Power Electronics

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Lecture - 31

In the last class we discussed the forward converter. The transformer which is used in forward converter requires 3 windings, 2 for energy transfer and the third 1 for continuity of flux. So, in our analysis, we connected the third winding to the supply to V_{DC}. It is not an essential condition that we need to connect the third winding to V_{DC}. Instead, we can have a fly back converter between primary and and the tertiary winding. Similar to fly back converter, if you have more number of secondary, you can have multiple outputs. So, even in forward converter multiple outputs are possible.

Now, coming to the the the third 1, the tertiary winding, we select the number of turns to be same as the primary. N_3 is equal to N_1, if that is the case; the cross sectional area of the conductor that is used for the tertiary winding should be very small because tertiary winding carries only the magnetizing current. So, number of turns in the primary as well as tertiary is the same. But then cross sectional area of the primary depends on the secondary current also because primary carries the magnetizing current as well as as well as the equivalent secondary current, whereas, the tertiary winding just carries the magnetizing current.

So, you can use a very thin conductor for the tertiary winding and the primary conductor depends on depends on the secondary current. So, if the number of turns is the same, the maximum value of D can be 0.5. So, if you go above 0.5, the flux will be continuous and it will so happen that it may saturate the core. So, D max is 0.5.

So, we discussed about the fly back as well as forward converters. Both converters operate in the first quadrant. H is either positive or 0, we are not applying the negative ampere turns or HIH. So, before going into other power supplies, I will solve a problem in forward converter as well as a fly back converter.

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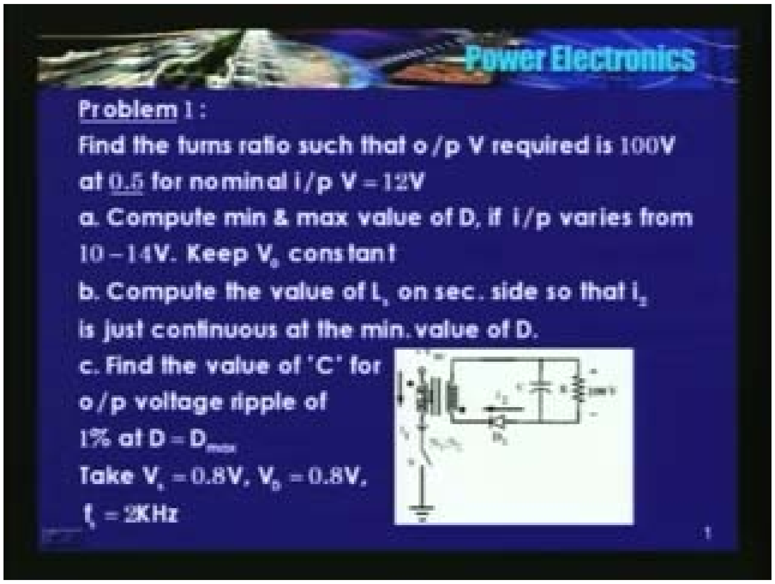

So, first one is on fly back converter. The problem states that see, required output voltage is 100 volts and nominal input is 12 volt, input is 12 volts. So, the the problem says find the turns ratio such that output voltage required is 100 volts at D is equal to 0.5. See, generally the nominal value of the D is around 0.5, even for fly back as well as as well as the forward converters, at 0.5 for a nominal input voltage of 12 volts. See, input is 12 and output voltage is 100 volts.

Now see, we are applying 12 volts to the primary. There is a device, a non ideal device when it is conducting even if it operates in saturation, voltage drop across it will be approximately 2 volts or so, it depends, again. So, maximum voltage that is applied to the winding is the of the order of 10 and that winding has its own resistance, again. So, maximum voltage that is applied to the winding is less than 10 and output is 100.

So, ratio of 10, the boost, output by input is ratio is of the order of 10. So, it would be extremely difficult if I do not use a transformer. If I just use a boost converter, it would be extremely difficult to get a ratio of 10 in this because we found in boost as well as buck – boost, it is a strong function of the ratio of the load resistance to the inductor winding resistance and part A compute the minimum and maximum values of D if input varies from 10 to 14 volts.

Keep V_0 constant, problem … (6:19). So, input itself is varying from 10 to 14. Output should be regulated at 100 volts. Therefore, as the input changes, we need to change the duty cycle. So, that is why I said a close loop control is a must. One for one reason is that if the load gets disconnected, I am storing the energy, dumping it. The output capacitor voltage goes on building up and for second reason in order to maintain a constant output voltage; we need to have a close loop control we need to have a close loop control.

Now, part B of the problem - compute the value of Ls; Ls is the secondary inductance or inductance of the secondary. So, that i_2 is just continuous at the minimum value of D. So, first we need to find out the minimum value of D and for that value, i_2 should be just continuous and the part C it says, find the value of C for output voltage ripple of 1% at D is equal to D max.

So, we need to find out the output voltage ripple or we need to regulate the output voltage at 1% for maximum value of D. Again, we need to find out the maximum value of D, nominal is 0.5. So, when we need to have minimum D and when we should have maximum D; when the input is varying from 10 to 14, we will find out.

See again, it is going to it is it is a non ideal converter in every sense. Take V_S is equal to 0.8 volts. V_S in the sense, voltage across the switch when it is conducting is 0.8 volts, looks like it is on the lower side lower side. V_d is 0.8 volts, voltage across the diode and switching frequency is 2 kilo hertz. Looks like all 3 values are on the lower side. If it is a fly back converter; may be, generally, a power rating is of the order of 100 to 150 watts or so. Switching frequency is definitely higher than 2 kilo hertz and in that case, voltage across the switch when it is conducting is is much higher than 0.8 volts. Anyway, we will take this and we will solve the problem.

What is the condition or how will you derive the transfer function? We said, volts second per turn balance is a must. In other words, at steady state, increase in flux should be equal to the decrease in flux.

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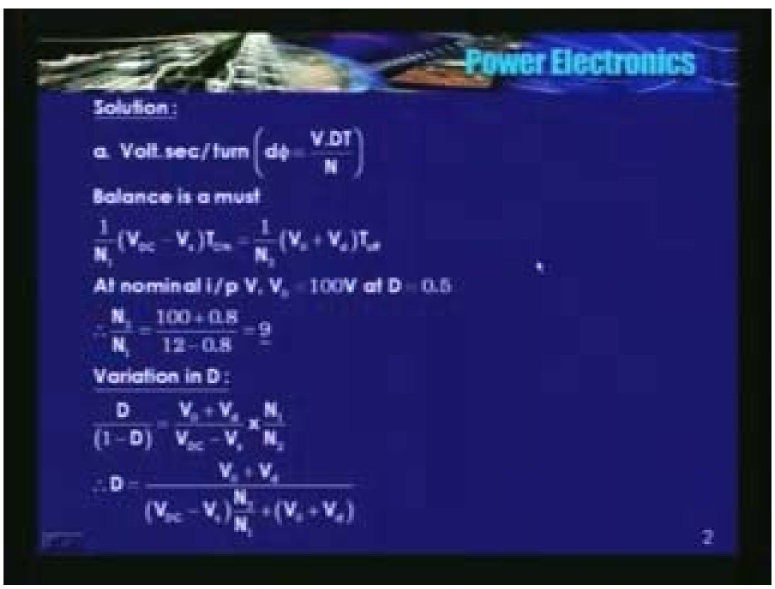

So, d phi, positive of d phi is when I close the switch and it is closed for DT seconds. N is the number of turns in the primary. So, voltage across the primary is V_{DC} minus V_S. See in this figure, V_{DC} is voltage applied to the primary the winding, 0.8 volts is the drop here, remaining voltage appears across the winding and in the secondary, what is the voltage here? Secondary is this is 100 volts. Output is regulated at 100 volts. There is a diode here, so 0.8 volts is the drop across the diode, plus, minus. So, voltage here is 100.8 100.8. This is 100 - the voltage drop across the diode, so this will be 100.8.

So, volt second per turn balance equation is this - N_1 into V_{DC} minus V_S into T_{on} should be equal to V_0 plus Vd into T_{off} divided by N_2. At nominal input that is V is at 12 volts, V_0 is 100 volts at D is equal to 0.5. So, you substitute in this. So, you will get N_2 by N_1 is 9 is 9.

Now, what is the variation in D that is required when the voltage varies from 10 to 14 volts? Definitely, D is higher than 0.5 when the input is is less than 12 and D is less than 0.5 when when input voltage is higher than 12. So, you substitute for T_{on} and T_{off} in terms of D and solve this equation. You will get the equation for D in terms of supply voltages and and the turns ratio.

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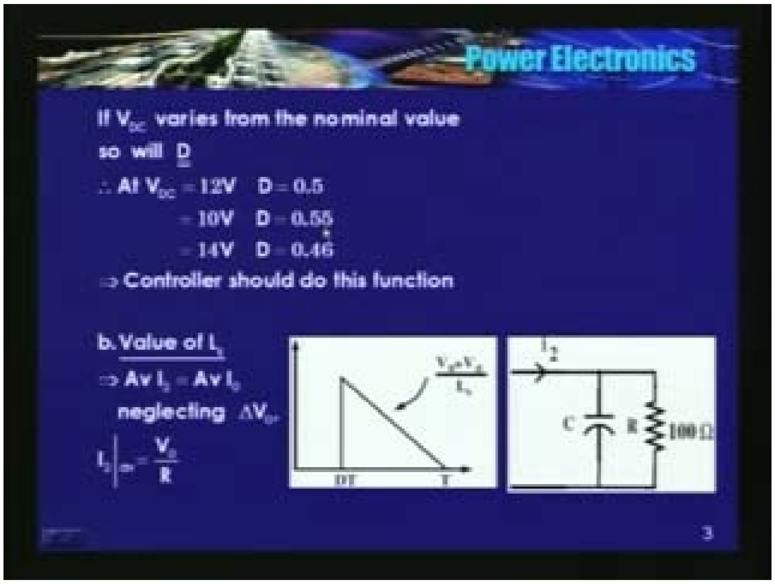

Now, V_{DC} is changing. All other parameters are constant. What should be the value of D? You just substitute it. You will find that at V_{DC} equal to 12 volts, D is 0.5, see and the input is 10 volts. D has increased to 0.5 5 and when D is 14 volts sorry when V_{DC} is 14 volts, duty cycle is 0.6.

Actually, a closed loop controller does this. There is a regulator or a controller which senses the output voltage. If I see, initially the input voltage was 12, D is 0.5, a steady state was attained. Now, the input has changed to 10, D is still 0.5. So, output voltage starts falling, immediately controller senses because this is a continuous process, sensing is a continuous process; measure the output, compare with reference, take the corrective action. So, reference has been kept at 100 volts. Output is falling because input has reduced, so immediately controller takes action; a suitable action. That action is nothing but increasing the value of D and it will attain a steady state.

Now, how do I solve the part B of the problem? The part b of the problem says that what is the value of Ls so that i_2 is just continuous when D is equal to D minimum? So, the current wave form of a secondary current is looks like, it is just continuous at DT. It jumps to the peak value.

It starts falling and it becomes 0 at T and slope of this line is voltage across the secondary winding which is nothing but V_0 plus V_D divided by Ls.

This is the slope of this line and this is the secondary circuit, a capacitor parallel with the resistor. So, at steady state, average value of the current that is flowing through a capacitor should be 0. So, i_2 average should be equal to average value of the load current. So, average value of the load current is nothing but V_0 by R. I am neglecting the ripple in V_0 I am neglecting the ripple in V_0. So, average value of i_2 is nothing but average value of the load current. Average value of the load current is 1 ampere now. What is the average value of this wave form from 0 to DT. i_2 is 0 and it is a right angled triangle. So, what is an average value of this? It is the area of this triangle divided by the time period.

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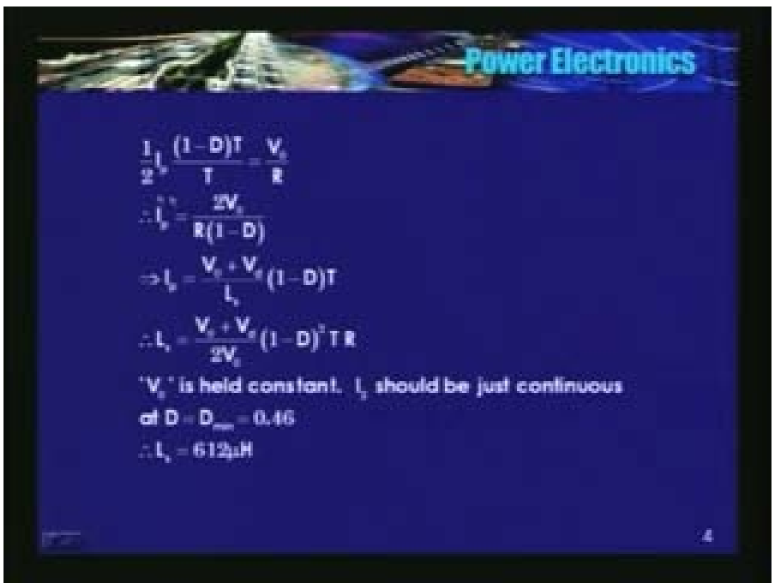

So, this is the equation; average i_2 should be equal to average i_0. So, the peak value of the current is given by this equation, Now, from this figure I know the slope, I know this time period. So, I can calculate this current, this value. I know the slope, I know this period; I can calculate this current.

So, what is the relationship between this duration and the slope of this line? It is this - 1 minus D into T is the time, this is the slope, the peak current. So, equate it; equate these 2 equations, we will get equation for Ls. V_0 is held constant, i_2 should be just continuous at D is equal to D minimum, it is been given. So, D is 0.46. So, Ls comes out to be 612 micro henries 612 micro henries.

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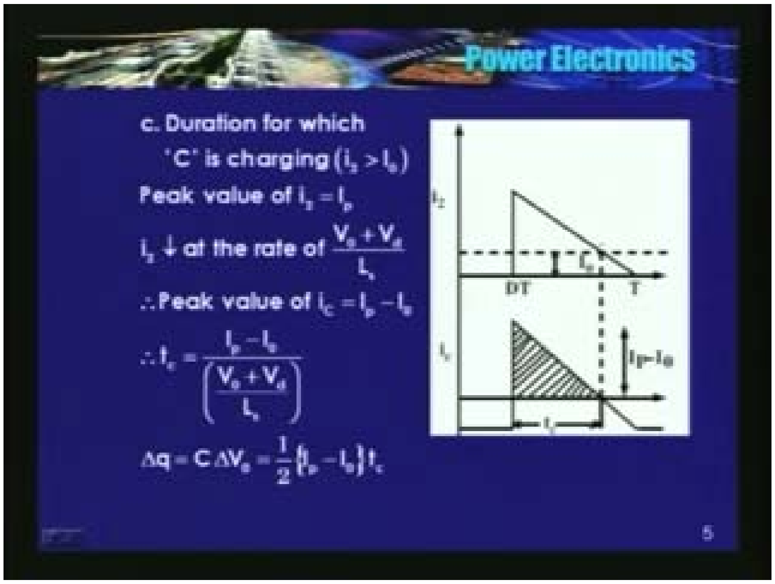

Now, that the last part of the problem; this is output voltage ripple is 1% at D is equal to D max. Previous is current should be just continuous at D is equal to D minimum. Now, we will see when the capacitor is charging and when is discharging? It is all depends on depends on the duration for which capacitor is charging and the duration for which capacitor is discharging. Secondary current wave form for a right angled triangle, average value is 1 ampere and the circuit is this; i_2 is the input current coming from a secondary, divides into 2 parts. This current is constant.

So, if i_2 is higher than 1 ampere, the difference between i_2 minus 1 ampere will flow through the capacitor and when i_2 falls below 1 ampere, capacitor starts discharging. So, we will go back. So, above 1 ampere the current that is flowing through the capacitor. So this duration, capacitor is charging and the remaining entire duration, from 0 to DT and from t_c onwards, capacitor is discharging.

Now, we need to find out the charge transferred to the capacitor or first we will find out the time for which the capacitor is charging or t_c below this slope because the voltage is V_0 plus V_D and the inductance is Ls. So, i_2 is falling at the rate of V_0 plus V_D divided by Ls, peak value of i_c. This current is I_p minus i_0. i_0 is 1 ampere, so our t_c is peak value of this current divided by the slope of this line.

So, del q or the charge that is transferred to the capacitor that is nothing but C dV_0 by DT is equal to this, the area of this triangle. That is nothing but half of I_p minus i_0 that is peak into t_c.

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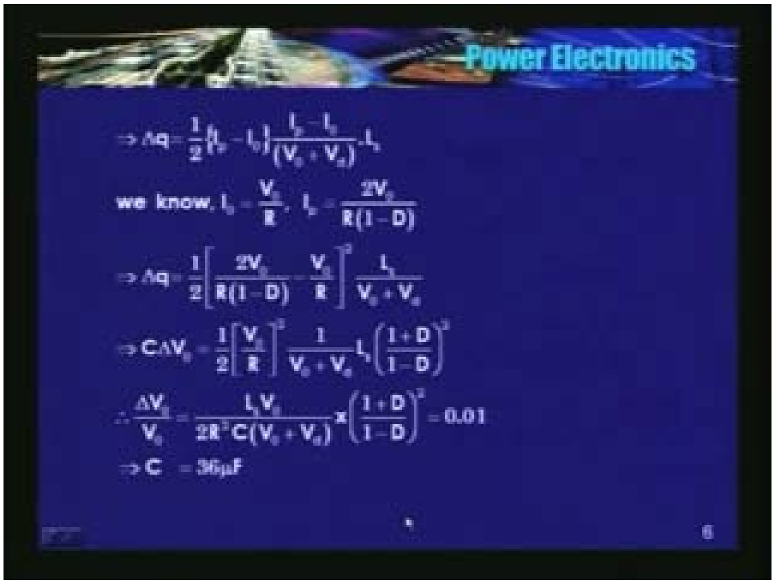

Now, value of t_c is again given by this equation. Now, you substitute it, you will get equation for del q. Now, i_0 is V_0 by R, I_p is $2V_0$ divided by R 1 minus D; this equation, we already solve in part B. So, you substitute here, you will get delta q is equal to this term. So, this is nothing but C delta V_0 and percentage voltage ripple is nothing but delta V_0 divided by V_0. So, C delta V_0 is this. So, delta V_0 by V_0 is this equation. Same; C is here, V square was here, so comes here, V_0. Remaining terms is the same. Now, this is 1%, it is given, value of D is also known. So, C is found to be 36 micro farads. This is about the problem on fly back converter. We will solve another problem on forward converter.

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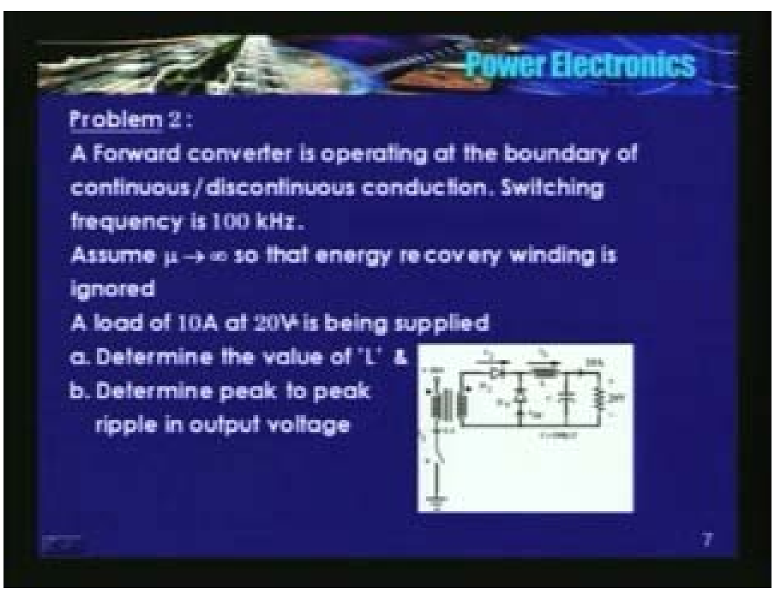

The problem says; a forward converter is operating at the boundary of continuous and discontinuous conduction, switching frequency is 100 kilo hertz; a realistic figure, 100 kilo hertz. Another ideal feature, assume mu is equal to infinity so that energy recovery winding is ignored. So, we have just 2 windings. We said that 1 is to 1, it does not matter, it does not matter. It was a 50 and a 20, so voltage ratios are not or voltages are not greatly different. But then problem says that they assume the forward converter, it is fine. May be, just provides isolation between input and output.

A load of 10 amperes at 20 volts is being supplied, 10 amperes at 20 volts is being supplied. Determine the value of L and peak to peak ripple in the output voltage. In the previous problem, we have to find out to C to limit the ripple of to ripple to 1%. Here, we need to find out the peak to peak voltage ripple and C is 100 microfarad, it is given. How do I solve the problem? I think we need to ignore all the device drops. We can take into account, not a it is not a problem.

Now, voltage across the inductor when the switch is on is how much? It is a voltage induced here, in this winding minus V_0. That is the voltage across the inductor. Diode is conducting when the switch is on, so voltage induced in secondary is V_{DC} into N_2 divided by N_1 and it so happens that N_1 is equal to N_2. So, voltage induced here is 50 volts itself, this is 20.

So, when the switch is on, voltage across the inductor is 30 volts and when the switch is off, DF starts conducting because I_L should be continuous. So, voltage across the inductor is 20 volts. See, mu is infinity; so, magnetizing current is 0. So, you do not require a tertiary winding; some sort of an ideal case.

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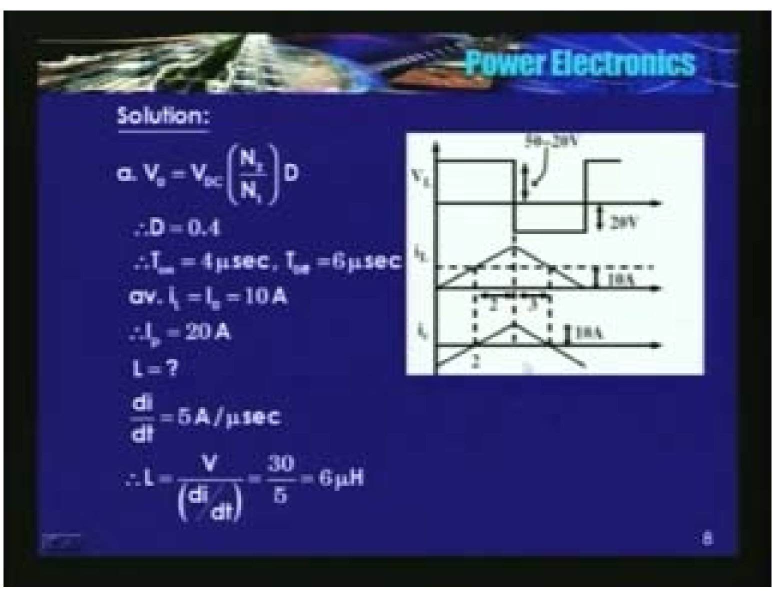

So, this is the voltage wave form across the inductor. Equate it, so we will get a transfer function; V_{DC} into N_2 divided by N_1 into D. Again, we have ignored the device drops. We can take this if it they are given, you can take into account and you will get another equation. So, D is 0.4. So therefore, T_{on}, this period is 4 micro second; T off is 6 micro seconds 6 micro seconds.

Here, by the way, problem says that forward converter is operating at boundary of continuous and discontinuous conductions. Part B says assume mu is equal to infinity. So, the energy recovery winding is ignored. Now, please do not get confused. I have told that for forward and fly back if I say discontinuous conduction; it implies that flux in the core is discontinuous. Load current for a fly back is nothing but a voltage source where it is continuous and here in a forward converter, I have an approximately current source. So, I can safely assume that load current is continuous.

But in this problem they have said that mu is equal to infinity. So therefore, neglect the recovery winding or third winding. So, there is the question of taking the I_M into account does not exist. Please, just try to understand. It is mentioned that energy recovery winding is ignored. So, there is no third winding. Therefore, current the continuity of current in third winding does not exists here.

So, when it is said that forward converter is operating at the boundary of continuous and discontinuous, here we need to assume that this current is nothing but the current flowing through the inductor L inductor L. So, i_L starts from 0, increases, just prior to closing the switch; it attains a peak and again it comes down. Average value of this current is 10 amperes, it is given.

Now, what is the peak value of the i_L? What is the peak value of i_L? Because, to plot I_C, current that is flowing through the capacitor and to determine the voltage ripple, I know I need to know the current that is flowing through a capacitor, this. So, when i_L is less than the average value of the load current, capacitor is discharging and it when it is, when the inductor current is higher than the 10 amperes, capacitor is charging.

So, what is this peak value? Peak value is nothing but area divided by area of this, the whole triangle divided by the time. So, we will find that this peak is 20 amperes, this peak is 20 amperes. Now, what is the value of the inductor L? Current reaches peak in 4 micro seconds, voltage that is supplied across the inductor is 30 volts. Therefore, L is 6 micro henries. I will repeat; this DT is 4 micro seconds, voltage applied to the winding is or voltage applied to the voltage applied across the inductor is 30 volts and this is the variation of current. So, L is 6 micro henries 6 micro henries.

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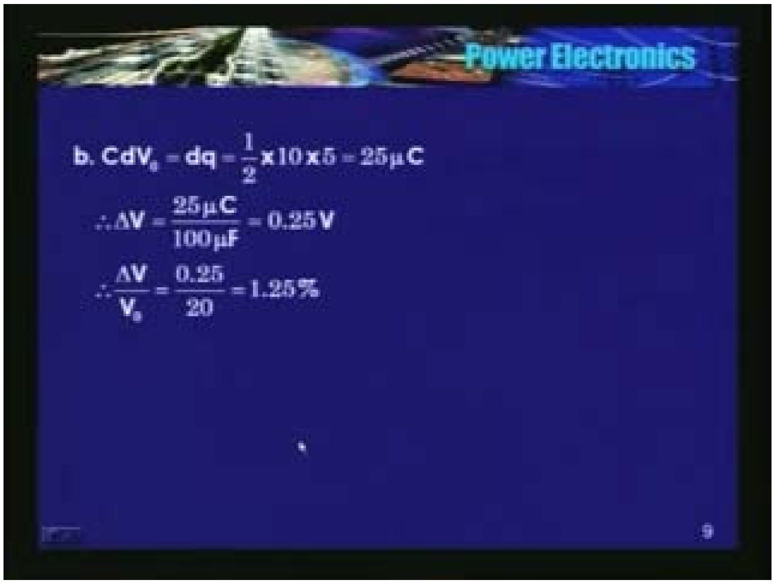

And, the same procedure to determine the output voltage ripple; C dV_0DTshould be equal to dq is equal to half. See, area of this angle. This is DT by 2 because entire DT is 4, this is linear, so this is this point is DT by 2 DT by 2 or midpoint in between 0 to DT and this is the midpoint between DT and T.

So, for 5 micro second, capacitor is charging. The peak value is 10 amperes. This is 10 amperes because peak of i_L is 20. So, this is 10 amperes. So, area of this triangle, I need to is 25 micro coulomb. So, del V is 25 micro coulomb divided by 100 micro farads is 0.25 volts. So, voltage ripple is is of the order of or is equal to 1.25 %. So, that is the reason we neglect the change in the average value of the load current because see, the voltage ripple itself is of the order of 1.25% 1.25%.

In other words, voltage change in output voltage is 0.25 volts at an and a average value of 20. For an engineer it is constant. So, that is the reason we always assume that i_0, the load current is assumed to be constant. Though we change the, we plot the variation of the capacitor voltage and we assume that output current remains constant. Somehow, there is a contradiction there. But then, see, this problem clearly says; change in the output voltage is 0.25 volts, average is 20. So, change in in the load current, average value of the load current is approximately 0 0. So, that is about the fly back as well as the forward converter.

In both the cases; we are using a transformer. In one case, source supplies only the magnetizing current in the fly back converter, whereas, in a forward converter; source supplies the magnetizing as well as the equivalent load current. But then in both cases, operation is always in the first quadrant.

Now, let us see the operation in both the quadrants. I have told you that fly back converter is very attractive if the power rating, if the power supply is is of the order of 100 to 150 watts. May be, from 100 to 500 watt or 600 watts, forward converter is preferred. Now, so high power range;

what sort of a power supply to choose? Now definitely, we need to use bidirectional core excitation.

See, in fly back and forward, it is a unidirectional core excitation. Current in the core is DC. Please, DC does not mean that constant value of DC, average value is finite. Now, bidirectional core excitation is nothing but AC excitation to the transformer. Now, again AC need not be a sinusoid. AC implies average value is 0 that is all. So, current that is flowing through the transformer should be AC now.

Input is DC, now how do I do this? So, what I will do is, I use 2 forward converters and connect them in anti phase. I will draw the figure and I will show you. So, 1 forward converter is pushing the power or it is apply it is working in the first quadrant, positive NI and another forward converter is negative NI. So, I am applying both; positive core excitation as well as a negative core excitation. That is why that is why I am calling I am saying that current that is flowing through the transformer is AC. It is AC because average value is 0 that is all.

So definitely, for high power high power applications, I need to use bidirectional core excitation. That I can achieve. One of the ways to achieve is to use 2 forward converters working in anti phase. So, both the converters are pushing the power to the load. In one one converter is working in when NI is positive or in when I working the or when I working the first quadrant, the forward converter supplies power to the load and even when I applied negative NI, forward converter still supplies power to the load.

In other words, both are pushing power to the output. So, the obvious name should have been a push - push converter; I do not know, the name that is prevailed is push - pull converter. I do not why this is push - pull converter. Here, both the converters are pushing power to the load; it should have been push - push converter but push push push - pull converter has prevailed. Let us see, how does it work? It is bit a bit difficult a bit difficult. Try to understand I need to find

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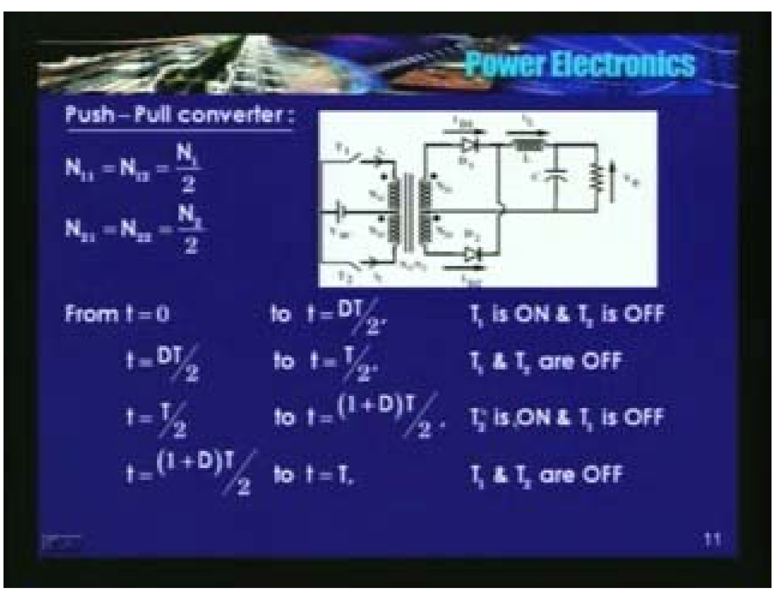

Here is push pull converter. I said it is a AC excitation, so therefore, voltage induced in the secondary is AC. Again, I am not saying that it is a sinusoid. So, I want a DC power supply. So, voltage induced in the winding is AC because AC excitation or bidirectional core excitation. I want a DC power supply; definitely, you need to have a 1 more stage which converts AC to DC or you can use either a bridge rectifier or a center tapped center tapped version of the full wave rectifier using 2 diodes.

So, I am using 2 diodes. So, this is secondary, secondary side of the push - pull converter. A center tapped winding, see the dotted polarities; number of turns in both the winding is the same. So, these 2; D_1 and D_2 are diodes and this is the output stage. Looks like a forward converter, isn't it? This is nothing but a forward converter stage or a buck converter stage and I said, 2 forward converters working anti phase. So definitely, transfer function should be should be same as that of a forward converter with some other multiplying factor and see in the primary; I have again again a 2 winding, a center tapped a center tapped transformer, N_{11} N_{12}. N_{11} is equal to $N_{12,}$ a V_{DC} power supply and 2 switches. I need to use 2 switches.

So, how would have this how would have this circuit worked? How would have this circuit worked? From 0 to DT by 2; see here, all this time I said 0 to dt, switch is on, it is fine. But then, here there are 2 switches 2 switches. So, from 0 to DT by 2, T_1 is turned on and T_2 should be off. I will repeat; from 0 to DT by 2, T_1 is on and T_2 should be off. Why? We will see later.

From DT by 2 to T by 2, that is half the wave cycle is over here, T by 2; T_1 and T_2 are off. Both the switches are off. Now, I am not going to tell you what happens in the secondary. Sometime later I will tell you. It is not very obvious. So, whatever that happened from 0 to T by 2, for T_1 it will happen from T by 2 to T over T_2. So, from T by 2 to 1 plus d into T by 2, T_2 is on and T_1 is off and from 1 plus D into T by 2 to t is equal to T, T_1 and T_2 are off. So, both the switches are off. I have not told anything about the secondary. Fine, we will see now.

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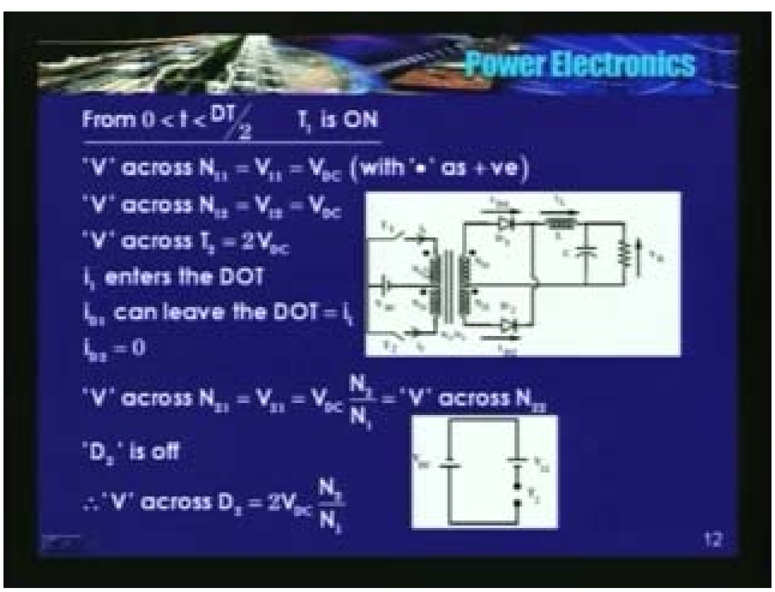

From T_2 T is equal to 0 to T is equal to DT by 2, T_1 is on. See, in this equivalence circuit; in the primary side, current enters the dot in N_{11} turns, current enters the dot. So, in this secondary if you see, current should leave the dot. Yes, D_1 can conduct now because current iD_1. So, D_1 is on, D_2 is off. So, voltage applied to N_{11} is V_{DC} with the dot as positive. Voltage induced in N_{12} is again V_{DC} because number of turns is the same with the dot as positive.

Therefore, voltage across the switch T_2, how much is that? It is V_{DC}. See, minus is connected to positive half the voltage induced in N_{12} or V_{12}; positive, positive voltage, so V_{12}. So, it is nothing but 2 V_{DC}. Voltage across this switch is twice the supply voltage, remember. So, T_2 should block twice the input voltage. Current enters the dot here, i_1 is; I will not talk about i_1. Current enters the dot, current leaves the dot, iD_1 starts increasing because iD_1 is same as i_L same as i_L. Voltage induced in N_{21} is V_{DC} into N_{21} divided by N_{11} or N_2 by 2 divided by N_1 by 2 because number of turns in N_{21} is half of the total number of turns and here also. So, I can write V_{21}, voltage induced in N_{21} is nothing but V_{DC} into N_2 divided by N_1.

Actually, it is N_{21} divided by N_{11}. So, N_{11} is nothing but N_1 by 2 and N_{21} is the nothing but N_2 by 2. So, voltage induced in N_{21} is same as voltage induced in N_{22} turns. Diode D_2 is off, so voltage across the diode D_2 is twice V_{DC} into N_2 divided by N_1. Sum of these 2 voltage sources sum of these 2 voltage sources because D_1 is conducting. This point gets connected here, so voltage across VD2 D_2 is 2 V_{DC} into N_2 divided by N_1.

i_L starts increasing slowly. Primary winding of the transformer, it has to provide the magnetizing current which again increases linearly and i_1 should have the equivalent secondary load current. I said i_1 also increases linearly, I_M also increases linearly. But then the rate of increase of i_L is not the same as rate of increase of I_M. I_M, rate of increase of I_M depends on depends on the magnetizing inductance of the transformer, whereas, rate of increase of V_L sorry rate of increase of the inductor current i_L depends on voltage across the inductor and a value of L value of L. So, they increase linearly but then rates are not the same are not the same. So, see here.

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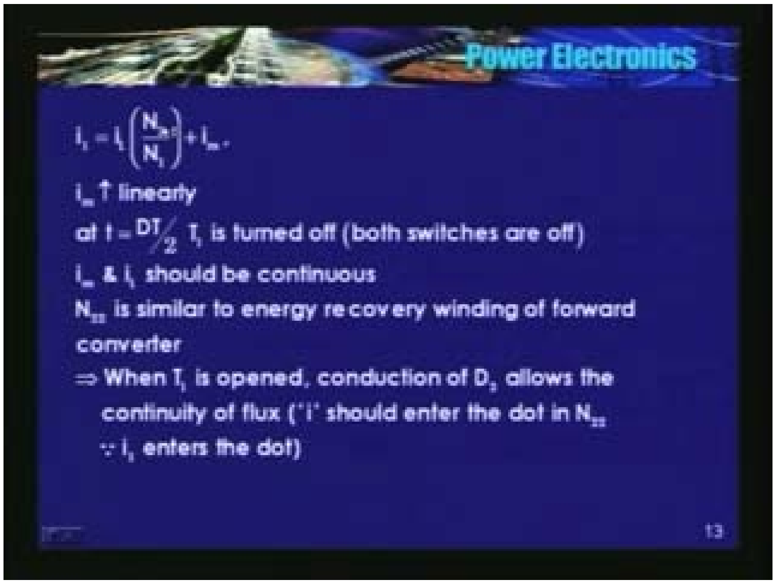

Therefore, i_1 is the load current. This i_L is flowing in N_{21}, this N_{21} is nothing but N_2 by 2 but whereas, i_1 is flowing in N_{11} and N_{11} is nothing but N_1 by 2. So, i_1 is equal to i_L into N_2 divided N_1 plus the magnetizing current. I_M increases linearly.

Now, at DT by 2, switch is turned off. What happens? What happens in the circuit? When the switch is turned off, magnetizing current should be continuous and the inductor current i_L should be continuous. Now, in the forward converter there was a diode which is which is providing a path for i_L and we use a tertiary winding for continuity of flux. Magnetizing current starts flowing in the tertiary winding but if you see in this figure, N_{22} is similar to the energy recovery winding of the fly back converter.

See, current is entering the dot here. So, any coil, wherein current can enter when the switch is turned off, can provide a path for the flux. I will repeat; current was entering the dot when I closed the switch in the primary. So, when I open the switch, current should enter the dot in some other winding which is mutually coupled with the primary winding.

Now, if you see in this figure, current in N_{22} can enter can enter. i_2 enters the dot. Here, T_2 is not closed, we have not closed T_2 we have not closed T_2. So, i_1 or the magnetizing current can enter N_2 or this coil or can enter this coil because of this diode and it can flow through this path. So, i_L also can flow through this path. I said; can. What happens? I will tell you later.

So, I can say that N_{11} and N_{21}, they form a forward converter and N_{11} and N_{22} of similar to a fly back or N_{22} is is similar to an energy recovery winding energy recovery winding. Now here, it is feeding power back to this load. This energy recovery winding is feeding power to the same load same load looks like and continuity of i_L also can be provided by the same circuit. But then if you see this circuit very carefully, N_{21} and N_{22} are also mutually coupled. I will repeat; N_{21}, N_{22} are mutually coupled. Current in N_{22} is entering the dot. I will repeat; current in N_{22} is entering the dot. So, the right direction for the current in N_{21} is to leave the dot and it is possible.

See, we have a very interesting case here. When switch is closed; current enters the dot in the primary, current can leave the dot in the secondary. That can happen only in the upper half or it can happen only in N_{21} coil because of D_1. So, no current in N_{22} because of D_2. So, when I open the switch, if there is a coil; wherein current can enter the dot, this will provide a path for the magnetizing current or the continuity of flux. Which is possible here? It is N_{22} coil. Current can enter the dot because of D_2. But then if current enters the dot in N_{22}, current in N_{21} will try to leave the dot and it is possible because diode is connected in that way.

So, in this circuit, just see here; if current tries to enter this dot here, current can leave the dot here and there is a path there is a path. So therefore, when I open the switch, both D_1 and D_2 starts conducting both D_1 and D_2 starts conducting. Let us see how they share the inductor current, sometime in our next lecture.

Thank you.