Power Electronics

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Lecture - 23

Last lecture, towards the end, I just introduced a new topic in power electronics that is DC to DC power conversion. This topic or DC to DC power conversion is very popular in SMPS - switched mode power conversion or power supplies because the moment someone says DC to DC convertor, first thing that comes to the mind is switch mode power supplies and may be, second application could be in drives, a chopper fed DC motor. Why are they so popular or why DC to DC conversion is so popular in switched mode power supplies?

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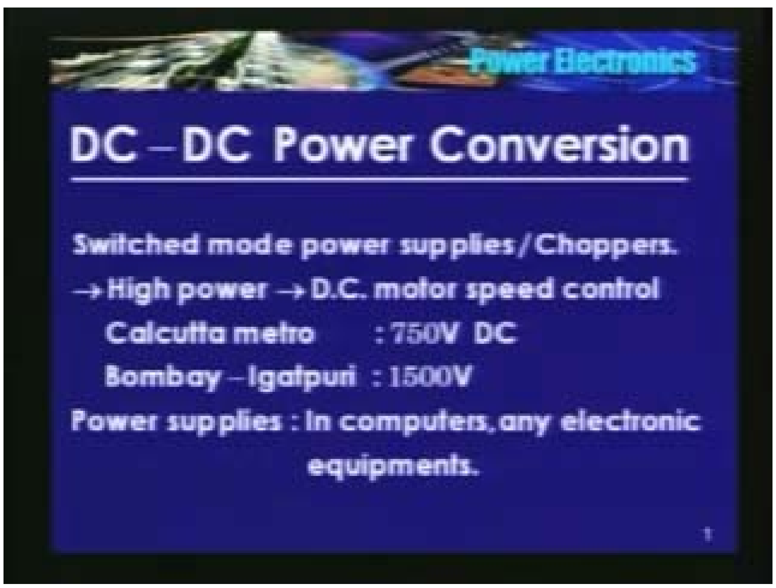

I am sure you all know, may be in 19, early 90's, around 1991, 20 mega hertz PC are the state of the heart PC, 20 mega hertz. 10 years down the line, we have PC's, Pentiums operating in giga hertz.

As the frequency range has increased, what happens to the biasing voltages which are required inside? In our lab, we just, all the TTL circuits are being biased using a 5 volts supply. As the frequency has increased, the trend or the trend is to use power supplies of lower voltages because of various reasons. I told you that when the device is being switched at a very high frequency, you know as to reduce the losses I have to reduce the supply voltage.

Same concept is true even in the power supplies or even in, for that matter even in computers. After all there are ICs, they have to be switched at very high speed or at very high frequency, so there is a 3.3 volts DSP - digital signal processer. Now, it is being used in drives and I was told that 2, 3 years down the line the requirement for a power supply is or the power supply rating that is required is 0.5 volts 100 amperes. I will repeat; 2, 3 years down the line, power supply that I required in computers or in VLSI design is 0.5 volts 100 amperes.

See, in the sense, for an electrical engineer if there is a short circuit, voltage is of the order of 0.5 volts, may be. Now, I do not know how to how to generate a V_{ref} for a supply voltage which is as low as 0.5 volts, how to protect it against over load or how to protect against short circuit because the rated voltage itself is 5 volts, current that is flowing is of the order of 100 amperes. See the challengers that are ahead in DC to DC power conversion. Application requires very stringent specifications, very stringent specifications. 0.5 volts, it should be maintained constant, ripple, again there is a limitation on the ripple or a change in output voltages is again very small. The challenges in DC to DC power conversion are tremendous.

Let see, before going into a switch mode power techniques, what is the power supply that we are using in our labs or you have been asked to design a circuit which requires a power supply and your teacher has told design or make use of your own power supply, do not use the power supply which is available in the lab, what sort of a power supply you would design? That is nothing but a linear regulated power supply. What is a circuit? Circuit is very popular and very simple.

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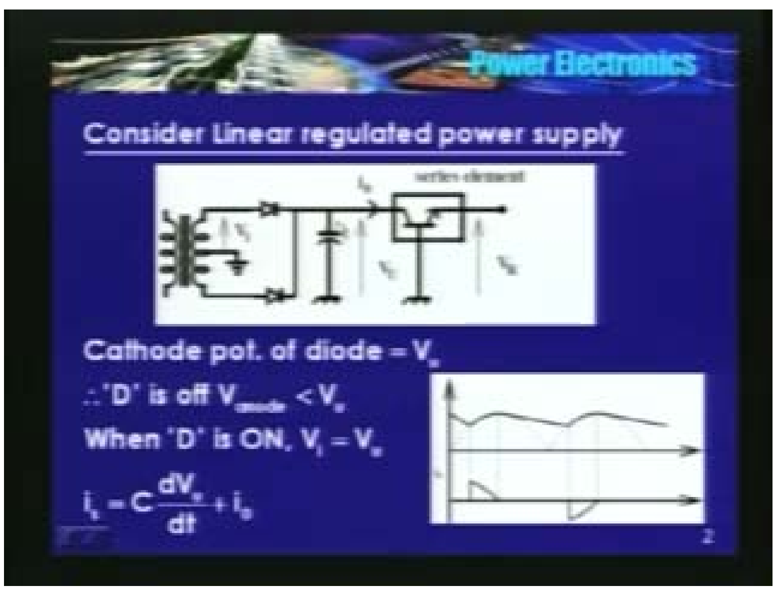

If I want to have a 5 volts power supply, I will use a step down transformer. May be, a 7 volts, 707 transformer, I will rectify it using 2 diodes, full wave rectification, I will filter it using a capacitor then I will use a series element, what sort of a series element we will see sometime later and out here, at the output, I will get a regulated power supply. 230 volts input, this transformer secondary winding depends on the voltage requirement at this point.

So, what happens the moment I use this sort of a configuration? This is nothing but may be, AC to DC conversion. I have discussed almost all the circuits in AC to DC conversion. Somehow, this part, I have not discussed. I had in mind that I have to teach this and I have postponed it now. So, what happens here? what is How does the source current look like? If there is if there is no capacitor here, at this point, V_u looks like a full wave or V_u is a full wave rectified version of the input wave.

I have connected a large, relatively a large capacitor here. I told you that filtering requirement in a 2 pulse convertor is much more compared to 6 pulse convertor because though it is, though I am calling it as a unregulated, voltage at this point should be remain approximately constant. Unregulated because if the input changes, at this point also voltage changes and thus very but there is a in another words, there is a significant ripple in the output voltage.

So, at steady state depending upon the current that is following out of this terminal, capacitor voltage varies in this band. The cathode potential is nothing but V_u, anode is a sinusoid, I told you that V_u remains approximately constant, diode cannot conduct till anode potential is higher than the cathode potential. So, if this is the variation in V_u and this is the dotted line is the anode potential, at this point cathode potential is equal to the anode potential. So, diode starts conducting.

When diode starts conducting, one of the diodes - the positive of here and negative of this diode, when diode starts conducting, input voltage is same as the output voltage. It follows the sin wave. Somewhere at this point input is input starts decreasing, now capacitor voltage cannot change instantaneously, load current is also very small or it depends on load application or the time constant of the circuit, it depends. The capacitor voltage variation here depends on the time constant of the circuit. So, this is the fashion, capacitor voltage falls approximately linearly, change is not much.

So, till here in the next cycle, source does not supply any power, diodes are reversed biased. At this instant, diodes are forward biased, source starts supplying current and what is the current at this point? KVL sorry KCL has to hold, Kirchhoff's current flow has to hold good. So, this current should be equal to the capacitor current and the load current. In another words, C dV_u by dt, the capacitor current plus the load current should be equal to source current.

By the way, can I differentiate this point? There is a discontinuity here, can I differentiate it? There is a discontinuity - C dV_u by dt, I have to differentiate this function. You find out an answer to this question. So, if you observe the source current wave form on the oscilloscope, there is a very peak current here, is high current starts flowing here. I am neglecting the inductance. If there is no inductance, large current will flow and it slowly dies down. At this point, current becomes 0.

So, there is a sharp pulse of current here and after pi in the negative half, this diode through this diode, a sharp pulse of current for a very short duration. So, in the linear regulated power supply, if I use this sort of a configuration and let me tell you, invariably, we use the same configuration, source supplies power for a very short duration and if I draw or if I find out the harmonic spectrum of this wave form using a Fourier series, it has a predominant third harmonic component apart from the fundamental component. Harmonic content is very high, source supplies a peaky current. So, what are the other reasons?

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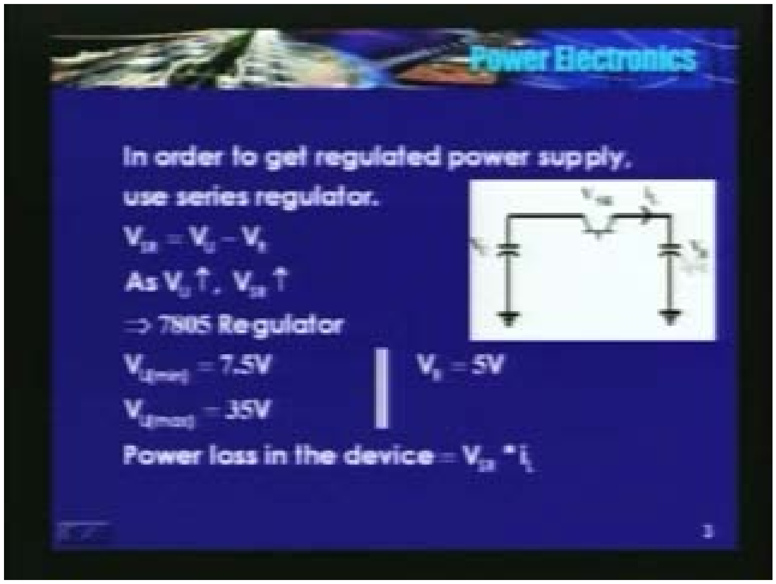

So, in order to get a regulated power supply, we use a series regulator. May be, in the lab you might have seen or you might have used this regulated power supply chip. A 3 lead chip, tip series, input, it is a 5 volt 78O5. It output is 5 volts regulated, input is the unregulated.

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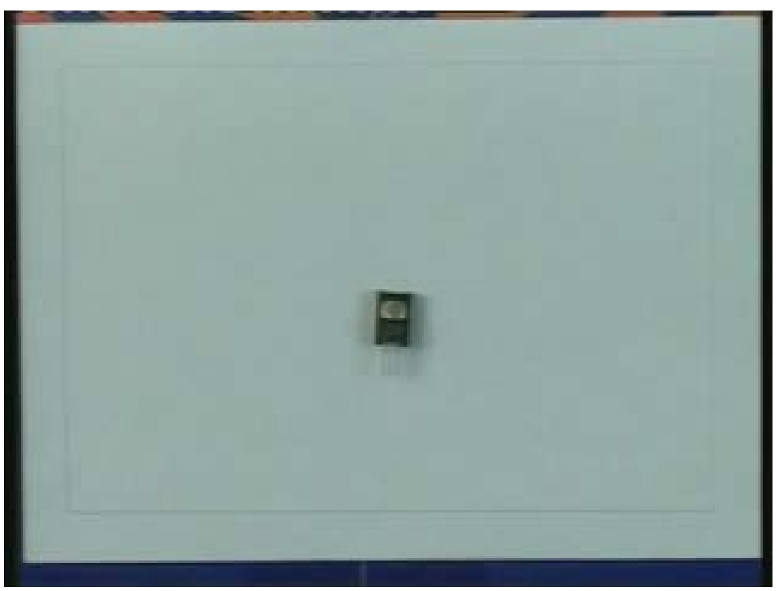

The third pin, the center point pin is the ground input and output. It is mounted on a heat sink, this is the heat sink and this is a regulator, series regulator which you might have used in the lab.

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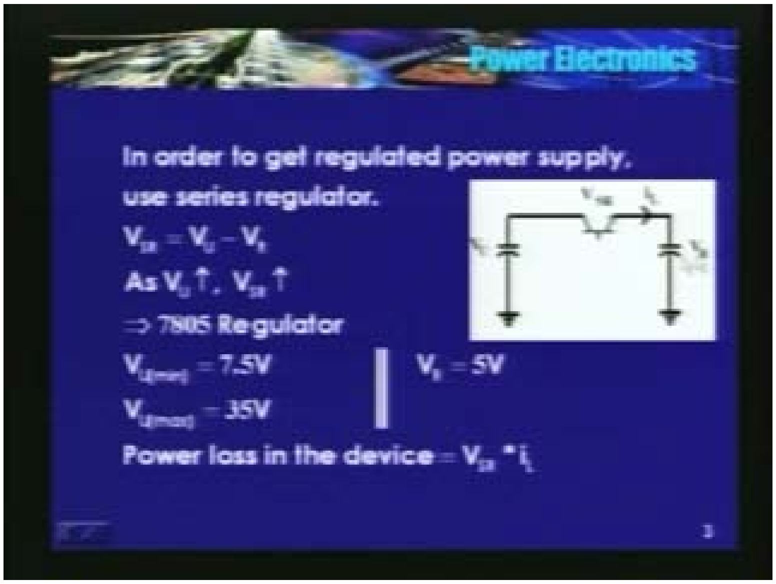

Now, here is this circuit - unregulated, series element, regulated. Regulated is supposed to remain constant. I said, 78O5 IC if I use here, output voltage is maintained at 5 and V regulated should be unregulated should be a minimum of 7.5 volts and maximum of 35 volts.

So, if you see the specification of 78O5, you mean unregulated minimum is 78 of 78O5, regulated is 7.5, only then you will get a 5 volts regulated supply and output could and the maximum value could be as high as 35. Till 35, you will get a regulated voltage of 5 volts.

Now, what happens to the difference in these 2 voltages? If it is 7.5, output is 5. If the input is even 35, output is 5. Where does the remaining voltage go? Answer is very simple. The remaining voltage is dropped across the device. So, what is the power loss? Power loss is voltage across the devices and current flowing through it. Therefore, as unregulated voltage increases or changes, power loss that is taking place in the series regulator also increases.

Why I am using or why I am using the term, linear power supply? That is because the series element that is used is operated in the linear region. All most in power electronics, the switch is better used. Either they are operated in cut off as current flowing through is 0, theoretically, ideally or in saturation when the voltage across the device is very small. We seldom operate the device in linear region. We may operate in a quasi saturation.

In other words, the saturation just begins to start, definitely, not on linear. In power electronic circuit, all the devices are operated either in cut off and in saturation. So, 78O5, the regulator chip that we are using in the lab to get a regulated power supply of 5 volts or minus 5 or plus 8 minus 8, plus 12, minus 12, you operate them in linear region. That is why they get very hot because power loss that is occurring in the device is voltage across it which is the difference between unregulated and the regulated and the current flowing through it.

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See, you might have seen this box. A regulated power supply in the lab, 30 volts 2.5 amperes, very common. Why it is so heavy? I do not think the computer - the Pentium 4, I do not think is as heavy as this. Wattage here is of the order of 150 watts power supply, I am not able to I am really finding it difficult to carry, heavy. Why it is so heavy and you might have seen, why there is, this is the heat sink, why there is such a big heat sink and all the devices, these are the devices, the series elements are regulated are mounted outside. Why?

You do not find them in a computer? Computer also requires a power supply. Let me tell you one thing, computer power supply requirement may be much higher than this and I can still hold it in my palm. A Pentium 4 power supply, I can, the requirement is higher than this, wattage is higher than this, still I can carry in my palm and I do not find such a big heat sink and all the devices there. This is the device, so heavy, why? because these elements are operated in linear region. So, if the input is fluctuating, output has to remain constant. If it increases, power loss increases. That heat has to be dissipated. That is why they are mounted outside. That is about linear process.

So, the disadvantages of the regulaed linear power supplies that are available in lab or which you design it for your circuits; one is efficiency is very low because series regulator is operating in the active region. So, power loss is high. If the power is loss is high, temperature raises high. So, I need to use a bigger heat sink, heat sink requirement increases.

I said, filtering requirement is also high because single phase, to maintain an approximately constant voltage, I need to use a larger a capacitor. So, overall size of the power supply increases. Source current is peaky, predominant component is third, it is difficult to filter and finally the most important, we require a step down transformer which is operated at 50 hertz.

In another words, I require a 50 hertz transformer, a step down transformer. That is why the overall size of the power supply becomes big and bulky. Why I am saying a 50 hertz transformer? What is being done in SMPS, in switched mode power conversion? Let us see, we will discuss.

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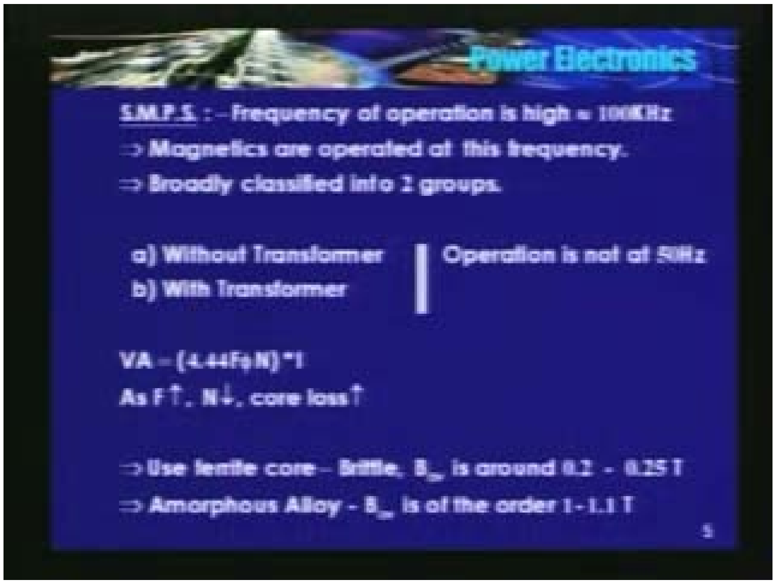

The frequency of operation in SMPS is very high. Minimum could be of the order of 100 kilo hertz. All the magnetics; inductor or the transformer that is being used are operated at this frequency, mind you. Now, you may say that DC to DC, how did you get DC from or where did you get this DC from? After all, the supply that is available is AC. So, do I need to have a 50 hertz transformer there? So, if I use a 50 hertz transformer, the purpose is lost. Somehow I have to do away with this 50 hertz transformer. Let us see.

As of now you assume that DC is available. How to get this DC without 50 hertz? I will come to that point some time later. So, this switched mode power supplies or DC to DC converters are operated at a very high frequency. All the magnetics, they are operated at this frequency. These SMPSs are broadly classified into 2 types; one is without transformer and second one is with transformer.

Now, immediately you may say, DC to DC, how can you use a transformer? Our machine teacher has told us that if you connect a transformer to DC supply, it will get damaged or it will, there will be a short circuit and transformer will get damaged. I am not saying that what your teacher has told you is wrong. It is correct but I am also using a transformer in a DC to DC power conversion, what exactly, what is a difference in operation, we will see some time later.

As of now assume that transformer can be used in DC to DC and they are being used. See a very popular equation. V_A a volt ampere rating of a transformer is approximately given by 4. 44 into

F into phi into N. This is voltage induced in the in the windings N_1. If it is N_1, it is the primary, if it is N_2, it is secondary into the current.

Now, if you see in this for a given V_A rating, as F increases, as F increases, N comes down, N comes down. N is nothing but the copper N is nothing but number of turns. If I reduce the number of turns, the copper that is used in the transformer also comes down, somewhere it comes down. But then you may say, the moment I switching at a very high frequency, as F increases core loss increases. I am not saying that, I am not disputing that fact, core loss do increase. But then I cannot use the so called CRGO core or CRGO laminations in our transformer. Laminations or 50 hertz transformer core material cannot be used for a high frequency transformer. There are special materials like a ferrite core.

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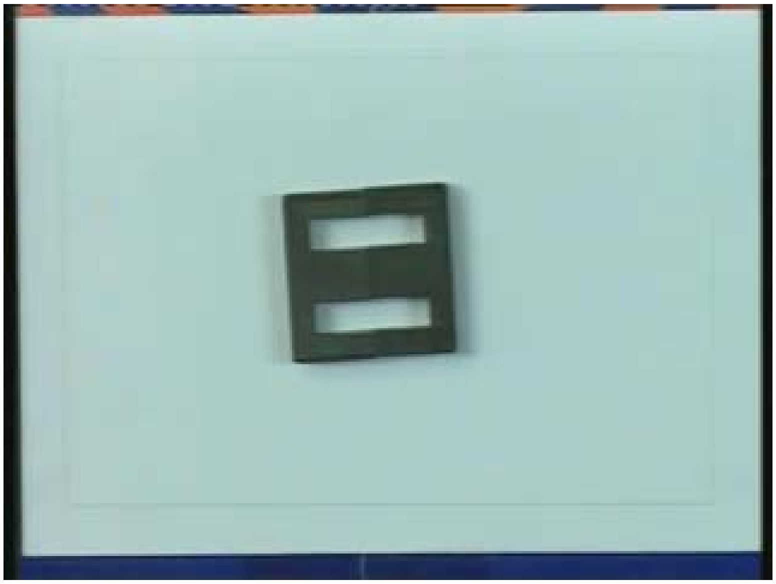

This is a ferrite core. So, here we see, this is a ferrite core, lamination for a sorry core for a ferrite transformer made up of, this material is of ferrite. I can use it for an inductor or I can use it for a transformer. It is very brittle. So, laminations, you cannot make thin laminations out of it. So, what is the average flux density in this core? It is again is low, is of the order of maybe, 0.2 to 0.25. Designer will take of the order of 0.2 to 0.5.

There are other cores, high frequency cores are available like amorphous alloy, V average is of the order of 1 to 1.1 tesla. So, as we increase the frequency you have go in for other type of course. That is the reason, I hope you all of you know, why all the communication equipments or communication people operate at very high frequency, in terms of giga hertz. Answer is very simple. As you operate, as your operating frequency increases, all the magnetics size comes down. The transformer size also comes down, comes down, the weight comes down. Yes, core loses, there are other, you can take care of it by using other material.

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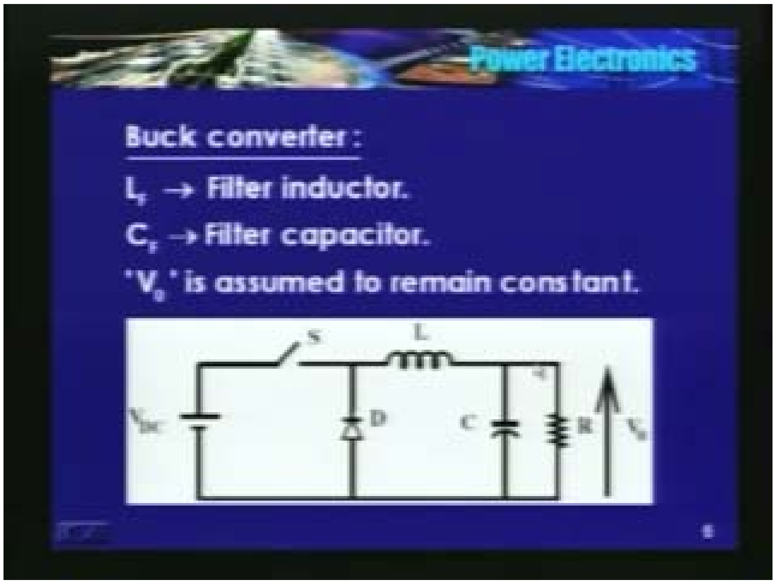

Now, the first one in switch mode power conversion or DC to DC conversion is the buck converter, a buck converter, a buck. Input is DC, output is available at this point, I am assuming that a resistive load is connected at the output, R, C is the filter capacitor sorry CF, it should be CF, is the filter capacitor, LF is the filter inductor, LF is the filter inductor, D is the freewheeling diode, freewheeling diode. S is the switch, S is the switch, what sort of a switch?

Can I use a SCR in this circuit? My question is can I use a SCR in the switch, in this circuit? Answer is both yes or no, yes and no. Why yes, in principle you can use. It is a control switch, I will apply a gate signal, it will turn on and I have to turn it off using some other means. We did use SCR's in AC in AC to DC conversion where there is only 1 pulse per half a cycle or a line commutated convertors. Why did we use there? We used there because turn … will be relatively easier. In a single phase bridge recall, if I trigger T_3 beyond pi, immediately it applies a negative voltage across T_1 and T_1 turns off.

But then we saw in pulse PWM converter, we wanted a switch large number of turns in the positive half cycle itself. We did not use there SCR's. I said I thought that I will I will use only switches here and I told the I told you that you need to use the self commutating devices or the devices which are capable of turning off using gate. If I use a SCR, I have to use a separate source and some other elements to turn it off because I can turn it off only by applying a reverse voltage across the thyristor. I can turn off a conducting thyristor by applying a negative voltage across it. Some sort of a, forcibly I have to turn it off or force commutation techniques should be used and there are techniques available and the present day with the technology that is available using SCR's and using a force competition technique does not make sense. It does not make sense.

Using SCR's only in line commutated converters make sense. They are still popular there, still popular there. For example, that is what even in HVDC power transmission, I told you that both sides there is a AC. AC to DC, again DC to AC, both side AC is available and SCR's are still being used there. They are popular there. Definitely, not in DC to DC power conversion, wherein, you have to use some other technique to put off the thyristor or turn off the thyristor.

So, the S here is is a self commutating switch, self commutating switch. If the power level is low, you use a MOSFET, invariably, invariably. If someone says SMPS, the device that is used is, the first thing that comes in our mind is, is a MOS. It could be a very safe assumption, it could be a MOS and it is a very fast device, very fast device. So, and all this inductors switched at because S is switched at a very high frequency, magnetics are operated at that frequency.

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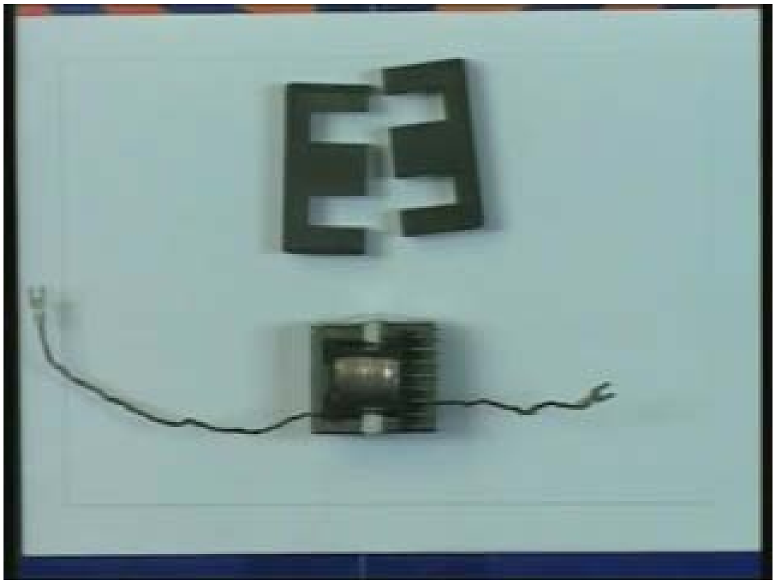

See, ferrite inductor ferrite inductor is made up of the same material. May be, a smaller core, ferrite core and see the leads, see the leads, why there are why there are more than 1 conductor twisted together? See, I am trying to untwist it. See, there are more than 1 conductors, there may be around 6, 6 thin straps of conductors twisted together twisted together make a make 1 conductor. Why not use, definitely, know, copper wire of single strand of this cross section area is available, is available copper conductor thicker than this is also available.

Why did the student who is using it in the lab, used 6 thin conductors, wind them together, of course, it is a difficult task and and made an inductor? The answer is if I have to use a single conductor, the quality factor of the inductor would have been very low. In other words, the resistance, the internal resistance of this inductor using 1 conductor is much higher compared to the inductor which is made up of large number of conductors. This is also known as something known as a litz wire, litz, litz, it is a litz wire. Using a litz wire if you use an inductor this has the properties or almost similar to that of an ideal inductor, ideal inductor ideal inductor. Q is very high, quality factor is very high. It implies that R, internal R is very small, internal R is very small.

So, while during analysis we will neglect the internal resistance R. All of them are all the elements are ideal. When the diode is conducting, voltage across it is 0. Same assumption that we made in AC to DC conversion, V_0 is assumed to be constant. Now, you may say, a capacitor is supplying power, so it should discharge. Yes, it will discharge. The 1, V_0 will change but what is the variation V_0? Very small, may be sometime tomorrow, I will give you the specifications that are generally mentioned at the output.

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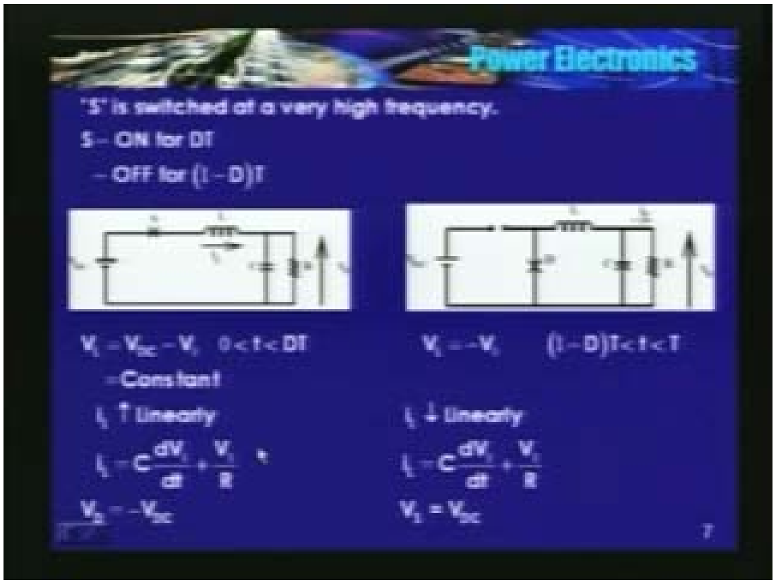

So, close the switch, switch is turned on or off at a very high frequency. So, S is on for a D into T seconds where D is the duty cycle and it is off for 1 minus D times T where T is the time period, time period. So switch is on for DT seconds and it is off for 1 minus D to T seconds where D is a duty cycle which is equal to T_{on} divided by T_{on} plus T_{off} and T_{on} plus T_{off} is nothing but the total time period T.

So, what is the equivalent circuit during these modes, when the switch is on and when the switch is off? How do the circuit works? Let me tell you one thing, working of DC to DC converters is relatively easier to understand because input is DC, output is also DC, time invariant and there are few passive elements here and there. It is relatively easier to understand compared to compared to AC to DC. In AC to DC, input itself is pulsating, input itself is pulsating like our circuit cores. DC circuits are easier to solve compared to compared to AC circuits.

So let me tell you one thing, if you understood AC to DC circuit operation or working of the circuits, this is going to be a relatively easier. So, we will that note I will start the working of to explaining the working of a buck converter.

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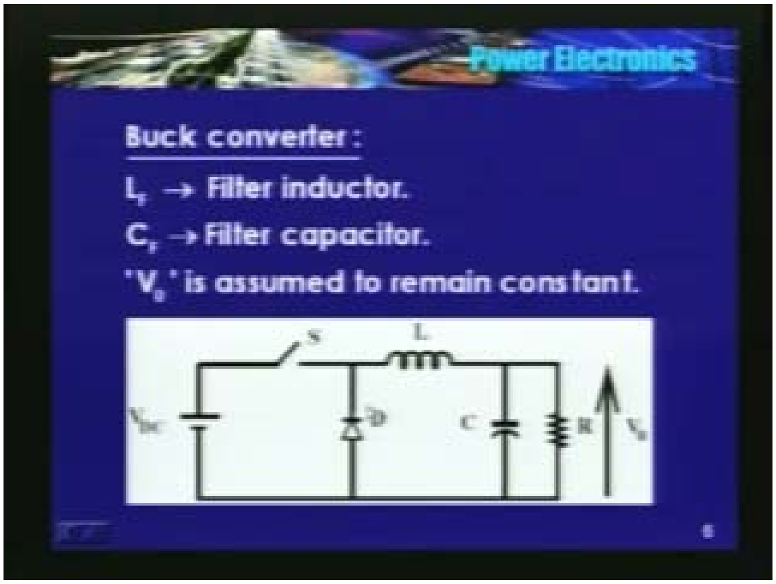

See in the circuit, S is when S is closed, the source voltage is applied across D in the reverse fashion. So, positive to the cathode: negative to the anode. So, diode is reverse biased. S is closed and it is closed and the switch that at a very high frequency. We have assumed that V_0 is constant. At that instant, even though V_{DC} is unregulated, we assume that V_{DC} is also held constant at that time, remains constant. A positive voltage, if it is a buck converter. V_0 is less than V_{DC}. I am saying buck converter, V_0 is less than V_{DC}. So, voltage across the inductor is V_{DC} minus V_0. At this point it is V_0 and at this point it is V_{DC}.

So, equivalent circuit is a switch, V_{DC}, L and output stage. After sometime I am opening S, when I open S, prior just prior to opening S, some current was flowing through L. Current has to be continuous, so current starts flowing through through the diode. This is the path it will take. This is the path it will take. So, the equivalent circuits are see here, V_{DC}, source which is short circuited, the remaining part of the buck converter.

After sometime, I opened S; there is an open circuit here, there is an open circuit across the DC bus here, diode, this is the equivalent circuit. So, voltage across the inductor is V_{DC} minus V_0 till the switch is on in this period which is constant. Therefore, di by dt is constant. It implies that I_L increase linearly, I_L increases linearly.

What is the KCL at this point? I_L is equal to capacitor current. This is the positive directional capacitor current and i_0, this is i_0. So, i_0 is nothing but current flowing through R which is given by V_0 by R. I_L is C dV_0 by dt and V_0 by R. See, I am here I am writing dV_0 by dt. In my, in this at this stage I am … that V_0 is constant, both are correct and let us see in what context I am saying this is constant and here I am writing dV_0 by dt? Have some patience. What is the voltage that is appearing across the diode? So diode is comes across the DC supply. So, voltage across the diode is minus V_{DC}, it is blocking.

Coming to the equivalent circuit when the switch is off, what is the voltage across the inductor? Now, diode is on, this point gets connected to this point. So, voltage across the inductor is minus V_0, minus V_0 for 1 minus D into t to T.

Now, I am assuming that V_0 is constant. So, I_L decreases linearly and KCL at this node is the same, I_L is i_0 plus i_C. i_C is nothing but C dVc by dt. What is the voltage across the switch? What is the voltage across the switch? Now, this is diode is conducting, this point is also connected at this point, isn't it? So, voltage across the switch is V_{DC} itself. Source is blocking, a voltage rating of the diode, a voltage rating of this switch should be, minimum should be $V_{DC.}$

So, these are the equivalent circuits and the circuit equations. How do I determine the relationship between output voltage and input voltage? We have an inductor in between the output and input, both are DC. So, I have only 1 condition that is nothing but average voltage across the inductor should be 0, average value should be 0 over the cycle. So, I will equate it, the areas. Positive area should be equal to negative area, what do I get? I will get this expression.

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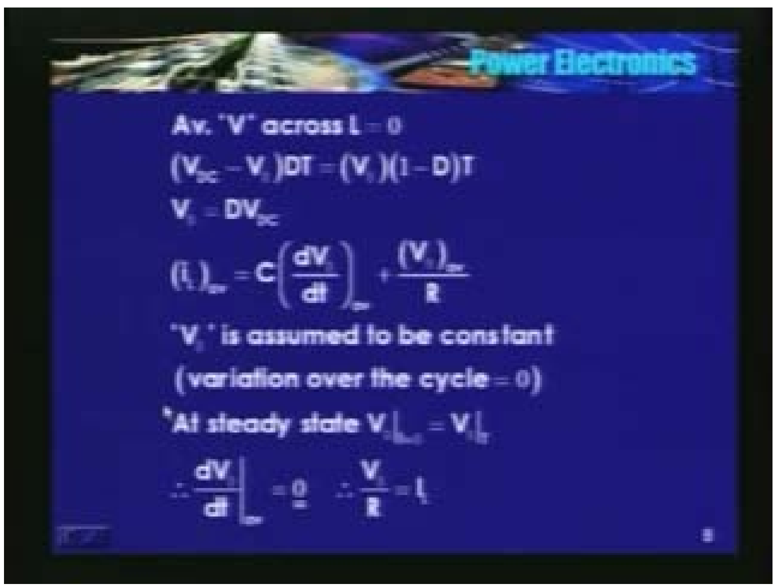

V_0 is equal to D into V_{DC}. This is a positive voltage, this is a negative voltage, V_0. Now, what is the relationship between the current?

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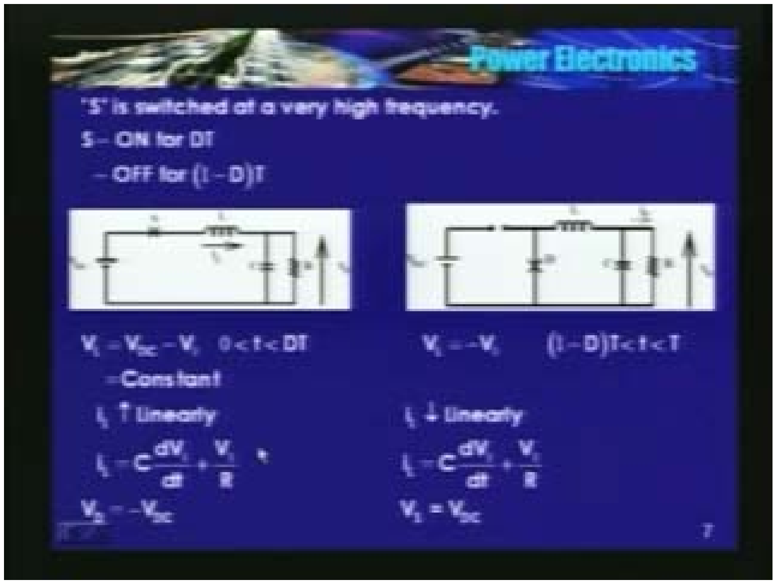

I have same equations, same equations, so over the cycle, is I_L average should be equal to dV_0 by dt average plus V_0 average by R and assume that V_0 is constant. What it means is, for some time capacitor is discharging and some time capacitor is charging. The variation in V_0 over the cycle is 0 at steady state. At steady state, variation of V_0 over the cycle should be 0. It charges for some time, discharges for some time and this variation should be small. That is being that will be specified by the requirement or the customer specifies; my V_0 changes in V_0 from for a change in load from 0 to full load should be of the order of less than 1% also. That is the, or it could be less? It is given by the customer, it as the system …

So, Variation of V_0 over a cycle is 0. So, that is at steady state V_0 at T is equal to 0, some T is equal to 0. So, T should be same. So, this is 0. In other words, at steady state average current flowing through the capacitor should be 0, remember. At steady state, average value of the current flowing through the capacitor should be 0. So, I_L average or inductor average current should be equal to V_0 by R, average value of the load current, this is the load current.

Now, let us plot the various quantities; the voltages across the switch, diode and the current. I had when I said current is continuous, in AC to DC conversion, in AC to DC conversion, what did I mean? I meant that the load current is continuous, remember. In AC to DC conversion, when I said especially a line commutated line commutated convertor, in line commutated convertors, current is continuous, we shall assume that the load current. In power supplies in DC to DC or in SMPS, when I am saying is when I am saying current is continuous, it implies that the inductor current is continuous, remember, it is inductor current is continuous.

What is the load here in buck convertor? See, load here is a resistive load is connected across a capacitor and I am saying that V_0 will remain constant, approximately constant. So, as long as these terminals are as long as this circuit is complete, i_0 will continue to flow i_0 will continue to flow and it is supposed to be supposed to remain constant. Do not say that load current is continuous, no. Load current is supposed to be continuous and is supposed to remain constant if the load is constant.

So, when I am saying that current is continuous, it implies that the inductor current I_L, inductor current I_L this, this is continuous. Now, how does the variation will look like?

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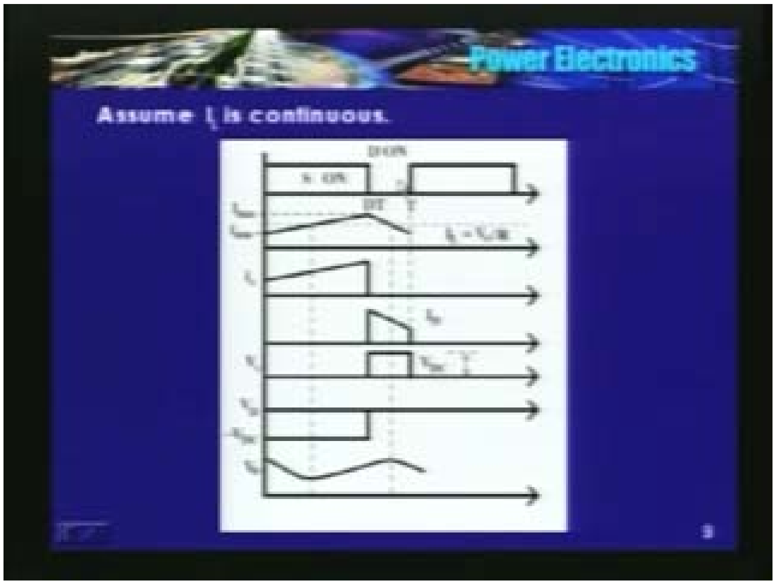

See here, S is on for D into T. So, I_L is continuous. During this period, D is on and again this is a second cycle. When S is on, voltage across the inductor is V_{DC} minus V_0 which is positive. The difference, V_{DC} minus V_0 is positive. So, I_L increases linearly I_L increases linearly which is I am calling this value as I_{min}, this as I_{max}, increases linearly and when I am opening the switch, voltage across the inductor is minus V_0 which is again constant, I_L decreases linearly.

So, at steady state this value should be equal to this value. I_{min} at this point and I_{max} and after I_{max}, somewhere here should be the same. And, this is the average value of current, this is the average value of current which is i_0, i_0 is equal to V_0 by R. i_0, this should be i_0 sorry this is i_0, V_0 by R, i_0. When S is on, when S is on, the inductor current is same as the switch current. Same current flows through the switch, the same current is flowing through the battery. See, the equivalent circuit. When S is on, inductor current is same as the inductor current flowing through the switch, is same as the battery or source current. So, I_s which is the source current is same as I_L at dts switch is opened, switch is open. So, instantaneously, source current or the device switch current becomes 0.

At this point, switch is turned on at steady state. Diode should turn off at this point, immediately I am turning on the switch here. So, this value of current immediately the switch should carry and that current will flow through the switch itself, increases linearly and at this point, it is being switched off. Current instantaneously becomes 0. The moment I turn off S, D is turned on. The inductor current has to be continuous. That current starts flowing through the diode D. So, this is the diode current variation. It jumps to I_{max}, falls linearly and at t, you switch on S again. The moment S is turned on, I am assuming that D turns off. It may have its own turn off time. That is neglected during analysis. D turns off, whatever a current that was flowing through the diode should be transferred or gets transferred to the switch and the source supplies that current.

So, this is the wave form that is appearing across or this is the current wave form that is flowing through the diode. So there is instantaneous jump when it is turned on, again there is a jump when is turned when it is turns off when it this turns off. So, when the switch is on, voltage across the switch is 0 and when the diode is conducting, voltage across the switch is V_{DC} itself. I explained to you, it is V_{CC} itself and when in this period, when diode is on, sorry, in this period the switch is on, sorry, switch is on in this period, voltage across the diode is the supply voltage itself, in the opposite sense, a source voltage - V_{DC}.

At this point, switch is turned off. Diode starts conducting and it is 0 till the next switch, next cycle when S is turned on again. How does V_0 look like? We assume that V_0, suppose, V_0 remains constant but then I had written in the equation dV_0 by dt then after sometime, I told that variation of V_0 over the cycle is 0. Variation, average variation, in the sense, it starts charges for some time and discharges for some time. So, when does it starts charging and when does it stops charging?

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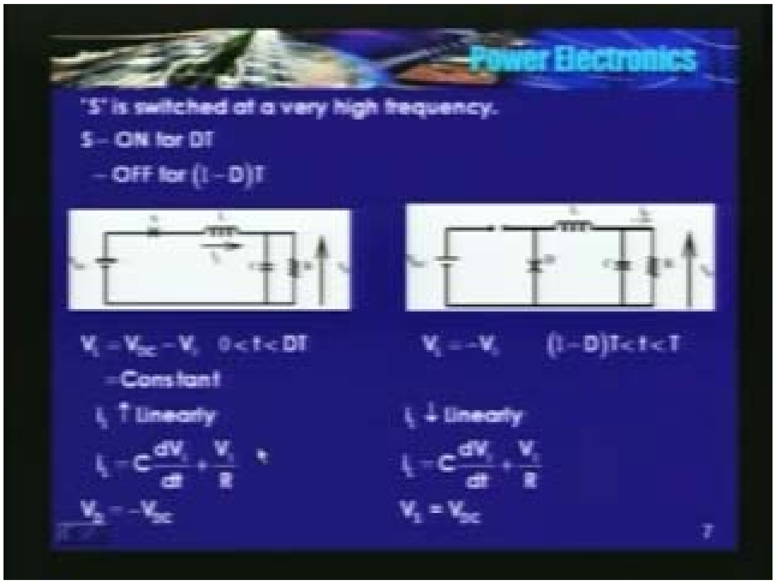

See the circuit here, KVL sorry Kirchhoff current law has to hold good. I_L should be equal to i_C plus i_0, i_C plus i_0. So, capacitor will starts charging if the inductor current is higher than the load current, i_0 which is equal to V_0 by R, I am i_0 is equal to V_0 by R and I am assuming that i_0 is constant. See, that is there is a bit ambiguity here, do not get confused. I am calculating or I am plotting the variation in the capacitor voltage, output voltage. While calculating or while plotting the variation of capacitor voltage …, I am assuming that current remains constant,

So, i_0 is V_0 by R. Now, if V_0 changes, i_0 should change. But I am assuming that i_0 will remain constant. The variation is not much, variation is very small. So, capacitor will charge when I_L

current - the input current is higher than the load current. When I_L is higher than the load current, i_0, the remaining current should go through the capacitor. When I_L is less than the load current, capacitor should supply the difference in the current.

Current through the capacitor can change instantaneously, remember. Capacitor current can change instantaneously, voltage cannot change. So, capacitor starts charging or current flowing through the capacitor is positive when the inductor current is higher than the load current. See, this is an inductor current, this a load current assumed to be constant. So, from this period, inductor current is less than the load current. So, difference should come from the capacitor. In other words, capacitor is discharging, V_0 is falling. At this point both the currents are same, capacitor current is 0. Inductor current starts increasing, capacitor currents also starts increasing. So, capacitor starts charging. You might have turned off the switch at this point. Once you turn off the switch, current starts decreasing. But this inductor current is higher than the load current till here.

So, in this period, capacitor charges, so see, capacitor charges during this period. Do not say that capacitor starts charging at this point and stops charging at this point, no. KCL has to hold good. At this point or beyond this point and after this point, inductor current is higher than the load current. So, capacitor starts charging during this interval and after this inductor current is less than the load current. Capacitor supplies current because we have assumed load current to be constant, capacitor discharges. More about it will see it in the next class.

Thank you.