In our last class I discussed the operation of a fly back converter. The fly back converter is nothing but an isolated, a buck - boost converter. The input output relationship is the same as a buck - boost or a chuck converter. In addition, there is a term; the turns ratio - N₂ by N₁. Now, because of this N₂ by N₁ turns ratio, the magnitude of V₀ and V_DC can be greatly different. What is the principle of operation? Though there is a transformer, only 1 winding is carrying current at a time. So, close the switch, energy is stored in LM where LM is the magnetizing inductance. Open the switch, stored energy is transferred to the load.

So remember, though I am using a transformer in fly back, current drawn from the source is the magnetizing current only, because in some other power supplies operation is going to be different. So, that is 1 of the reasons, the fly back converter is very attractive for low power range. Generally, if the power rating is of the order of 200 watts, fly back converter is a very good option.

I told you that invariably, fly back converters are operated in discontinuous mode. In other words, we are resetting the flux completely because operation is always in the first quadrant of BH characteristics. So, if there is a finite current flow in the secondary, in other words, there is some finite flux in the core, so when you close the switch in the next cycle and in case, the value of D has increased; it may so happen that core may get saturated. So, if it get saturated, you may be able to see the smoke coming out from the fly back converter or a black bucks. How do you avoid this?

One way is to have an air gap in during the transformer fabrication. So, if I have an air gap, there is going to be a leakage flux. So when I open the switch, you may be providing a path for the magnetizing energy or magnetizing current. But then there will be a spike due to the leakage inductance. So, we need to change the power circuit configuration. So, that is why you try to solve 1 problem in order to try to avoid the saturating the saturation of transformer by providing an air gap. The moment I do that it gives another problem, leakage flux.

So, that is why if we try to solve 1 problem, another problem is created. It is almost similar to the law of conservation of energy. Energy can neither be created nor destroyed. It can be transformed. Similarly, sorrows you know, you cannot destroy them nor create them. We can transform them from 1 form to another form. Here also, you had a problem, try to solve 1 problem; it gives rise to another problem.

Coming back to fly back converter, another major advantage of a fly back converter is we can have multiple outputs and 1 point I forgot to tell you in the last
class is that close loop operation is a must. Like any boost converter or chuck converter or a ... close loop operation is a must here. Why? Because, I am storing the energy, dumping it to the output. So, accidentally accidentally load gets disconnected. Capacitor voltage goes on building up, may be. So, close loop operation is a must.

(Refer Slide Time: 5:26)

Now, coming back to we also discussed the forward converter which requires a 3 winding transformer. See in this figure, \( N_1, N_2, N_3 \), see the dotted terminals here. So, when I close the switch, current enters a dot. So, in the secondary, current can leave the dot. So, current so, \( i_2 \) starts flowing when I close the switch. But then that cannot happen in the tertiary winding because of this diode connection.

So, the primary current here is the sum of the equivalent secondary current plus the magnetizing current. When I open the switch, magnetizing current has to be continuous. In addition, the inductor current should be continuous. So, this current can be made continuous by connecting a freewheeling diode here. So, so inductor current starts flowing through DF when I open the switch. So, the magnetizing current starts flowing through this winding. So, operation of these 2 branches; the primary and the tertiary is same as that of a fly back converter.

Current enters the dot, so direction of flux should be the same. So, here also current enters the dot current enters the dot. So, for a non ideal transformer which is used in a forward converter, we require 3 windings 3 windings. So, this is nothing but an isolated isolated buck because this entire structure, this part is nothing but a buck converter. Forcing function here is is the reflected voltage to the secondary. The primary is being connected to \( V_{DC} \). So, secondary is \( V_{DC} \) divided by \( N_1 \) multiplied by \( N_2 \). So, that is the forcing function and the operation is similar to a buck converter.
So, transfer function is $V_{\text{DC}}$ into $N_2$ by $N_1$ multiplied by the duty cycle. So, what is the voltage that is appearing across $D_3$ when the switch is on? So, in this circuit, voltage applied to the primary is $V_{\text{DC}}$ with the dot as positive. So, this is positive. So, this terminal voltage induced in this one is going to be negative and its magnitude is $V_{\text{DC}}$ divided by $N_1$ into $N_3$.

So, this is positive, negative and I have a source $V_{\text{DC}}$. So, equalant circuit is something like this; $V_{\text{DC}}$ into $N_3$ by $N_1$ in series with $V_{\text{DC}}$ is a voltage that is appearing across $D_3$. So, diode should be able to withstand this voltage, $V_{\text{DC}}$ plus 1 plus $N_3$ by $N_1$. 

(Refer Slide Time: 8:14)
So, open S, current starts magnitizing. Current starts flowing through the tertiary winding. Voltage applied to the tertiary winding is $V_{DC}$. So, what are the voltage that is appearing across the switch and the diode that is connected in the secondary, the $D_2$? Same, you need to use transformer principle. If I know the voltage applied to 1 winding, so voltage induced in the secondary is or voltage winding induced in the other winding is it just depends on the turns ratio. But then what is the magnitude of the current that is flowing through the tertiary winding?

Just prior to opening the switch, the magnitude of the magnetizing current is the magnitude of magnitizing current $V_{DC}$ divided by LM into D into T. $V_{DC}$ by LM is a slope of the rate of rise of magnetizing current, DT is the duration for which the switch is on. So, the peak value is $V_{DC}$ divided by LM into D into T. So, when I open the switch, the current gets transferred to the tertiary having $N_3$ number of turns. So, peak value of the current that is flowing in $N_3$ is $I_m$ into $N_1$ divided by $N_3$ because $I_m$ is the peak current that was flowing in $N_1$ turns. Now, the current gets transferred to $N_3$ coil or the coil which is having $N_3$ number of turns. So, this is the peak value of current that is flowing through the diode and the tertiary winding.

Now, voltage applied to the tertiary winding is $V_{DC}$. So, voltage induced in the primary is $V_{DC}$ multiplied by $N_1$ into $N_3$. Remember, when when $N_3$ is carrying current, $d\phi$ by $dt$ is negative, flux is decaying now. So, this is the equivalent circuit. So, voltage across the switch is the sum of these 2, $V_{DC}$ plus $V_{DC}$ into $N_1$ plus $N_3$ is the voltage across the switch.
What is the voltage that is appearing across diode $D_2$? Voltage is the same principle, voltage applied to the tertiary winding is $V_{DC}$. So, voltage induced in the secondary is $V_{DC}$ divided by $N_3$ multiplied by $N_2$. Again, $d\phi$ by $dt$ is negative. So, this is the equivalent circuit, the voltage induced in the secondary. $DF$ is conducting. When I open the switch, because of $LF$, $DF$ is conducting. Freewheeling diode is conducting. Voltage across the $D$, voltage across the $D_2$ is only $V_{DC}$ into $N_2$ by $N_3$.

So, the transfer function between the input voltage and the output, it depends on $N_2$ and $N_1$. Now, how many number of turns should be there in the tertiary winding? How do I choose the number of turns in the tertiary winding? By the way, what is the purpose of providing a tertiary winding? It is for the continuity of flux. What is the condition? Flux in the core should become 0 just prior to closing the switch, again in the next cycle. Invariably, even in forward converter, we need to operate in discontinuous mode of operation discontinuous mode of operation. Again, same concept as that of the fly back converter. Discontinuous current in the sense, flux in the core is 0 or in other words, we are completely resetting the flux in the core. Now, let us see what should be the number of turns that are required in $N_3$? So, peak value of current, magnetizing current $I_m$ that is flowing in $N_1$ turns is $V_{DC}$ divided by $LM$ into $D$ into $T$. That is the peak value of current that is flowing. Now, when I open $S$, that current gets transferred to the tertiary. So, this value of current is $I_m$ into $N_1$ divided by $N_3$. So, here is the equivalent circuit. See, even I close the switch, $LM$ starts flowing. When I open the switch, it starts flowing through diode $D_3$ and this is the voltage.

Now, $V_{DC}$ into $N_1$ and $N_3$, this is the voltage referred to the primary. So, when I close $S$, $d\phi$ by $dt$ is positive or flux increases. So, it is given by $V_{DC}$ divided by $N_1$ into $d$ into $t$, volts second per turn volts second per turn. Now, what is decrease in flux or $d\phi$? It is $V_{DC}$ divided by $N_3$
and $T_a$ is the time for which $D_3$ conducts or this is the time $T_a$ because for continuity of flux or continuity of flux is being provided by tertiary winding.

So, at steady state, increase in flux should be equal to decrease in flux or if it starts from 0, it should reach 0 at $T_a$. So, I will equate it, I will find that $T_a$ is equal to $N_3$ divided by $N_1$ into $D$ into $T$ and for discontinuous conduction; $T_a$ should be less than 1 minus $D$. I will repeat, for discontinuous conduction, $T_a$ should be less than 1 minus $D$ because $DT$ is the time for which the switch $S$ is conducting. The remaining time, 1 minus $D$ into $T$ is for which if the current is continuous, $D_3$ will conduct. For discontinuous conduction, so $T_a$ should be less than or equal to 1 minus $D$ into $T$.

(Refer Slide Time: 18:03)

So, if $D$ is equal to $D_{\text{max}}$, this is the relationship. I will choose $N_1$ is equal to $N_3$ number of turns in both the windings is the same. So, I will find that maximum value of $D$ is 0.5. In a forward converter, if the number of turns in the tertiary and the primary is the same, the maximum value you can go is 0.5. Can you go or is it possible to go above 0.5 or what happens if I increase $D$ above 0.5?

See, this is the situation; when I close S, rate of rise of current is determined by LM. Voltage applied is $V_{\text{DC}}$. So, slope of this line is $V_{\text{DC}}$ divided by LM. I will open the switch. See here, current starts flowing into in tertiary winding. Number of turns is the same is the same. Voltage applied is also the same. So, this voltage increases the flux, this voltage because this voltage, flux decreases and magnitude of both the voltage, this is the same.

So, if this switch is on for a time which is greater than the time for which diode is on, I will repeat; if the switch is on for a time which is greater than the time for which diode is on, flux will not become 0 when I close the switch for the second time. Because, rate of rise is the same, rate of fall the slope is also the same but then on time is higher than the off time. So, there is
going to be some residual flux. See here, if if the flux is being completely reset, we have something this sort of a situation. Flux becomes 0, it starts from there. 

So, when I close the switch for the second time and assume that same value of D has been maintained, now magnitude of flux that is flowing in the core is higher than or this value is higher than this because D has been not changed, D has been kept same. So, when I open the switch for the second time, again this point is higher than this and if you continue, it may so happen that core may is get saturated or core will get saturated because you will have a some sort of a build up process of the flux because time for which in this circuit just see, time for which S is on is higher than the time for which the diode is on. 

(Refer Slide Time: 21:49)

So, this is positive D phi and this is negative D phi. Flux increases, flux decreases flux decreases. Now, voltage applied is also same, number of turns in both the windings is also same. So, I can have a just continuous conduction with D is equal to 0.5. So, for D is equal to less than 0.5, you will have a discontinuous conduction and if you go D is equal to and if you go D above 0.5, you may end up with saturation. 

Now, let us draw the waveforms for a forward convertor. Now, let me tell you 1 thing, I think I have not drawn the waveforms for a fly back convertor. But then I have drawn all the waveforms when I was discussing the recovery of trap energy. So, both are the same. So, I will expect you to go back and draw the various waveforms for fly back convertor. Principle of operation is the same.
Now, forward converter we will draw. S is on and in this period DF, the freewheeling diode and D3 are on. They may be on if the flux becomes 0. So, D3 is on till here and I told you that this part can be approximated to a current source and expect that $i_L$ to be continuous. So, so in the entire this period or from DT to T, D3 is assumed to be on. See, $i_L$ increases when I close the switch because voltage that is induced here is $V_{DC}$ divided by $N_1$ into $N_2$. See here, diode D2 is on, nothing but a buck converter nothing but a buck converter. Current increases when I open S. So, load current starts flowing through DF and it is assumed to be continuous.

So, DF is on for the entire off period of the switch S. But then D3 conducts only for a finite duration. So, voltage applied to the inductor when the switch is on is $V_{DC}$ divided by $N_2$ divided by $N_1$ minus $V_0$ is a voltage applied to the inductor LF and when the switch is open, since DF is conducting, voltage applied to LF or this inductor is minus $V_0$ minus $V_0$. So, by equating you get the transfer function. When I close S, inductor current is same as $i_2$. $i_L$ is same as $i_2$. We said that $i_2$ is increasing, so this is the waveform for $i_2$. Why it starts from a finite value?

It is because just prior to closing the switch in the next cycle, current through DF was finite. So, this is the current that was flowing through the diode DF, just prior to closing the switch S. So, this current starts flowing through D2. Open the switch, D2 becomes 0 and this current jump to or starts flowing to through DF. So, this is the current waveform. Mutually this magnitude should be equal to this magnitude.

How does $i_1$ look like? $i_1$ has 2 components, $i_1$ has 2 components; 1 is the reflected secondary current and the magnetizing current. We are assuming that $I_m$ has become 0. In the sense, we have completely resented the flux. So, $I_m$ starts from 0. But then, $i_2$ prime is non 0. It is finite because we have connected an inductor in the load circuit. In other words, load can be represented by current source and I told that current increases and decreases and it is off
and just prior to closing the switch S, current that is flowing through DF is finite so that current starts flowing through i₂. So, i₂ dash is a finite quantity.

So, the primary current, see, Iₘ starts from 0 and varies linearly and this dotted line is i₂ prime. The sum of these 2 is the primary current. See, because i₂ is finite, i₂ prime is again is finite. So, this is i₂ prime, Iₘ and this is i₁ and this peak value of Iₘ is V₇ divided by LM into D into T. So, when I open S, this current or flux has to be continuous. Continuity of flux is being provided by the tertiary winding. It gets transferred here. So, Iₘ into N₁ divided by N₃ is the peak current that is flowing through the tertiary winding. Voltage applied is V₇ and L₃ is an inductance of the coil N₃ having N₃ number of turns. I am I have taken here some arbitrary number of turn N₃. I have not assumed N₁ is equal to N₃, I have not assumed N₁ is equal to N₃. So, slope here is L₃ because it is flowing through a coil having N₃ number of turns.

(Refer Slide Time: 29:11)

Now, see the various voltage waveforms. S is on, so voltage across the switch is V₇ plus this quantity when diode D₃ is conducting. What happens when D₃ stops conducting? What is the voltage that was coming across various devices? Flux is 0, no current is flowing in any of these windings – primary, secondary, tertiary. So, you cannot use the transformer action principle. So, entire V₇ is blocked by D₃ diode here because no current that is no current is flowing in this coil.

Similarly here, the entire supply voltage is blocked by the switch S which appears across S. So, it is very simple here. Tertiary and primary voltage, these are V₇. What happens in the secondary?

Diode is conducting. So, DF is conducting. So, voltage appearing across N₂ turns is the voltage across the diode D₂. But then there is no current flowing in these 2 windings. There is no voltage here there is no voltage here. If one of the way to carry your current, that
would have been a reflected voltage or induced voltage. Now, no current is flowing, so no relationship at all. So, there is no voltage induced in this coil, no current in this as well as this.

So, in practical, it is a 0 voltage that is appearing here, 0 voltages because this is this point. So, see the waveforms here; \( V_{DC} \) that is voltage across the switch, similarly \( D_2 \). When the diode \( DF \) is conducting, it is \( V_{DC} \) divided by \( N_3 \) into \( N_2 \) and it is 0 and similarly, voltage across the switch or voltage across \( D_3 \) is this waveform and it is 0 when it is conducting and when current has become 0, voltage across jumps to \( V_{DC} \).

So, if the current is just continuous or if the flux is just continuous in the core, so you will not have this jump. That is only the difference; you will not have this jump. If the flux is just continuous, you will not have this jump at all and this is the voltage appearing across the freewheeling diode, \( DF \). So, when it is conducting, voltage across it is 0 and when it is off, voltage across it is voltage induced in the secondary winding itself. See here, \( D_2 \) is conducting. So, voltage induced in \( N_2 \) is a voltage appearing across the diode \( DF \). So, there is a short here. Voltage across \( N_2 \) induced in \( N_2 \) is a voltage across \( DF \). This is nothing but \( V_{DC} \) divided by \( N_1 \) into \( N_2 \).

So, these are the various waveforms of \textit{for} a forward convertor using 3 winding transformer. Now, let us discuss some special cases in forward convertor. So far we discussed a forward convertor wherein the tertiary winding is connected to the supply voltage \( V_{DC} \). Same voltage that is being applied to the primary or the coil having \( N_1 \) number of turns and I told you that \( N_1 \) and \( N_3 \), they form a fly back connection.

You do not have to connect the third coil to the same supply voltage. The purpose of the third coil is to just to provide the flux continuity, nothing else. So, instead of feeding the energy stored in the magnetizing branch to the source, you can transfer it to a capacitor and a load, nothing but a fly back convertor.

(Refer Slide Time: 34:33)
11

See something like this; N₃ coil, diode D₃ and C and R. This is nothing but a fly back convertor. I have not shown the primary here, primary does exist because see here, in the previous see, this current is entering the dot here, current is entering the dot in the primary. So, for a flux continuity, the tertiary current also should enter the dot.

So, see here current is also entering the dot. So, I connected D₃ where this capacitor voltage polarity is this, this is positive, this is negative. So, I can have 1 forward and 1 fly back convertor. So here, the V₀ is again, you can use the transfer function that we derived for fly back convertor please, the principle is the same. Again, you need to find out when the flux become 0? If it is just continuous, you use the same transfer function that we derived for the fly back convertor. So, you do not have to connect the tertiary winding to the same source. You can have a fly back supply convertors in a forward convertor itself.

By the way, why we using the third winding? What if I do not use a third winding using a non ideal transformer? In an ideal transformer, I told you that you do not require the third winding because reluctance is 0, μᵣ is infinity, so ampere turns required to establish the flux in the core is 0. So, there is no magnetizing current. So, you do not require a tertiary winding. Now, I will use a non ideal transformer wherein there is a finite magnetizing current. But I will not use the third winding and I will do some modification. Let us see what happens?

See here, this is what I have done. Let us see what happens, whether it will work or if it works what is going to happen? I have not connected or I have not used D₂ here. There is no D₂. So, when I close S, what happens? Current is entering the dot. Current can leave the dot in the secondary.

Of course, DF is reverse biased, current starts flowing here, iₐ starts increasing, iₐ therefore, i₂ starts increasing. i₁ does have a component of magnetizing current. Magnetizing current is still there. It is a non ideal transformer, i₂ plus i₂ prime plus Iₘ. So, this is the primary current.
Opening the switch after DT, what will happen? Flux must be continuous and second is the inductor current $i_L$ should be continuous.

Now, for the continuity of flux, the correct direction for the current in the secondary is to enter the dot. See, I will repeat; when I close the switch, $i_1$ enters the dot. The correct direction in the secondary is to leave the dot. It is possible because there is no $D_2$. I will open the switch after DT. $i_2$ becomes 0. But then magnetizing current has to be continuous. Now, that can be made continuous by suitable current that is in the secondary. What is the correct direction for the current that is flowing in the for in the secondary. If current is entering the dot in the primary, when I open the switch, current must enter the dot in the secondary.

I will repeat; see here, current starts entering the dot and current is leaving. This is perfectly a transformer action now. I will open the switch; magnetizing current has to be continuous. So, it is entering the dot. Now, current starts entering or current should enter this terminal.

(Refer Slide Time: 40:03)

So, the equivalent circuit is here. So, this is the path and this current also should be continuous. So, $DF$ carries the magnetizing current as well as as well as the inductor current $i_L$. Of course, it is a reflected magnetizing current. See, this is the equivalent circuit; close $S$, $I_m$ starts flowing, $i_2$ prime also starts flowing because there is nothing here. Open $S$, $I_m$ starts flowing through this branch, $i_L$ also starts flowing through this branch.

So, in a 3 winding case, since I used $D_2$ in the secondary, it cannot happen there because reverse flow of current is not possible in a diode. So, I have not used $D_2$. Now, $i_2$ or the equivalent magnetizing component of current can flow in the secondary. It should enter the dot and it tries to enter the dot and it flows. But then what happens to the rate of decay of flux?
See the equivalent circuit here; I am connecting a diode across an inductor. If the resistance is 0, what will happen to I_m? Ideal diode is also ideal, this coil is also ideal, no R, I_m will remain constant. Whatever that was there, that was flowing through the primary winding, it get transferred and the magnitude will remain constant. In the sense, it will not decay. Now, if there is a finite resistance, it starts decaying slowly decaying slowly because whatever the stored energy is dissipated as heat in the winding resistance and may be internal resistance of diode DF. So, very slow decay. So, when I close the switch for the second time, may be, after some time, there was finite flux. On rate of decay, flux is very slow. It may so happen that core will saturate, core will saturate.

So, when I use a 3 winding transformer, I am using a negative voltage across LM. See here, see in the previous, see here, a negative voltage is applied across LM. So, decay is faster decay is faster.

(Refer Slide Time: 43:25)

Now here, decay is very slow, very slow may be, some time just the opposite that we what we did in AC to DC conversion. In my very first lecture in AC to DC when I introduced the concept of freewheeling, I said that we have to maintain some current in the load. If there is no freewheeling diode, voltage that is appearing across the load becomes negative beyond pi. I will repeat; because beyond pi the input voltage becomes negative. So, if I apply negative voltage to a load which is RL, rate of decay is going to be faster. So, I want to reduce the rate of decay, so I said I will apply 0 voltage. In other words, I will connect a freewheeling diode. I have told this in the very first lecture of AC to DC conversion. So, if you apply negative voltage, decay process is going to be faster. If I apply 0 voltage, decay is very slow. May be, just the opposite that is required here, I want to reset the flux in the core because again unidirectional, excitation.
Operation is always in the first quadrant. So rate rate of decay is very slow and it may so happen that in the second cycle the core will saturate.

(Refer Slide Time: 45:13)

What is the third case? The third interested case is there is no LF at all. Do not use LF, do not use LF, do not use LF. Just because we had used LF, we wanted we connected a DF here because when I open the switch, this current has to be continuous. So, it will start flowing through DF. So, if there is no LF, you may not even require this DF. But then what will happen?

See in this circuit, there is no LF, there is no DF. Close the switch in the primary, current enters the dot, current leaves the dot. So, this capacitor gets connected across the secondary because this is not there, even L this is also not also there. So, when diode is on, so this gets connected to the secondary. So, we have a case something like this; primary, a voltage source of $V_{DC}$,
secondary, I have another voltage source of some other magnitude $V_0$ and wave forms of $V_{DC}$ may not be the same the waveform of $V_0$.

So, I have a case wherein the transformer, both sides of a transformer, I have connected 2 voltage sources. I do not think you can have this sort of a situation, wherever, even in AC supply I connect a source to the one of the winding, second winding is connected to the load. We do not connect 2 voltage sources of 2 different waveforms to the power transformer.

So, if I do that, it may affect the power transfer or energy transfer. So, I should not allow the capacitor voltage to appear directly across the secondary turns when the switch is on. So, I use an inductor. So, since I am using an inductor now, current has to be continuous. So, I use a freewheeling diode. So, that is how we have reached to this stage. We should not allow the capacitor voltage directly to appear across the secondary when primary is carrying current. So, you connect an inductor here. If you connect an inductor, this current has to be continuous. So, use a diode, DF here.

So, that is it about the forward converter. Generally, it is used for voltage above 200 watts, from 200 to approximately 5 to 600 watts. This could be more also, could be more also. But then as the power rating increases, the trend is to go towards a forward converter. Now, you may be able to reason it. What could be the reason? What happened in fly back when I close the switch and what happens in a forward converter when I close the switch?

In a fly back converter, we are storing the energy in the magnetizing inductance, transferring it to the load. Source current is only the magnetizing current. What happens now in a forward converter? Source current is the sum of magnetizing as well as the equivalent load current equivalent load current. So, may be every obvious, there are only magnetizing energy, store it and dump it. Here, source supplies equivalent current or source supplies power directly to the load here.

So, when I close the switch, there is an equivalent current in the primary. So, as the power rating increases, the size of the transformer that is required in a fly back is going to be high, it increases. So, that is one of the reasons to go towards the forward converter for high power range. More about it, we will see later in the next class.

Thank you.