Power Electronics
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Lecture 5 - Single Phase Uncontrolled Rectifiers

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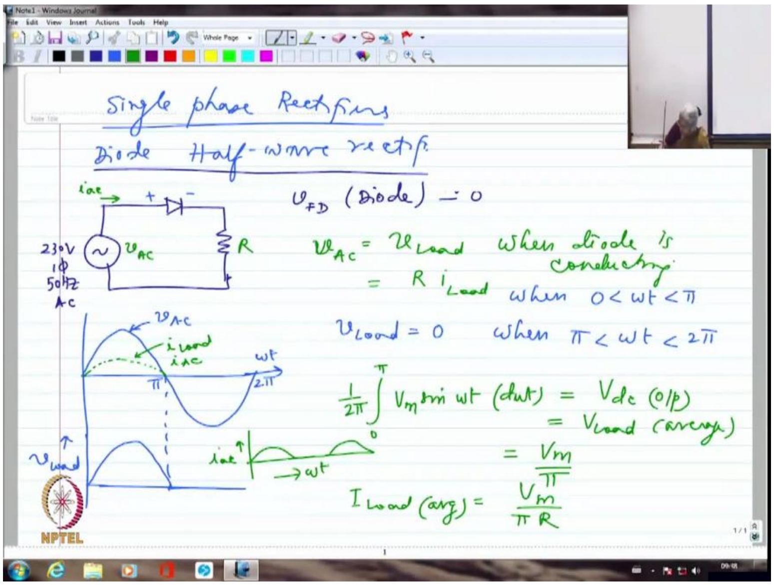

We are really going to start on the power electronics circuits today. So, we will start off from single phase rectifiers. So, I am going to start off with the simplest of circuits, which is a diode half wave rectifier. And first to understand the basic working, I am going to explain it with resistive load, then we will go over to inductive load, then probably RLE load and so on and so forth. So, I am looking at a power supply which is normally 230 volts, single phase 50 hertz AC, this is what normally we use if we are talking about single phase AC.

So I am assuming that we are taking it from the power grid and here I am going to put the diode and here is the load, which is a resistive load. And when we consider the diode, compared to 230 volts, 0.7 volts is very very small, so I am literally going to take it as though it is ideal diode, hardly any voltage drop across the diode. So, diode voltage drop V forward voltage drop for the diode. I am assuming it to be approximately 0, I am not going to take into account 0.7 volts because compared to 230 volts AC, this is negligibly small.

Now, if I draw the waveform, I am going to have basically a sinusoidal voltage that is being applied to this particular diode circuit. So, diode will conduct whenever I am going to have positive here and negative here. When it is forward biased, it is going to conduct and that will happen only during positive half cycle. So, I am going to have essentially conducting exactly at the beginning of the positive half cycle assuming that the forward voltage drop is negligible, forward biasing voltage I am assuming almost as 0 volts.

Of course, you require 0.7 but I am assuming that that is negligible, so I am going to have the diode conduct and I am going to have the diode stop conducting exactly at this point, so this is actually the current I. So, the current is exactly going to follow the wave shape of voltage itself, there is hardly any difference because I am going to have essentially V, if I call this as V_{AC}, so I should say $V_{AC} = V_{load}$ when diode is conducting, which is also incidentally equal to Ri_{load}, if I me call this as R.

So, because of which i_{load} is going to be, whatever is my V_{AC}/R, so the wave shapes are exactly similar. And if I try to look at the load voltage, I am going to have exactly until here the load voltage will appear and after that it has to be 0 (V_{load}=0). This is how the voltage has to be, I have to essentially 0 voltage whenever it is reverse biased. So, this is between when ωt, if I say this is ωt, then 0 to ωt until π and I am going to have V_{load} equal to 0, then ωt is between π and 2π.

So, this is going to be the load voltage, so I should say this is supply voltage and this is load voltage. And this is π and this is 2π. So, I can calculate of course, you guys might have done it already in some other course that is,

$$\frac{1}{2\pi}\int_0^{\pi}(V_m sin\omega t)d\omega t = V_{dc}\ (o/p) = V_{load}\ (average) = \frac{V_m}{\pi}$$

This is going to be the value of voltage that I am getting from the half wave diode rectifier, provided I have a resistance load. And if I try to look at, I_m or I_{load} (avg)= $\frac{V_m}{\pi R}$. Because it is only related by the resistance, nothing more than that. So, obviously although this is an average DC voltage, that is DC component as well as AC component, I am not going to have the voltage completely steady, it is continuously oscillating. In fact it is going from 0 value to peak value and again 0 value and persists at 0 value for another half cycle.

So, it is not a steady DC voltage, so if I apply this to for example a DC motor, it is not going to perform as well as if I connect a battery whose value is $\frac{V_m}{\pi}$. There will be a difference in terms of the operational characteristics of a DC motor which is supplied with a battery of voltage $\frac{V_m}{\pi}$ versus this kind of voltage waveform. Because for quite some time there is not going to be any current, if there is no current, clearly it is not going to develop any torque.

If it will not develop any torque it has to essentially come down in terms of its speed. At least for a short while it will come down, depending upon the inertia, how quickly it comes down or how slowly it comes down. So, this is the way the waveform is going to be. Now, if I look at the current here on the AC side, if I may call this as AC current, AC current is same as whatever is going through the load, they are connected in series. So, obviously this is not only the load current, this will also be the supply current. It cannot be any different.

So I am going to have the supply current now, not completely AC, it is DC, I hope you understand what we mean by DC is it is unidirectional. So, I will essentially have a current waveform repeating itself like this, for some time it is 0, again it will repeat itself. This is the way I am going to have i_{ac} waveform with respect to ωt.Which means by chance if I have a transformer in the input side, normally the transformer accumulates flux during the positive half cycle and then it will give back the flux during the negative half cycle.

Now it will essentially go on accumulating flux, if it does not have sufficient time to give away the flux, there is no current, because of which during the other half cycle so it can result in saturation of the transformer. Whenever I pass DC through a transformer, I can expect that the core is not able to get the flux and defluxing will not happen properly, effectively and that is the reason why half wave rectifiers are not recommended in those circuits where I am going to use a transformer.

Because if I use a transformer, the transformers can normally get saturated because it will carry only unidirectional current, not bidirectional current. So much so far half wave rectifier circuit with resistance load. Let us try to look at the circuit with RL load. So, I am having a diode, I am having R, I am having L.

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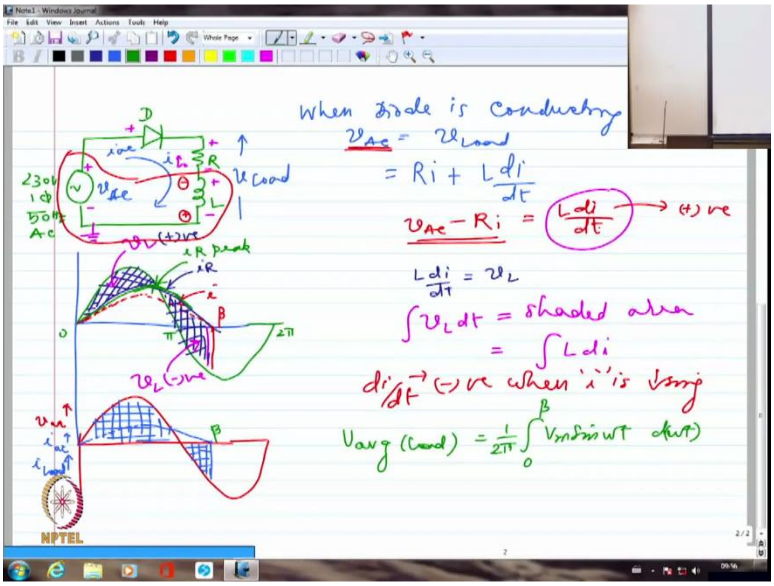

And I am going to have a sinusoidal voltage here. Now, again I am going to have 230 volts single phase 50 hertz AC. And I am assuming again ideal diode, no doubt. So, when the diode is conducting and I am assuming that the diode is not having any forward voltage drop or negligible voltage drop, so I should say when diode is conducting, I am going to have V_{AC} =Vl_{oad}, if I say this is what is V_{load}, I should say $V_{AC} = V_{load}$.

$$V_{load} = Ri + L\frac{di}{dt}$$

If I am saying that i is the current that is passing through this particular circuit, so I am going to show as though this is the current i that is flowing, load current i that is flowing. Now, if I say that initially, let me draw the waveforms as well, so that it will be clearer. So, this is my AC voltage that I am taking up. So, now this is of course 0π, 2π, I am probably going to have the current rising from some value, say from 0 value it is rising slowly and it will go on and on, how long will it rise? Is the question.

Because when it reaches maximum, that is where the rising ceases, after that it will start falling. So, I should write $V_{AC} - Ri = L\frac{di}{dt}$ and $\frac{di}{dt}$ =0 when V_{AC} = Ri. From this equation I can say that is the maxima, wherever the maximum occurs, at that point I am going to have V_{AC}=Ri. So, let us say probably at some point it reaches maximum let us and then from here it is going to fall. It will fall further, please note I have not made this particular value exactly coincide with the zero crossing of the sinusoidal voltage waveform.

The peak will also not coincide with the peak of the voltage waveform. Please note that the peak of this voltage cannot coincide exactly with the peak of the sinusoidal voltage waveform, that would happen if and only if I am going to have inductance equal to 0. Previously whatever we drew was for pure resistive load. In pure resistive load, the voltage peak and the current peak were exactly coinciding with each other, whereas in this particular case I am actually looking at V_{AC} - i R.

In the previous case that was equal to 0 because there was no inductance but in this case it is not equal to 0, it is equal to L $\frac{di}{dt}$. So, whenever I supply a voltage, now it is going towards two work, one work is dissipation of energy in resistance, the second one is storing magnetic field energy in the inductance. So, it is doing 2 works and in that magnetic field energy can be retrieved. It is not like resistance loss which is gone, so I am going to have to retrieve that energy.

So, when I am retrieving that energy, let me draw the voltage waveform as well, so let us say this is current, so i R should have exactly a similar wave shape, it is only a scalar multiplication. So, I can draw iR somewhat like this, maybe my iR is somewhat like this. And when I draw I R further, I should probably draw it somewhat like this. i times R is basically a scalar multiplication of the current with resistance. So, iR will exactly have the same wave shape as that of the original current I have drawn. So, let me mark this as iR.

Now, V_{AC} - iR = L $\frac{di}{dt}$.

Student: If iR is the resistance drop, then how much is the inductance drop?

Professor: We are going to come to that, that is the reason why I am giving so much of explanation. When I am having V - iR, this is the difference between V_{AC} – iR. This is iR, so this is V_{AC} - IR, that is going towards L $\frac{di}{dt}$. So that area indicates the amount of energy stored in the inductance. So, I am essentially looking at this portion as, because I write L $\frac{di}{dt}$ = V_L and this is V_L, this particular portion what I have written is V_L, that is what is V_L, because V_{AC} - iR, that is what is V_L.

So, V_L, $\int V_L dt$=shaded area =$\int L di$.

so, indirectly I am showing the energy stored in the inductance by this shaded area. Now, this is L $\frac{di}{dt}$, no matter what whether I am going to have the resistance drop dominating over the AC voltage or vice versa. Please note here that the AC voltage is dominating over the resistance drop. Whereas, here please note, I am going to have this as the resistance drop, whereas this is the AC voltage. So, AC voltage is subdued as compared to the resistance drop.

So, if I look at the difference between these two, I am going to have it as though this is actually the shaded area which is coming as the difference between iR and $V_{AC.}$ So, if I call this as the positive area, I would have this to be the negative area. So, whatever the inductance have accumulated during the portion of AC voltage being greater than iR, all that energy is returned when iR is dominating over the supply voltage.

So, the crux of the matter is whenever there is a larger amount of energy that was available, the resistance was dissipating part of it, rest of it was being stored by the inductance. And when there was a shortfall in the voltage that was being supplied, the inductance could join hands with the voltage, AC voltage supply and it was trying to supply whatever was required by the resistance. To look at it in terms of more mathematically, I would say when the current is flowing like this, this is plus and this is minus, similarly this is plus and this is minus. That is the reason why the diode is getting forward biased, because I am having plus here and minus here, so obviously this is plus. And if I may call this as a common ground. Now, when I am having this current increasing, when this current is increasing which is shown here with this red colour, it is increasing, when the current is increasing, this is plus and this is minus. $\frac{di}{dt}$ is positive.

After sometimes the current has increased quite a bit, V_{AC} - Ri becomes 0. Because it has become 0, the current has reached its peak. Beyond that the supply voltage is not in a position to supply anymore energy to the inductance because all the energy that it is giving is going towards dissipation in the resistance itself, we are not going to have any further energy left over. At that point, now inductance will say that I have stored all the energy, now let me return the energy because it cannot get any energy, not that it is being very generous, it cannot really get any more energy.

So, it is going to start giving back. When it gives back, it is essentially getting defluxed. When it is getting defluxed, $\emptyset$ is going to decrease, if $\emptyset$ is decreasing, i has to decrease, both of them are dependent on each other. So, current is going to decrease, when the current decreases $\frac{di}{dt}$

becomes negative, so if $\frac{di}{dt}$ becomes negative, this will become plus and this will become minus.

Obviously, I am going to have plus and minus completely reversed. So, the inductance now is not like a load, it is rather acting like an energy source. It has saved some energy, now it is giving that back. When it is giving back the energy, please note this is minus plus, this is plus minus like this, both these things become additive. If the inductance is having plus minus in such a disposition, that I am going to have it added to whatever is V_{AC}, both of them are added together.

Now, I have to look at the overall voltage that is visualised by the diode, whether that is going to be positive on its anode and negative on its cathode or not. Now, the inductance is pitching in, the overall voltage is going to look positive because of the fact that the inductance is also returning energy. So, until the inductance is returning energy, the diode will be able to retain the current in the same direction because of the inductance voltage, it will be forward biased, that is the reason.

So, that is one reason why the current continues beyond the zero crossing of the supply voltage. The higher the inductance, this point will get delayed further and further. The lower the inductance, I will have obviously less and less amount of current flowing during the negative half cycle or the duration will get shrunk. Because if you understand this concept, any RL load further we will be discussing will become a cakewalk. This is the first concept you have to be really clear, especially in RL load.

Why, despite a diode sitting there, why I am having actually the current in the negative half cycle, it is continuing in the negative half cycle? And how long this is going to continue, that depends upon how dominating the inductance is. So, this has to be solved for only by complete solution of the differential equation along with the particular integral derived corresponding to $V_m sin\omega t$, it is not going to be easy. Because it will start off with the transient and then it will go through. This is starting from 0, so in this case there is no transient. When we come to full wave rectifier, we will see a transient anyway.

So, in this particular case, we are going to see that if the initial condition is 0, i (0)= 0. You will be able to solve this by solving the differential equation $Ri + L\frac{di}{dt} = V_m sin\omega t$. Where ωt will be from 0 degrees until whatever point this is conducting, this is β. If I may call this as β, this point is where the conduction ceases. So, how long this conduct, heavily depends upon what is the value of inductance relative to the resistance, both of them, relative to the resistance.

So, RL load becomes slightly complicated because of this reason and of course if I try to look at the voltage, my voltage is still the same as far as supply voltage is concerned and if I try to look at the current, whatever we have drawn just now, so I am going to have the current may be reaching a peak somewhere and then finishing it somewhere here. So, this is going to be i_{AC} as well as I_{load}, both of them are the same. So, this is that i_{AC}, both of them are obviously the same.

Load voltage is clearly, how much is the load voltage? Load voltage should be completely all this voltage because we are writing not only V_L, it is V_R + VL and then it will come here also, until here. So, this entire portion will be load voltage. I will get definitely some portion of the negative voltage as well and it is not going to be easy really to calculate this particular voltage because this β is not setting stone, the β is going to change, the$\beta$is not going to be exactly a constant. Depending upon R and L value, it will change.

If inductance changes, correspondinglyβ will change. So, I should be able to write this as the V average load, $V_{avg(load)} = \frac{1}{2\pi}\int_0^{\beta} V_m sin\omega t d(\omega t)$. So, shall we proceed to RLE load.

Student: Where will the current reach its peak?

Professor: Exactly, wherever I am going to have V_{AC} = iR. The way I have drawn I should show it as though this has reached the peak here and this is iR, so this is iR peak. iR peak must have happen whenever the current was reaching the peak. You understand because iR has to meet with the supply voltage, wherever it meets with the supply voltage.

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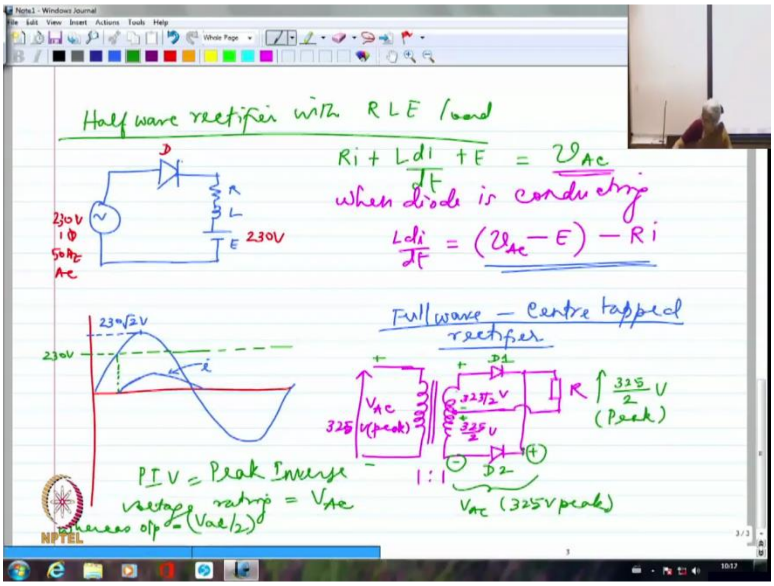

Let us now try to go to a half wave rectifier with RLE load. So, we are basically talking about a diode rectifier, a sinusoidal voltage, I am going to have R, L and E. This is typically the case whenever I want to charge a battery. The battery will always be connected like this so that the charge is getting into the, the current is getting into the positive terminal, positive terminal of the battery, only then it will get charged. So, this is again 230 volts single phase, 50 hertz AC and this is the diode.

Let us say I take maybe a battery of 230 volts itself, DC. Now, obviously when I am actually having the voltage waveform like this, this is $230\sqrt{2}$, the peak is $230\sqrt{2}$, so that is approximately 325 volts or something. So, this is going to be 230 $\sqrt{2}$. So, if I take 230 volts, it will be somewhere here divided by 1.5. So, it is going to be somewhere here. So, whenever there is no current, I am going to have the battery voltage directly showing up at the cathode of the diode.

If there is no current, it is open circuit, so obviously the cathode of the diode will have the same 230 volts. So, only when the anode reaches 230 volts, it can have any conduction, otherwise it cannot have any conduction. The diode can start conducting only when the positive voltage here reaches 230 volts. So, it cannot conduct until this portion. Diode will not be able to conduct until the anode also reaches at least 230 volts ideally. So, the current can start flowing only from here.

The current cannot really flow before this because the diode cannot be forward biased before this particular voltage, AC voltage reaches 230 volts magnitude. So, the current will start flowing at this point. If I write the equation here, I have to write when it is conducting, $Ri + L\frac{di}{dt} + E = V_{AC}$. When the diode is conducting, this is how it is going to be. So, the current will start flowing from this point.

Now look at the work of this V_{AC}, it has to now take care of 3 things, one is the resistance drop, the second one is inductance stored energy, the third one is snubbing E because E is not going to allow conduction very easily, it is opposing the current. So, it has to take care of all these 3 things, only then you are going to have any rise in the current. The rise in the current is only because inductance is storing the energy. So, I should say in this particular case,

$$L\frac{di}{dt} = (V_{AC} - E) - Ri.$$

So, only when the voltage crosses 230 volts in the positive half cycle, it is going to start conducting and then the current starts increasing. But at what point the current will reach peak depends upon when this whole thing is 0. So, I am going to have probably a current reaching the peak here and then it might probably end up here or here depending upon how much is really the inductance stored energy. The inductance is really dominating over the resistance, then I may have the current continuing for longer.

So, now if I try to look at this as my value of current, so I can again draw iR, I can say what is V_{AC} - 230 volts - iR, that is what is the voltage that is available for inductance to store energy. And after that I have to see how much the voltage is it will return. So, I want you guys to complete this exercise. Please draw the waveforms of V_L, that is the shaded portion and you try to get what is iR and then you try to get what is V_{AC} - E -iR.

That will give you what is the inductance stored energy portion and what is retrieved, please look at both of them. So you are going to see that whenever you have an inductance in your circuit, you are going to have the current going beyond whatever it would have normally gone. So, so much so far half wave rectifier. So now that we have seen half wave rectifier with diode, R load, RL load and RLE load, let us now try to take a look at a full wave, first of all a centre tapped rectifier.

I think I drew it last time when I was probably explaining power supplies but we will take a look at this once again. We call this as centre tapped rectifier because we will always use the transformer with a centre tapped. What we mean by centre tap is if I am going to have a transformer secondary like this, I am going to take from the midpoint a connection. So I am taking a tap from the midpoint, from the centre, so we call this as centre tap, so centre tapped rectifier.

And I am going to have basically a transformer which is supplying this voltage V_{AC}. And of course because it is power, normal it will be iron core transformer, so I am showing the 2 lines to indicate that it is an iron core transformer. Now, I will have one diode here and one more diode here. I can short these 2 and then I am going to connect the load here between the centre tap point and this. Some of the books might have shown a load in between, between this point and this point which is same exactly. .

So, this is typically a centre tapped rectifier and let me start off with a resistance load itself. Let us say here the peak value of voltage is something like 325 volts peak, 230 volts AC I have taken, so this will be 325 volts peak. Now, if I have 1:1 turns ratio for example for the transformer, I should have here 325 / 2 and again I should have here 325 / 2 volts as the peak. I should have half of the voltage as the peak value in either of the sides.

Whenever there is a positive half cycle, I am going to have plus here and minus here, because of which I will have again plus here minus here and if I am taking half the tapping, I should have had the minus point here for the upper half and again plus point here for the lower half, that is how it will be because it is series connected, series addition. Like when we talk about the auto transformer, we used to say series addition and series subtraction, this is series addition, so we are going to have plus minus like this.

If plus is here, obviously this diode will be forward biased but at the same time this diode will be reverse biased. So, I am going to have only this carrying the current. Only the positive portion, for the positive half cycle, only the upper portion will carry the current through diode D_1, if I may call this as D_1, D_1 will conduct during the positive half cycle, only the upper portion of this particular transformer secondary will be active. Similarly, during negative half cycle only D_2 is going to conduct, which means I will have only the lower portion of the transformer being active, secondary side being active.

So, what I get across the load will be only 325 / 2 volts peak, definitely not whole of 325. I will not be able to get exactly whatever is the voltage I am applying here, only half of that voltage will come at the output. I cannot get full voltage unless I have 1:2 turns ratio or something. And one more thing is when this diode is conducting, this is going to be a short circuit, this is a short circuit, hardly any voltage drop. So I am going to have essentially whatever is the voltage here, that voltage will come at the cathode of the other non-conducting diode.

So, I will get the same positive voltage connected at this point and after all this negative voltage is here. So, I am going to have the entire 325 volts with negative here and positive here coming up across the diode which is not conducting, that is coming in inverse form, that is minus here and plus here. So, the diode will not be able to conduct, but the amount of inverse voltage or reverse voltage that is coming across the diode will be not V / 2 but full V. The output is only V / 2 but the voltage that comes across the diode is going to be the complete V because both these windings, because this is positive, this will also be positive and this is negative.

So, this voltage will be the complete V_{AC} or 325 volts peak. So, the peak inverse voltage rating, we call this as the peak amount of reverse voltage that the diode has to block, how much the diode has to block? Although the output what you get is V_{AC} / 2, the amount of voltage that it needs to block during reverse biasing condition is full V_{AC} and whatever is the peak at that point in time. So, you are going to have the peak inverse voltage rating of this diode is going to be V_{AC}. Whereas output is going to be only V_{AC} / 2.

I have to completely derive the expression for average value of voltage, which we have not done. So, we are using a diode of higher value of rating but we are deriving only a lower value of output voltage. What is the big advantage of doing this? Only that is one advantage, that advantage is whenever this is conducting, I have only one device conducting and after that the load comes directly.

So, if one device voltage drop is 0.7 volts, I will have whatever is my output voltage minus 0.7 volts as the output. If there had been 2 diodes conducting, like a bridge which we will see eventually, we are invariably going to see that 1.4 volts are dropped, 0.7 + 0.7. When you are talking about 5 volts power supply or 3.3 volts power supply, this 1.4 volts matter so much because out of 3.3, 1.4 is going away, then I get very minimal output voltage. Or correspondingly, I have to design the transformer secondary for a higher voltage.

So, whenever I am worried much more about the voltage drop, not about really choosing a higher voltage rating for the diode, so typically power supply applications. In many power supply applications, instead of getting a 15 volts diode, if I have to get a 30 volts diode, the cost will not increase much, it is fine, perfectly fine. But I will be able to save on the voltage drop. Whereas, if I am talking about a 6 kV application, obviously I will not use a rectifier like this because instead of 6 kilovolts if I have to choose a 12 kilovolt diode, the cost will increase enormously and it may not be available.

So, centre tapped rectifiers are generally used only in the case of power supplies, not in any other application. If you talk about DC motors and so on and so forth, we will never use the centre tapped rectifier. Centre tapped rectifiers are generally the speciality only for power supply applications. One particular case I forgot to discuss with the freewheeling diode, half wave rectifier with the freewheeling diode.

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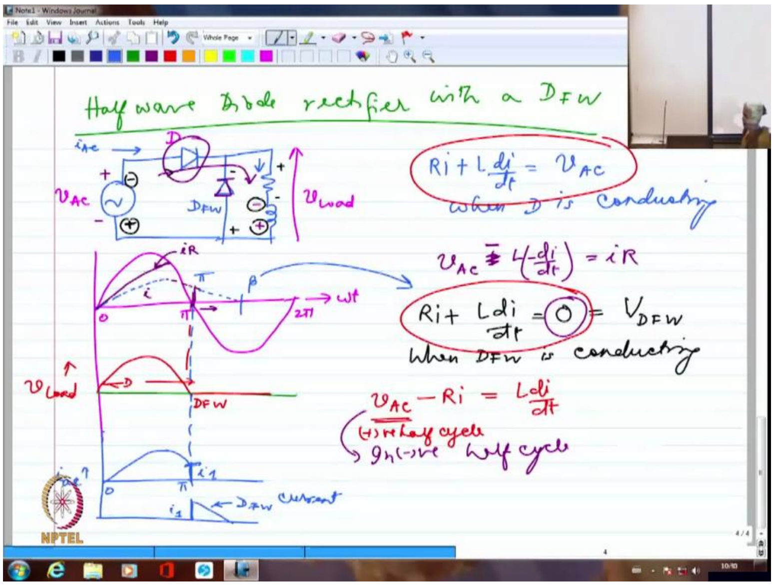

Let me take that up also because this will come up repeatedly when we are talking about other rectifiers, that is the reason I would like to go for this. So, this is my normal half wave rectifier, I am showing with RL load. We had drawn the waveform already. Let us say I am going to connect a diode like this, which is across the load which I would call as freewheeling diode which will be able to take the trapped energy across the inductance. It will essentially pass the current because of the trapped energy in the inductance, so we call this as freewheeling diode.

It is essentially simply going to circulate the current, it does not have any other job other than to do this. So, let us say this is my diode which is a normal diode, which is meant for rectifying the AC voltage into DC voltage. So, here is my V_{load} and this is my V_{AC}. So this is my supply voltage and initially the diode starts conducting at this point. And if we write the equation, we wrote it earlier also, $Ri + L\frac{di}{dt} = V_{AC}$, when D is conducting.Now, we will have obviously the current peak reaching somewhere here, I am drawing the current like this, so it has reached somewhere here. So, if I try to draw the voltage, hopefully at this point it should have touched whatever is the AC voltage.

So this is actually iR, whereas this is i. So that is where it reaches the peak. And after that the current is going to come down, we said that current will come down. When it is coming down, I will have to look at what happens to this diode, does it come into picture at all or not? That is what I will have to check. When this was positive and this was negative and when the current was decreasing, this became minus and this became plus.

And both of them put together was able to circulate the current in the same direction through the resistance load. So, if I actually look at it, I was having , $V_{AC} + L\left(-\frac{di}{dt}\right) = iR$. This is what was happening. You get my point? This is what was happening earlier. So I should say that maybe V_{AC} minus, let me put minus into minus becomes plus rather. That is why I am saying that L $\frac{di}{dt}$ is joining hands with V_{AC}, both of them together is circulating the current through the R i, that is what it is,$V_{AC} - L\left(-\frac{di}{dt}\right) = iR$

Now, when it comes into negative half cycle, when the current is actually when the voltage is coming into negative half cycle, at that point I am going to have actually, this is going to be plus and this is going to be minus in the reverse half cycle. But as far as this is concerned, I am still going to have this as plus and this as minus and this R i was originally supplied by joining hands with both of them. Then I was having the power supply voltage also aiding the current circulation in the same direction as that of this.

And then resistance was wanting to have a voltage drop in this particular direction because the current is still flowing in the same direction, the inductance was aiding it basically. Now the power supply voltage is trying to oppose the flow of current in this direction because of the reverse half cycle, this being plus and this being minus if the power supply had its way, it would have had the current in the opposite direction. So obviously it is going to put up a stiff resistance to the flow of current in the same direction, it will not allow it to flow as much as possible.

So, if somehow this power supply can be bypassed, obviously the circuit will try to find another way. So, under that condition if the inductance stored energy is still dominating, because this is plus and this is minus for the inductance, this particular diode now gets forward biased and takes over. The moment this diode takes over, if I neglect the drop across the freewheeling diode, I should write the equation as $Ri + L\frac{di}{dt} = 0 = V_{DFW}$,which is actually the voltage drop across the freewheeling diode.

So, this is when DFW is conducting. When the freewheeling diode is conducting, I will get literally 0 voltage across the load, I will not be able to get any voltage across the load except 0 voltage, because the freewheeling diode is essentially short-circuiting the RL load. So if I try to look at actually the voltage waveform corresponding to this, I am going to have until this portion a positive voltage and after that it will be 0 voltage until the freewheeling diode conducts, I will not have any voltage coming into picture at all.

So this portion is going to be due to freewheeling diode, whereas this portion is going to be due to D and RL load. Now because it is 0 voltage, that is coming up across the load, I am drawing the load voltage, this is V_{load}, $V_{load} = V_R + V_L$. I have to add both of them, not just R alone or L alone, it is a summation of both. Now I have the freewheeling diode voltage coming up as 0, compare with the previous case where I did not have freewheeling diode.

When I did not have freewheeling diode, always the equation was this. But now the freewheeling diode, the equation is this. So, when I was looking at the case without freewheeling diode, I had $V_{AC} - Ri = L\frac{di}{dt}$. When V_{AC} was in positive half cycle, fortunately for me it was actually aiding the inductance stored energy. V_{AC} and inductance stored energy together actually made up for whatever is the resistance loss once the current started declining.

But when this is reaching negative half cycle, in negative half cycle I am going to have V_{AC} also of the opposite sign. So, V_{AC} will also become a drain on the inductance stored energy because that is also very actively opposing the flow of current. So, despite V_{AC}, despite resistance drop, the current has to be sustained by the inductance. That was the case when I actually had no freewheeling diode. Especially when the voltage becomes or comes into negative half cycle, I am going to have a stiff opposition from the supply voltage, I am going to have a stiff opposition from the resistance in the form of voltage drop or dissipation.

So, both of them are going to put up a stiff opposition. And still the inductance has to sustain the current. Whereas when I have a freewheeling diode, this opposition is gone. I do not have the supply voltage opposing at all, supply voltage is completely isolated. This diode is sitting here D, which is not conducting anymore, it will not conduct anymore, only thing that conducts will be the freewheeling diode. So, between the supply and the load, there is hardly any connection.

No current is flowing between the supply and the load at all when the freewheeling diode is conducting. So, the opposition offered by other supply voltage is absent. In the absence of that opposition, this current can continue for a little longer. So, freewheeling diode case is, normally the current can continue for longer because the opposition is somewhat decreased as compared to what we had in the previous case without freewheeling diode. So, this will be the kind of current continuation that will take place.

And for getting whatever is the value of beta, we have to use this equation $Ri + L\frac{di}{dt} = 0$, not equal to V_{AC} beyond π. So, correspondingly if I try to look at what is i_{AC}, it becomes somewhat different, it will not be the same as what I had as the load current. So, if I try to look at what is i_{AC}, I am going to have only until then, until this portion, until π, I will have the diode carrying the current. The main diode D will carry the current until then, until π.

After that only the freewheeling diode carries the current. So, I will have the current to be somewhat like this and then it comes down and then that is it, abruptly it comes to 0. This will be i_{AC}, after that whatever is the current is coming up, this is D_{FW} current. So, AC current happens to be different from the load current whenever I have a freewheeling diode. It is definitely going to intervene in the conduction, take away all the current, depriving the supply of any current, it is discontinuous. You can see that abruptly the current comes down to 0 and here abruptly the current rises.

Student: Device current (SCR and D_{FW}) are changing abruptly, will the load current also change abruptly? Load current is continuous.

Professor: Whatever is going through the load that is continuous. Initially, that current was being supplied by the D, from the supply. Later on, it is continuing because of the inductance but it is freewheeling through the diode. So, it does not matter for the load, it does not care. Wherever the current has to go, it will go but the load current is continuous, there is no discontinuity. I should not say continuous because it comes only until here, again it will start, in that sense it is discontinuous.

Student: Basically, at that point the summation of the 2 currents will be same here, right?

Professor: So, whatever this leftover, that current should come here. So, if I say that this is some I1, this has to be the same I1, no doubt. Why is it? It is happening at value π because until then this fellow was not opposing, this fellow was also aiding the current. As long as this fellow was aiding, there is nothing to really look for a smaller resistance part, this fellow was not opposing, so it was not really offering resistance. Now this particular fellow is also opposing. So, it might as well look for a path where least opposition will exist, that is what is happening, So, so much so far diode rectifier, we have still not seen the full bridge rectifier, we will look at the full bridge, then we will go to thyristor.

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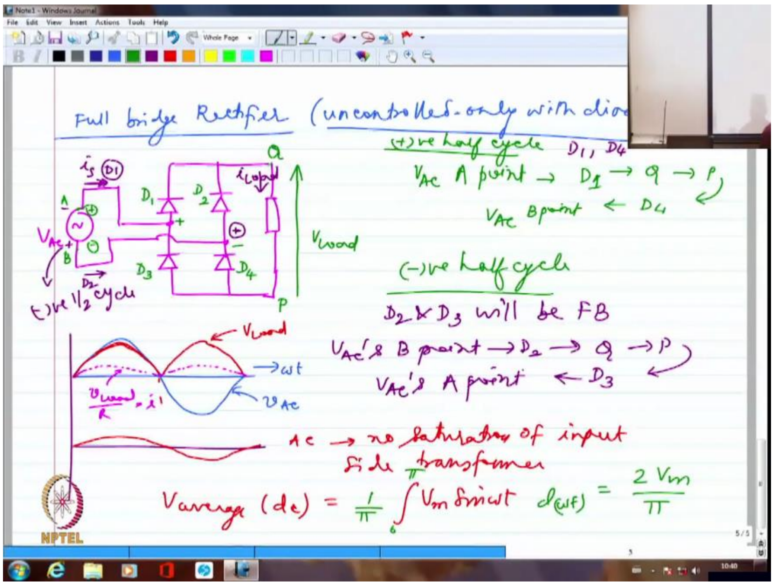

So, we are going to call this as uncontrolled bridge rectifier which is only with diodes, so we call this as uncontrolled. So, I normally draw it like this, I am sure you would have learnt it sometimes differently with diamond kind of structure and so on but it does not matter because this is easier for us, especially when we are going to go to three-phase rectifier. So, I would like to draw it somewhat like this with the load here and power supply at this point.

So, AC voltage is at this point and I am going to have a load voltage like this. So, let me call them as D_1, D_2 and I am going to call this as D_3, D_4. So, I am sure you guys know the basic way of conduction. So, let me call these terminals also A and B, so it is going to start from V_{AC}'s A during positive half cycle. I am going to have this as plus and this as minus. So, I am going to have from V_{AC}'s A point, from that it is going to go towards D_1, then it is going to go through the load, let me call this as maybe P and Q. So, Q, then to P, then to D_4 and then back to V_{AC} 's B point.

This is during positive half cycle, during negative half cycle you need D_3 and D_4, this is during positive half cycle when I am having plus here. So, the diode D_1 is connected to the plus terminal of this, so this is also plus and similarly this is minus.

We have talked about this only for one half cycle, so you need them for the negative half cycle. So, during the negative half cycle. I am going to have plus here and minus here, this is during negative half cycle. So obviously this is plus, I am going to have this portion as plus. So, if this is plus, I am going to have D_2 forward biased, so D_2 and D_3 will be forward biased. Here of course D_1 and D_4 will be forward.

So, you can definitely write the path again, it will go through D_2, Q, P and then it will return through D_3 and then go back to the negative, which is A is now negative and B is positive in the AC supply. So, you are going to have the other way around. So, we will have, let me write again the path, V_{AC}'s B point D_2, Q, P and from there it will go to D_3 and then V_{AC}'s A point, this is the way it is going to conduct.

So, if I am looking at the waveform, will have to look at many things, one is the I load and I am going to look at I source or I AC, whatever, I source and I load and of course the output voltages, we will see that also. So, this is my AC voltage and when I am assuming that the 2 diodes are having hardly any drop, please note 2 diodes are conducting in this case, which is definitely going to give me more drop than the previous centre tapped case.

Centre tapped case will not have this much of drop, whereas here I will have 2 times 0.7 volts definitely. So, I am going to have probably during positive half cycle I will have the voltage as it is being reproduced and during negative half cycle again the same voltage being reproduced but in the opposite direction. So, red colour whatever I have drawn will be the voltage of the load and blue colour is V_{AC}.

If it is your resistance load, the voltage waveform and the current waveform should be exactly matching with each other, because of which I will have the current waveform somewhat like this, I am showing as though there is a very large resistance, so small current. Anyway, so it is a sinusoidal current waveform that I am going to get which is whatever is the V_{load} / R. So, I am going to have this as V_{load} / R = I, provided it is a pure resistance load.

Purely resistance load I will have something like this. Let me look at what is I source. Whenever D_1 is conducting, the current is in this direction, whereas whenever D_2 is conducting, the current is in the opposite direction. So, I am going to have the current flowing this way whenever D_2

is conducting, whereas this direction will be whenever D_1 is conducting. Please note that the source current reverses its direction depending upon whether it is positive half cycle or negative half cycle.

So, if I try to draw what is the kind of source current I am having, I will have the source current to be sinusoidal which is something like this. So, I will have an AC current coming into picture in the source, which is good for me if I am using a transformer. It will not get saturated because flexing and defluxing keeps on happening because of the currents that I am having in the positive half cycle as well as negative half cycle. So, I am going to have basically AC current flowing in the case of full bridge rectifier, whenever I am considering a diode bridge rectifier that will be AC current flowing, so this is AC, so no saturation of input side transformer.

I am sure you can derive the expression for voltage, you have to essentially say

$V_{average(dc)} = \frac{1}{\pi}\int_0^{\pi} V_m sin\omega t \, d(\omega t) = \frac{2V_m}{\pi}$. What happens when I replace this resistance by an RL load?

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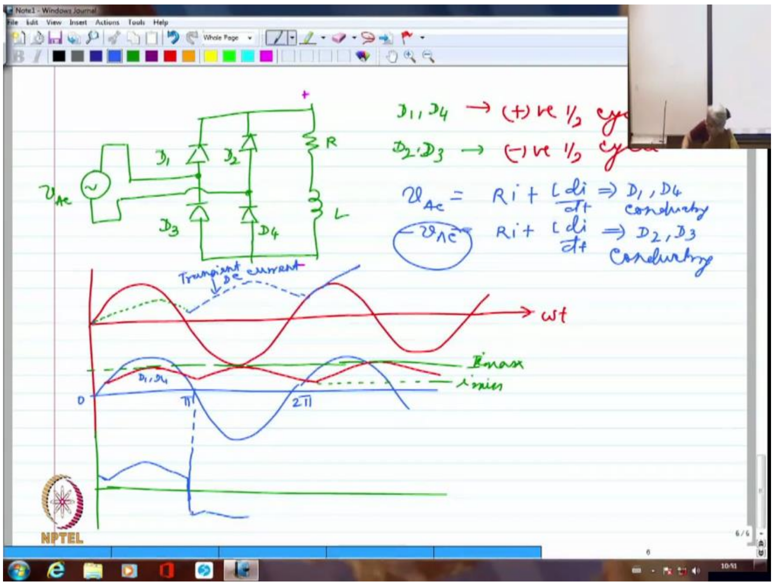

So, let us say I am going to have again a full bridge rectifier uncontrolled and I am going to have RL load. Obviously, I am going to have D_1, D_4 conducting during positive half cycle and I am going to have D_2 and D_3 conducting during negative half cycle. Let us say I am just starting out, I have just turned on the power supply and then I am going to have multiple cycles like this for the input side voltage. Circuit is dead, so the current will start from 0, no doubt, the initial condition will be 0.

So, maybe the current would start flowing, it will reach some peak somewhere and then it will start declining. But when the negative half cycle starts, I am going to have again D_2 and D_3 taking over. When the negative half cycle starts, I will have D_2 and D_3 taking over. Because D_2 and D_3 are taking over, previously in the half wave rectifier we saw that in the negative half cycle V_{AC} will start opposing the flow of current.

Whereas, here that will not exist, that opposition will not exist, because the moment the negative half cycle starts D_2 and D_3 are going to jump into conduction. Once they jump into conduction, again I am going to get the positive and negative voltage like this, whether I like it or not, still I will have positive and negative coming up like this. And because positive and negative come up like this, in all probability I may have the current again increasing.

It depends definitely upon, because I have to write the equation somewhat like this, $V_{AC} = Ri + L\frac{di}{dt}$, this is what we wrote. But this is true when I am talking about D_1 and D_4 conducting. If D_2 and D_3 are conducting, I have to write $-V_{AC}$, because I am having opposite sides connected now. If I say, $V_m sin\omega t$, that was connected directly, $V_m Sin\omega t$ was directly connected to the load when D_1 and D_4 were conducting.

Whereas $V_m sin\omega t$ when it became beyond π, the reverse of that is connected to the load. So, I should write that as $-V_m sin\omega t$ being connected to the load. That is what I am trying to write this as minus $-V_{AC} = Ri + L\frac{di}{dt}$ that will be when D_2 and D_3 are conducting. So, at this point maybe the current would come down for some more duration depending upon this value, whether it is good enough to dominate over iR.

But if iR happens to be still higher than, V_{AC}, $L\frac{di}{dt}$ has to pitch in. I am having iR value, let us say at 20 volts, V_{AC} is just starting out from 0 volts and it is going towards 10, 20 and so on. If it happens to be only 10 volts, it will not be able to fill up really the requirement of the resistance. So, it has to borrow from the inductance. So, whenever it is borrowing from the inductance, the current will still come down. The moment my supply voltage again reaches 20 volts or 25 volts, now the supply voltage is strong enough to take care of the resistance drop.

So, it can give whatever is available with it, with itself, it can give it to inductance. The moment it starts giving it to inductance, the current will start rising. So, I would see that the current probably falls a little bit more and after that it will start rising. Again, it will reach a peak and then it will fall and maybe again it will start rising and so on and so forth. Please note the way I have drawn.

Initially it started from 0, in the next half cycle it is not starting from 0, it is starting from slightly higher value. And in the next half cycle it starts from further higher value, eventually it will reach a steady state where the beginning of every half cycle it will be at a particular value, that is when we call it as steady state. There is no steady state otherwise like DC, you are not going to have a steady value here.

Rather than that, whatever is the initial point I am getting at the beginning of the half cycle, is it becoming a constant eventually? The maximum value and the minimum values, are they becoming constants eventually? Once they become constant, we call it as a steady state has been achieved. Do not please confuse with the DC, you cannot see a steady DC here. You would always see an oscillatory DC current.

So, this is the way the current is going to increase. If I have very high inductance, the oscillation that happens between maximum and minimum will become smaller and smaller, that is why we call inductance as a current ripple filter. Inductance will always even out, any increase or decrease that happens in the current, that is why inductance work as a current filter, just like how capacitance acts like a voltage filter because it gets charged and retains it.

So, you will always have inductance, higher inductance always producing a current where the ripple or the difference between the maximum and minimum is kind of brought down. So, it evens out any oscillation in the current. So, if I say finally in the steady-state, I may see something like this, if this is my supply voltage, so this is the transient current, this is a transient DC current.

So, if I say that this is my voltage waveform, I am going to see that maybe the current is starting from certain value, it rises and it falls, again rises and then it falls, again rises and it falls and so on. So, all the maximums will be at the same value. If I have not drawn it that way, it is wrong, but all the maximums have to be at the same value. This is i_{max}, similarly this will be i_{min}. All the minimum currents and maximum currents have to be at the same value. So, if I try to draw the supply current now, please note that 0 to π, D_1 and D_4 will conduct.

Student: Will the current start from zero at the beginning of every cycle?

Professor: Here it is starting from 0. Once it reaches steady state, please note this is at 0, the next one is not at 0, the next one is even higher. It is still going through transient, so it started from 0 and slowly it is going towards higher and higher value until it reaches steady-state, where the minimum and maximum becomes within a certain range. They do not really change anymore. The minimum value becomes like a constant, maximum value becomes like a constant, same thing is true here.

So, whenever D_1 and D_4 are conducting, I will have probably positive half cycle current. And whenever I am going to have, I told you that it can still decrease, so the small decrease I am showing here, the current could decrease because inductance might have to pitch in. So, this is the way it is going to be.