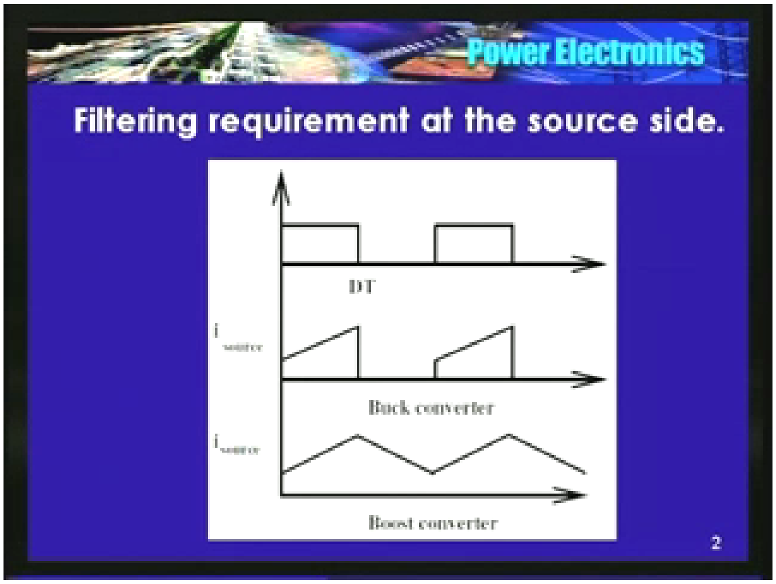

So, the source current wave form if I plot, source current wave form is same as the inductor current, same as the inductor current. It looks something like this; it is a smooth change, smooth change. So, if I select an inductor such that this current ripple is minimum or is very small, I can say that the source side is approximately a current source. Though I have a voltage source and an inductor, I can represent the input side; source and the inductor as a current source, current source in the sense, current is approximately constant. In an ideal current source, current is always constant, whereas, a non ideal source I can I can assume that the input stage for a boost converter is approximately a current source.

I have an inductor as well as, as well as a DC source. Inductor is selected in such a way that ripple is controlled. So, current varies within a small band. It increases when the when I close the switch and when I open the switch, current decreases. So, current is controlled within hysteresis, within a small band. So, I can represent the input stage of a boost converter by a current source. So, I may not or an input filter may not be required, whereas, an input filter is required for a buck converter. Current changes in a step, drastically changes. It it starts with a finite value and stops, comes to 0, abruptly. There is an abrupt change in the source current. So, in order to smoothen the current, you need to have the input filters.

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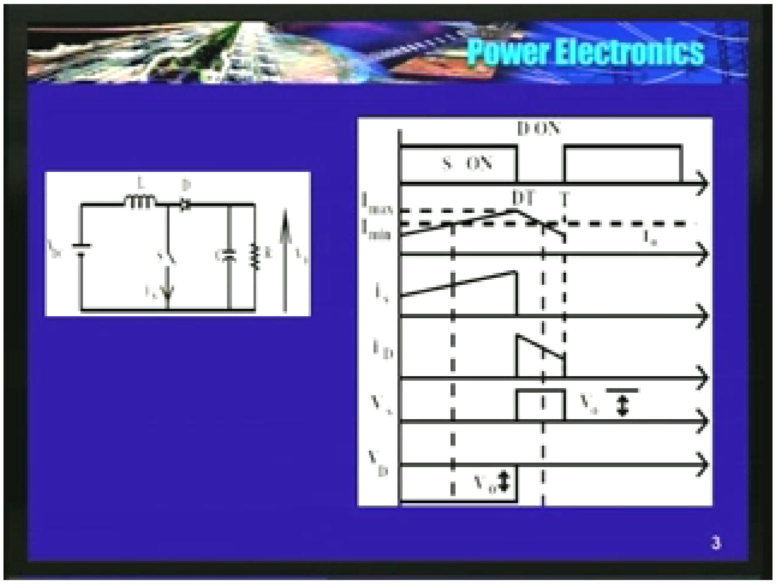

Now, let us plot the various wave forms for a boost converter for a when the current is continuous. We will assume that inductor current is continuous. When I say current is continuous, in buck as well as boost, it is the inductor current and not the load current. Load current is supposed to be, supposed to remain constant because we are assuming V_0 to remain constant and this is true for, invariably for low values of D, low values of D.

So, here is the circuit. Switch is on for D into T duration and from DT to T, D it is on. So, current increases from I_{min} into I_{max} and from I_{max} to I_{min} it decreases, from DT to T. So, when I close the switch, the source current or the inductor current is same as the switch current, I_S. I_S, I have representing as the switch current. I might have said I_S is the source current in the in the buck converter, may be, it does not matter.

But here, I am saying I_S is the switch current. So, it when I close the switch, it jumps to the current is flowing through the inductor or through diode D, increases linearly. When I close the switch, it becomes 0. Immediately the current that are flowing through S, just prior to opening it, starts flowing through the diode and this is the diode connector. So, what is the voltage across the switch when the diode is not, when the diode is conducting? When the diode is conducting, $V_{0,}$ a voltage across the C appears across S. That is a short here. So, V_0 appears across S.

So, this is the voltage wave form, voltage across the switch, V_S is voltage across the switch, V_0 and what is the voltage across the diode when the switch is conducting? It is V_0 itself because when switch is conducting, there is a short here. So, this point gets connected here. V_0 appears across D, 1minus V_0.

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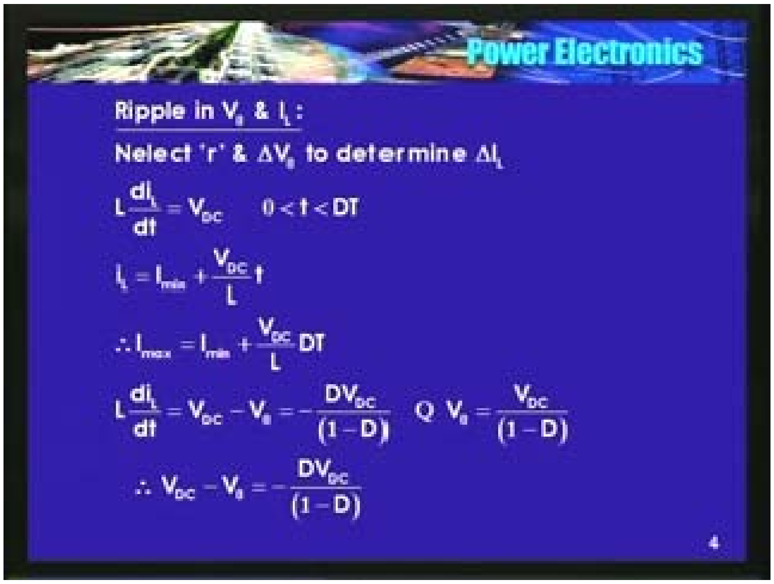

Now, let us calculate the ripple in the output voltage and ripple in the inductor current. For temporarily, we will neglect the resistance of the inductor and we will assume that output voltage remains constant. Delta V_0 is neglected. So, when the switch is on, what is the input side equation? L di by dt is equal to V_{DC}. So, the equation for current I_L is, equation for I_L is I_{min} plus V_{DC} by L into t. This is the equation of the line or slope of the line is V_{DC} by L, V_{DC} by L is equal to dI_L by dt. So, this is the equation for the inductor current when the switch is closed. I reaches I_{max} or I is equal to I_{max} when T is equal to DT and just substitute for T, so I will get an equation for I_{max}.

Now, when I open the switch, what is equation for the inductor current? L di by dt is equal to V_{DC} minus $V_{0,}$ V_{DC} minus $V_{0.}$ I will substitute for $V_{0,}$ V_0 is given by V_{DC} divided by 1 minus D, is equal to this, should be negative, only then current will fall. In other words, V_0 should be higher than V_{DC}. That is the essential condition. So, V_{DC} minus V_0 is given by d V_{DC} divided by 1 minus D.

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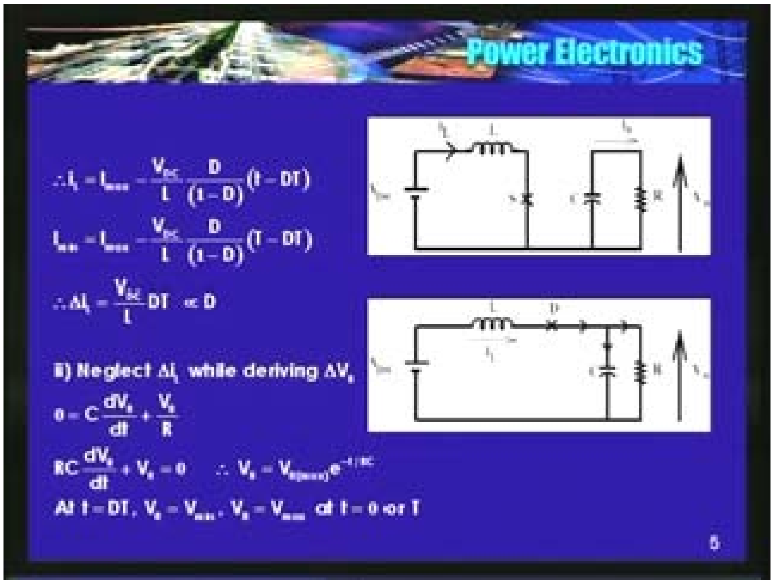

Therefore, I_L is given by this equation and I_L is equal to I_{min} when t is equal to T. I will just substitute for T. So, this is what is delta I_L? Delta I_L is I_{max} minus I_{min} which is nothing but this term, this term, this term. So, we will prove that we will find that, of course, 1 minus D gets cancelled with 1 minus D. So, I will get V_{DC} divided by L into D into T. So therefore, ripple in I_L is proportional to D in a boost converter. So, it is very obvious, in the sense, when I if I close the switch for a longer duration, I_L increases linearly. So, in a boost converter, ripple is proportional to T. It goes on increasing, whereas, in buck converter we found that both d V_0 and dI_L, ripple in output voltage as well as the inductor current is maximum at D is equal to 0.5.

Now, how do I determine the ripple in the output voltage? By the way, when the capacitor is charging and when the capacitor is discharging? When the switch is closed, capacitor supplies the load. So, entire on period of the switch, capacitor is discharging which is different, in a buck converter capacitor is charging even when I open the switch. It starts charging somewhere in between in between 0 and DT, when the inductor current is higher than the load current, capacitors starts charging.

So, capacitor is charging in between 0 and DT and it is continues to charge beyond DT in a buck converter, whereas, in a boost converter, we will see here in the equivalent circuit that capacitor is continuously discharging when the switch is closed. So, I will assume, we have assumed that V_0 is remains constant. Of course, it may change but then V_0 by R is going to be very small. Change in V_0, very small. So, V_0 by R is still smaller. So, if I assume that I_0 is remains constant, d V_0 decreases linearly. Capacitor is discharging at constant current rate. So, it is capacitor voltage decreases linearly. So, I will come to it.

When does it charge? When does it charge? When I am saying that capacitor is discharging for the entire DT period, I will assume that capacitor continues to charge in the entire half period of the switch. I will assume it may not be true, it may not be true. I will tell you under what condition it will not be true. But then if someone says that switch is capacitor is continuously discharging when the switch is closed and still it is discharging, still it is discharging when the switch is opened, there is, definitely, there is going to be a ripple, a high ripple in the output voltage.

Let me repeat; if if the capacitor is discharging even when the switch is opened, it is continuously discharging when the switch is closed. Capacitor is continuously discharging when the switch is closed. Now, it is still it is discharging even when the switch is open, it means that it means that there is a significant ripple in V_0. Having said that input is an input is an approximately a current source, I can safely assume that when the switch is opened when the switch is opened, capacitor, capacitor is charging. So, if I neglect I_L while deriving $V_{0,}$ this is going to be the equation. KCL at this point is a capacitor current should be equal to $I_{0,}$ minus sign indicates that capacitor discharging.

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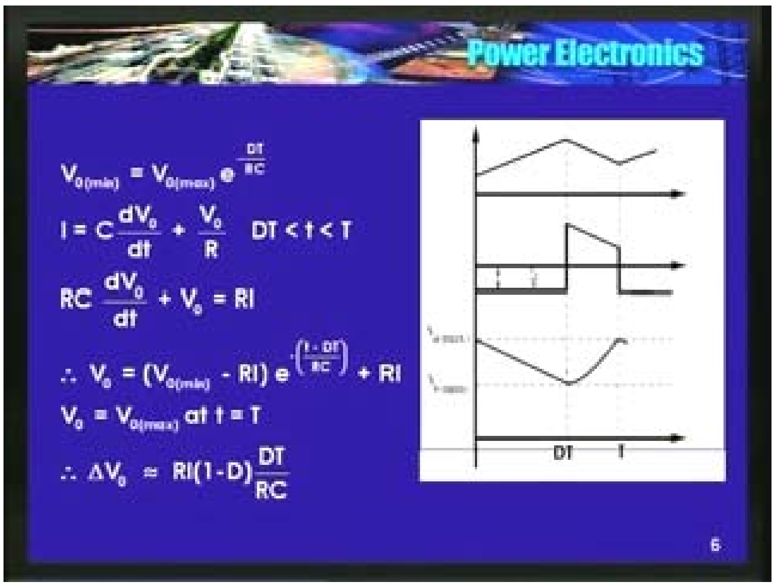

So, what is the equation for V_0? That is this. Why am I saying $V_{0\ (max)}$ here? It is because capacitor is I have assumed that capacitor is charging when the switch is open. For the entire duration, entire duration, entire duration, capacitor is charging. So, it is discharging and it is charging here. At this point, switch is closed again, switch is closed again and inductor current starts increasing, inductor current starts increasing.

So that is why I am calling V is equal to V_{max} because if the current is continuous, capacitor is charging in the entire entire half period of the switch. So, just prior to closing the switch, capacitor voltage has attained a peak value. Now, once I open the switch, capacitor starts discharging which is not the case with the buck convertor, they are different. Go back, draw the current waveform through the capacitor and through the capacitor for both buck as well as boost, and find out.

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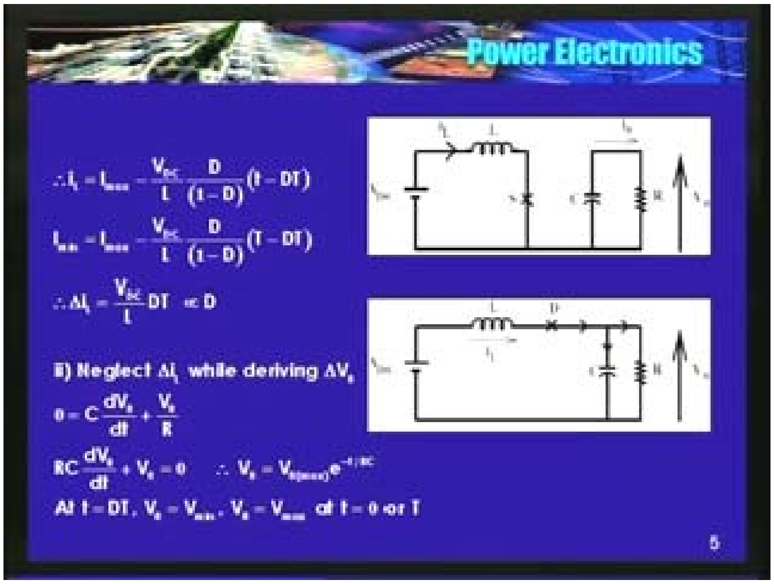

So, this is the equation for the output voltage when the switch is closed. At t is equal to DT, just prior to opening the switch, capacitor voltage has attained a minimum because the moment I open the switch, capacitor starts charging. In the sense, now current that is flowing through the capacitor is difference of I_L and I_0.

When I open the switch, the inductor current divides. Some part, it flows through the capacitor and some parts flows through the load current. Now, you may say that I_0 could be higher than I_L. If that is the case, capacitor continues to discharge, capacitor continues to discharge. So, it is just not possible. It was discharging when the switch was closed. It should charge when the switch is open because we assumed that average voltage across, average voltage, average output voltage remains constant. It charges for some time, discharges for some other time. So, average voltage remains constant.

So, I_L has to be higher than I_0 when I open the switch, when I open the switch. So, it is minimum when V is equal to when T is equal to DT. At this point, voltage is minimum: at this point, voltage is maximum. It is also equal to 30, equal to this. So, this is the equation for the capacitor voltage. This is the KCL at or when the switch is opened, this is the KCL. Inductor current I_L, inductor current I_L should be equal to C dV_0 by dt plus V_0 by R.

I will simplify this and I will write. This is the final equation. This may not be very obvious, may not be very obvious. I will request you to go back and derive this expression. Now, let me tell you one thing. The aim of the course is not to derive an equation or prove something, no. If you understand the working of the circuit, you can always write an equation. After all we have used only KVL and KCL. There are only 2 elements, 2 passive elements - L and C and an input DC source. You can always solve it and derive an equation.

The basic aim of the course is that you should understand the working of the convertor, deriving the equations is secondary. I am not saying that is not important, it is important. If I understood, I can always write an equation and I can derive it, not a problem. After all that is L, C and it and may be, R and and an input DC source, life is simple, input is DC. It is not even a sinusoid. So, after doing some mathematical jugglery, I can write that delta V_0 is approximately is this equation approximately this equation, is given by this equation.

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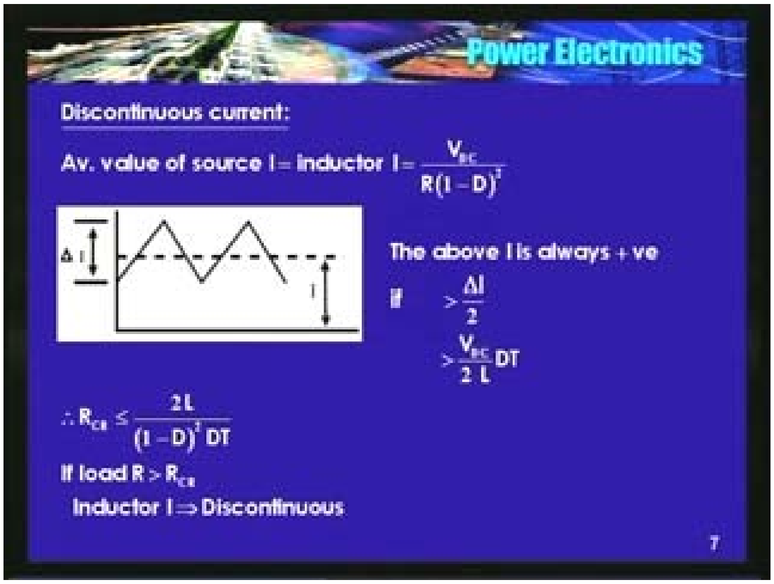

Now, let us see about the discontinuous current, when will it be discontinuous? What is the average value of the source current? Average value of the source current is same as the inductor current is given by V_{DC} divided by R into 1 minus D square. This we have derived in the last class. This we have derived in the last class, average value of the source current is equal to the inductor current V_{DC} divided by 1 minus D square. This we have derived in the last class.

Now, if this value of current is higher than delta I by 2, this is the ripple, inductor current is always positive. Therefore, it is in continuous. So, if this current is higher than this limit, I_0 is higher than this limit, therefore, I is always positive. So, this can happen only when I will substitute here, this condition.

I will repeat; when this source current, average value of the source current is higher than half, this part, half of delta I then I is continuous or I substitute and I will get the critical value of the load resistance R. So, if this critical resistance is higher than the, the load resistance is higher than the critical resistance, inductor current is going to be discontinuous. I will repeat; if the load resistance is higher than the critical resistance, inductor current is going to be discontinuous. It is true even in the buck convertor but then condition to determine condition to determine the critical value of R is different. It is a 2 different situations. Now, how does the waveforms look like?

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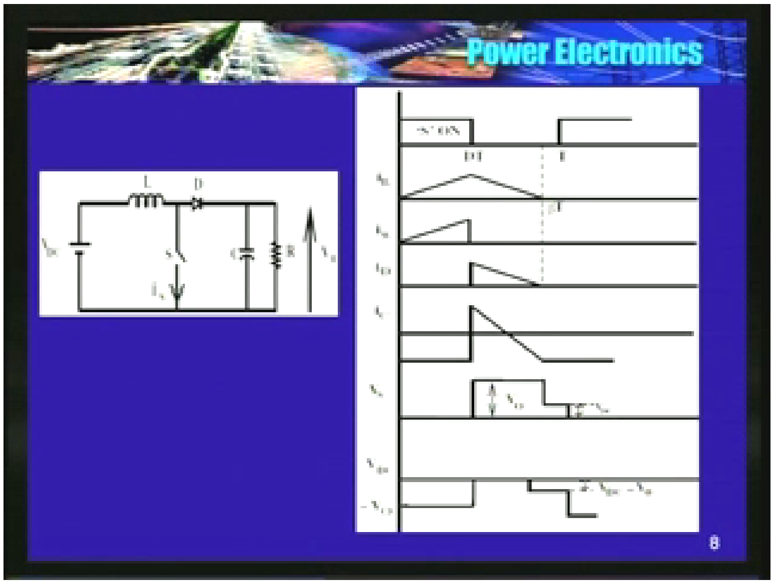

Just simple, I will just draw for the boost convertor and the remaining convertors, I will not draw. You may have to draw yourselves. So, current becomes 0 at beta but before I close the switch for the second time. So, when I close the switch for the second time, current starts from 0. Current starts from 0 and comes down to 0. This is the inductor current.

So, source current or sorry the device current, the switch current also starts from 0. It increases linearly and when I open S, it becomes 0, diode takes over, diode takes over. See, another difference here, capacitor current, I have drawn the capacitor current here, is constant current. It is discharging at a constant rate discharging at a constant rate. The moment I open the switch, it starts charging, it starts charging. When the inductor current becomes equal to the load current, capacitor current becomes 0. At this instant inductor current is equal to the load current. So, capacitor current become 0, beyond this point, inductor current decreases, capacitor starts charging discharging, capacitor starts discharging and when I when the current has become 0, current has become 0 capacitor, entire load current is being supplied by the capacitor. It continues to supply the same current till you close the switch for the next time. I am assuming that V_0 remains constant.

So, if you see a continuous, the conduction period, see here, it is capacitor is charging for the entire off period of the switch, entire off period of the switch. So, at this point, just prior to closing the switch, inductor current is higher than the load current. That is why capacitor current is finite, capacitor current is finite and positive, positive.

See, I will repeat again, just prior to opening the switch inductor current is higher than the load current. That is why the capacitor current is positive at this point. I close the switch, immediately the diode turns off. The entire load current is being supplied by the capacitor, whereas, in this case, you will find that is it discontinuous conduction. At somewhere at this point, inductor current becomes equal to the load current. Beyond this point, inductor current is less than the

load current. Capacitor has to supply the remaining current. So, it discharges and continues to discharge till I open the switch in the next cycle.
So capacitor is charging only for a shorter duration here and for the entire remaining period, capacitor is discharging, is a constant current here, here it is assumed to be linear, assumed to be linear. So, that is the difference. So, I am just using a Kirchhoff's current law to plot the current waveform. That is all.

Now, how does the voltage across the switch and the D and the diode look like? When the current is flowing through the diode or when the diode is on, voltage across S is V_0 itself. What happens when I when the current becomes 0? Diode is reverse biased sorry diode turns off. No current is flowing through the diode now. No current is flowing through the diode, no current in this circuit also. So, voltage at this point is V_{DC}, voltage at this point also $V_{DC,}$ no voltage drop across the inductor because no current is flowing, so V_{DC} appears across S now. No current flowing here, it is an open circuit, no current flowing here also, so potential at this point is equal to potential at this point. So that is nothing but the voltage across S. So, V_{DC}, it drops to V_{DC}, may be for the better for the switch. Now, voltage across it comes voltage across, it reduces.

What happens to the diode? Cathode potential cathode potential is V_0 with respect to the ground. Cathode potential is V_0 with respect to ground. What about the anode potential? Anode potential is V_{DC} with respect to the ground, isn't it? Just now I said that no current here, this point is same as this. So, V_{DC} appears across S. Now, V_{DC} is the potential of the anode of the diode with respect to the ground or the negative DC bus. So, anode potential is V_{DC} with respect to the ground, cathode potential is V_0 with respect to ground. So, what is the voltage across the diode?
It is nothing but V_{DC} minus $V_{0,}$ V_{DC} minus V_0 and V_0 is higher than V_{DC}, is a negative voltage. When the diode is when the switch is on, it is V_0, when the diode is on, voltage across it is 0 and the moment current becomes 0, it is V_{DC} minus V_0 till I close the switch for the next time and the cycle repeats.

So, drawing the waveforms is fairly simple. After all KCL and KVL, only 2 theorems, basic theorems I am using. Now, let us see what happens to the output voltage if the current becomes discontinuous? For a given value of D what happens? In a buck convertor we found that output voltage is higher than D into V_{DC} if the current becomes discontinuous. So it is d V_{DC} divided by beta, beta is less than1. What happens then? The boost convertor.

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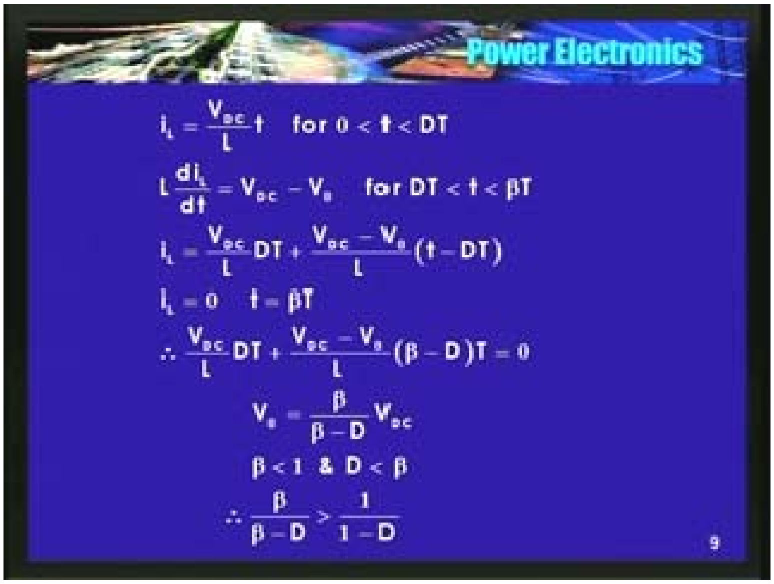

We will see the same equations, i_L is equal to V_{DC} by L into t for 0 to DT, current increases linearly here. Now, I will open the switch at DT and current becomes 0 at beta into T. So, during this period voltage across the inductor is V_{DC} minus V_0. When the current becomes 0, voltage across the inductor is, there is no current flowing now. There is no current flowing through the inductor at all. So, when is when the current is flowing, voltage across the inductor when the switch is open is V_{DC} minus V_0.

So, the maximum value of current or current has attained its peak when T is equal to DT. This is I_{max}, it started from 0, initial value is 0. It started from 0 because current is discontinuous, when I close the switch, it starts from 0, it attains a peak at DT and starts decreasing and this is what it is. This is the equation of the line when the switch is open. V_{DC} minus V_0 by L and this is what it is. i_L is equal to 0 when T is equal to beta into T. So, I will substitute here, so it will become 0 only when this term is equal to this term.

So, you will get as V_0 is equal to beta divided by beta minus D into $V_{DC.}$ So, if beta is 1 that implies that current is just continuous, current is just continuous. We have still had a same expression which is for an ideal boost, V_0 is equal to V_{DC} divided by 1 minus D. Current is at the boundary, in the sense, current becomes touches just 0 at just prior to prior to closing S. So, beta is equal to 1, at that time you have same equation.

Now, beta is less than 1 and it is greater than D. You can find that you can find that beta divided by beta minus D is greater than 1 divided by 1 minus D. You need to be practical because just cannot give arbitrary values. For all practical values, beta divided by beta minus D is greater than 1 divided by 1minus D. So, you will find that similar to a buck convertor, output voltage is higher in a boost convertor if the current is discontinuous. So, V_0 is higher than 1 divided by 1 minus D that is true even for the boost convertor and when it is suppose for a given values of D, or what values of D current is going to be discontinuous?

If the value of D is very small, in the sense, I am I am storing the energy for a very small duration and most of the time, I am discharging. Whatever the energy is stored is being dumped to the capacitor and the load. I am storing for a very short duration and dumping it or keeping the switch open for a longer duration. At that time, there are very good chances of you going in for or inductor going in for the discontinuous conduction current, current is going to be discontinuous or if you increase the value of R beyond a critical value, you got a …

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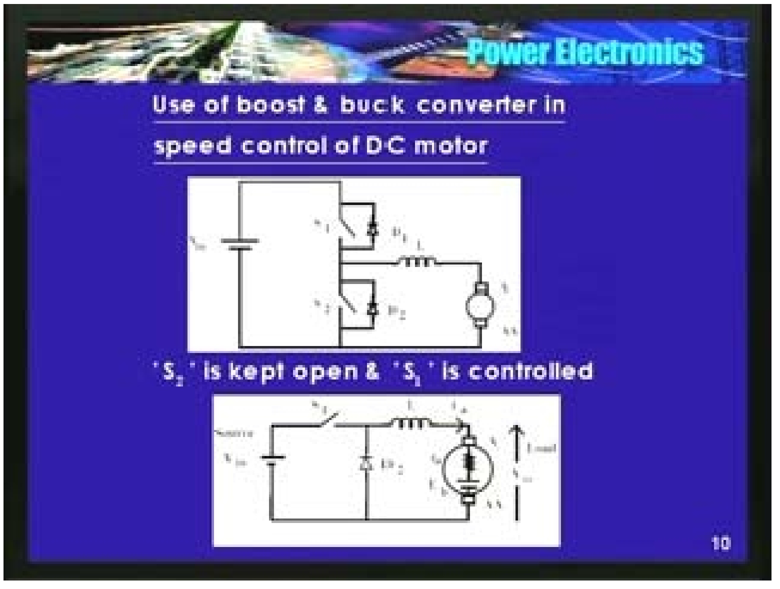

Now, let us see where will I use this buck convertor and boost convertor in drives, apart from power supplies? I have not told you the application of boost convertor. I will tell you some time later where there is a very important application and a very elegant application also and whatever that I told you in switch mode rectification, there also we call it as boost convertor. Remember, a closed loop control for a boost convertor is a must, closed loop control for a boost convertor is a must. In the sense, you need to know the output conditions. It should not happen that accidently the load or load that is connected across V_0 is open circuited and here you going on closing and opening the switch. As you go on opening closing the switch, you are go on dumping the energy to the capacitor and there is nothing to dissipate. Capacitor voltage will go on building up.

So, closed loop control is a must or in other words, we need to monitor the output voltage always. That is true in almost all the boost convertors. Now, coming to the application, see what I am doing is this is a circuit a DC source, I am taking 2 switches - S_1 and D_1. In fact, I do not need to connect a separate diode across a switch. Any controllable switch you take, either a BJT or IGBT or a MOS, there is a built in diode. This is a freewheeling diode or a diode that is connected across S which is built in.

I will take 2 switches, S_1, S_2, an inductor and a DC motor armature here. This is used to make the current continuous or to reduce a ripple here or could be a filter inductor, could be a filter inductor. Now, I will keep S_2 open and S_1 is controlled, in the sense, S_2 is permanently open. That does not mean that D_2 is permanently open, D_2 is an uncontrolled device. You cannot control it. So, I can control only on and off of S_1 and S_2, not D_1 and D_2. So, I will control S_1. I will use some duty cycle close for S_1, close S_1 for some duty cycle and I will open S_1. What happens?

See the equivalent circuit; S_1, inductor, armature and D_2. Though I kept S_2, D_2 will come in the circuit. What is this? This is nothing but a buck convertor, a buck convertor or a step down chopper, step down chopper. E_b is the back emf, R_A is an armature resistance, L is the total inductors of the armature circuit. It is including the external inductor as well as the armature inductor.

Buck convertor or a buck chopper, V_0, V_0 is equal to D into V_{DC}, provided, i_A is continuous. I repeat; V_0, it is this voltage is equal to D into V_{DC} if i_A is continuous. So, when I close S, i_S starts increasing. When I open S, inductor current freewheels through D_2, freewheels through D_2. So, by controlling the duty cycle S, duty cycle of the switch S_1, I can control output voltage and therefore the speed. Voltage applied to the armature will determine the speed of rotation. Omega is directly proportional to voltage applied to the armature.

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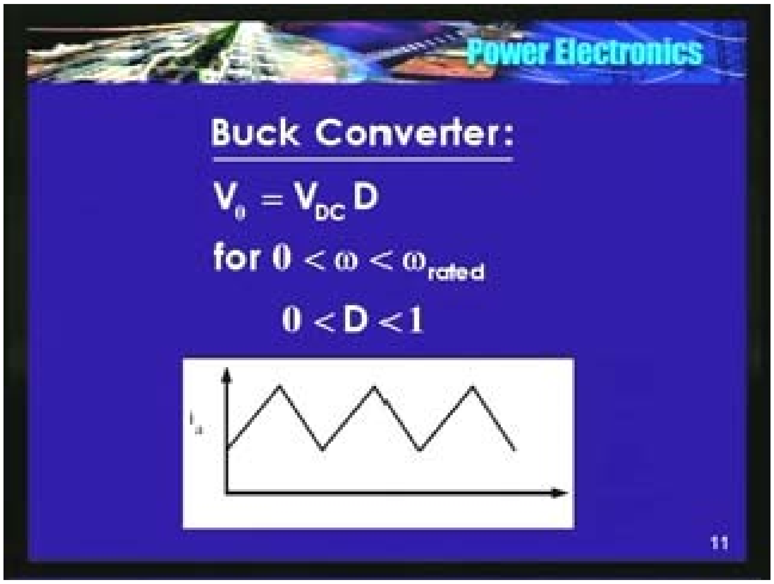

So, if I have to control the current, I can control it in this fashion or at steady state, current increases decreases for a continuous mode of conduction. For omega 0 to omega rated, D will vary from 0 to 1. That is about the buck convertor.

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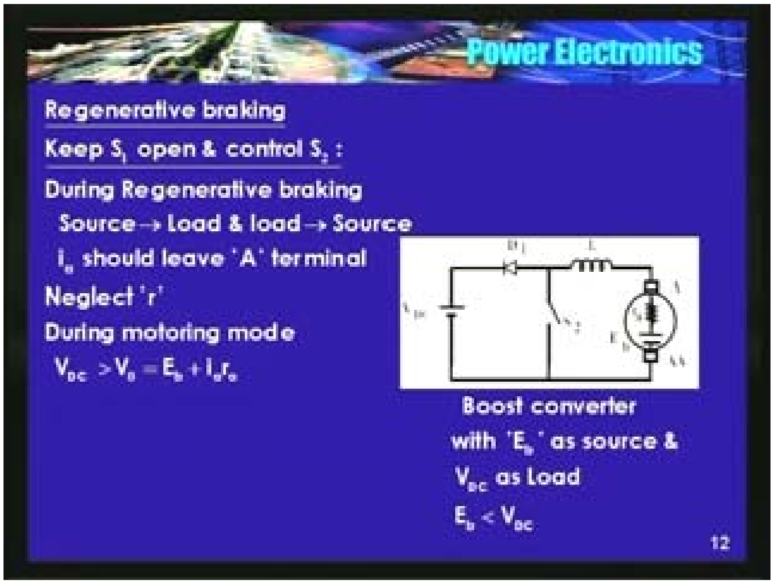

Having applied a rated voltage or having applied some voltage, motor has attained some steady state. Now, you want to do a regenerative braking or you want to stop the motor. Most efficient way is to do a regenerative braking, feedback the energy to the source. How do I feed it back? Now, I will open, keep open S_1 permanently and I control S_2.

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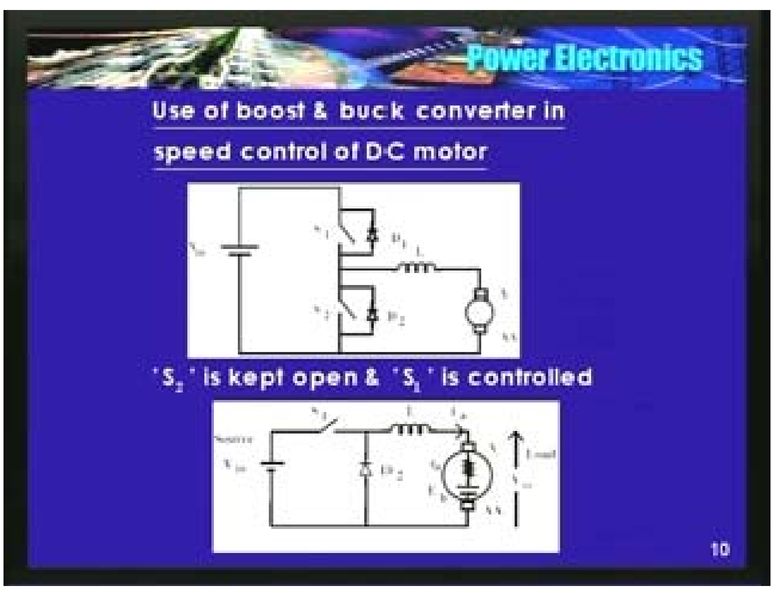

In this circuit, I will keep open S_1 permanently and control S_2. In the previous case, I had kept S_2 open, S_1 I had controlled, this is the circuit, V_{DC} is the source, V_{DC} is the source and DC motor armature is the load. I will repeat; this is the source, this is the load. V_0 is D into V_{DC}. If

D is equal to 1, V_0 is equal to V_{DC}. But then, that V_{DC} is equal to i_a r_a plus E_b. This V_0 is equal to i_a r_a plus E_b.

So, even if is D is equal to 1, even if D is equal to 1, E_b is less than V_{DC}. When D is equal to 1, V_0 is equal to V_{DC} but V_0 is equal to i_a r_a plus E_b. So therefore, E_b is always back emf is always less than this V_{DC}, source voltage, remember.

Now, in this circuit, I said I will keep S_1 open and control S_2, this is the polarity with current was entering A when S_1 was controlled. Now, for regenerative braking, for motor acts like a generator, current should leave A, current should leave A. In a now, this becomes the source and V_{DC} is the load. In the sense, V_{DC} is receiving power. Source is battery is receiving power from the load.

Now, what I will do is, this I will call it as source and this we will call it as load during regenerative braking. Now, just prior to closing S_2 or just prior to just prior to regenerative braking, we have been in the motoring mode and we and we found that E_b is less than V_{DC}. In the motoring mode, when S_1 was controlled, E_b is less than V_{DC}.

Now, see this figure. This is nothing but a boost chopper, a boost converter, boost converter wherein, E_b is the source, V_{DC} is the load, V_{DC} is the load and condition should be V_{DC} should be higher than E_b. Output voltage V_0 is always higher than the source voltage, Vtg for the boost converter to work satisfactorily. Same thing is true here. Just in the motoring mode, E_b was less than V_{DC}. Now we are going for regenerative braking, E_b is smaller compared to less than V_{DC}.

Now, I will make a control S_2. When I close S_2, current starts flowing in this fashion, now current is leaving A, store the energy in inductor, open S_2 and it flows back to the source, flows back to the battery, flows back to the battery. So, this is nothing but a boost chopper feeding back the energy to the, to the source. Actually, now we have considered when boost converter is coming, when the in, in the regenerative braking, we are naming this as the load, this as the source.

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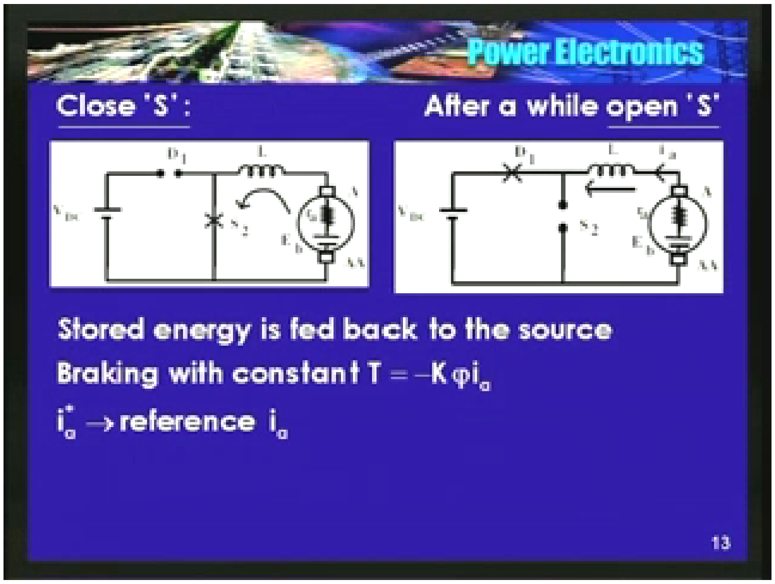

Now, how do I control S_2? How, do I control S_2? Same thing, whatever that we did in the converter for DC motor, we need to decelerate at a constant torque. Torque developed by the motor should remain constant. It can remain constant only when phi and i_a are held constant. Now, what I will do is if I keep i_a constant, my torque will remain constant. The motor the developed torque by the motor remains constant. So, what I will do is I take a reference current, a constant value of i_a, a constant value of ia. This is the I reference.

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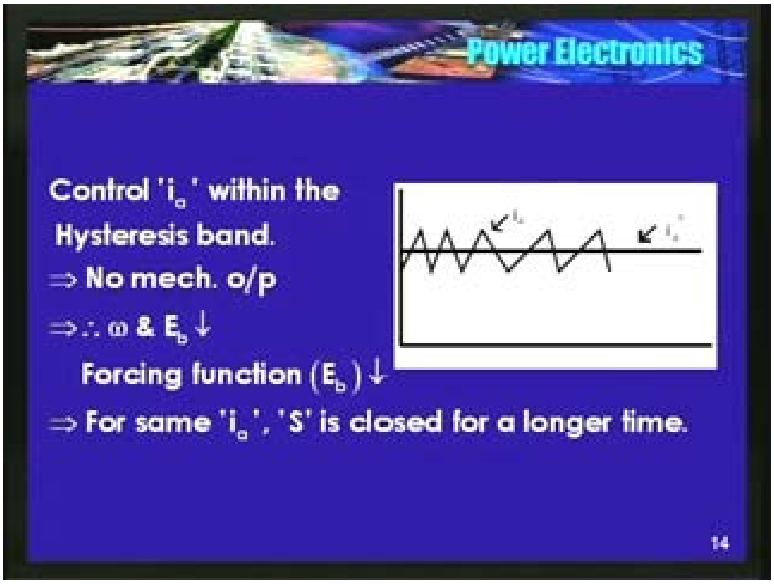

I will close the switch, i_a increases. I will open the switch, i_a decreases. So, I will control the current within a hysteresis band and small band. Close, i_a increases: open, i_a decreases. So, i_a is approximately constant. Therefore, torque developed by the motor remains constant. So, I have a deceleration under, deceleration rate is remains constant. So, in the circuit if you see, the stored energy in the armature is being fed back. There is no mechanical input, no mechanical input. Therefore, speed will fall. So, if the speed falls E_b also will fall.

No mechanical input, the stored energy is being fed back to the source, so omega will fall, if omega falls, E_b will fall. So, if E_b falls, see in the circuit what happens? It is E_b which is forcing the current through the inductor. If E_b falls, E_b is E_b is the one which is forcing the current through the inductor, if E_b falls, the rate of rise of current itself falls. It is E_b divided by L is the rate of increase in current.

If E_b falls, di by dt when the current is increasing is decreases. So, rate comes down, rate of increase comes down. But then what happens, rate of decay? Rate of decay, E_b is decreasing, assuming V_{DC} is constant, the difference between the these 2 voltages appears across L. This is falling, this is held constant. Therefore, voltage across the inductor is increasing. As the speed falls, as the speed falls, E_b falls. Therefore, the difference between E_b and V_{DC} increases.

So, when the switch is open, voltage across the inductor increases as the speed falls. Therefore, the decay falls, decay rate is faster now. Here, rate of rise is slow because E_b is falling. Since, Eb is falling voltage across the inductor when the switch is opened is high. Therefore, rate of decay increases.

So, if you see in the oscilloscope, say, you will get some sort of a waveform like this. Current is slowly increasing and falls faster. Current is slowly increasing falls faster, slowly increasing falls faster. So, as speed falls, current increases slowly, decreases faster and after some time, E_b has fallen to so low value, you may not be able to control the current. So, braking under constant torque is possible till a certain speed. Beyond that it may not be possible.

So see, there is a change in a switching frequency also. Current increases slowly, decreases faster because here E_b is falling, forcing function is falling. Now here, the voltage across the inductor, V_{DC} minus E_0 or V_{DC} minus E_b, E_b is falling, V_{DC} is held constant. So, voltage cross inductor increases as omega decreases, decay is faster, decay is faster. That is about it. Rest, we will see in the next class.

Thank you.