Power Electronics

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Lecture 06: Single-Phase Controlled Rectifiers

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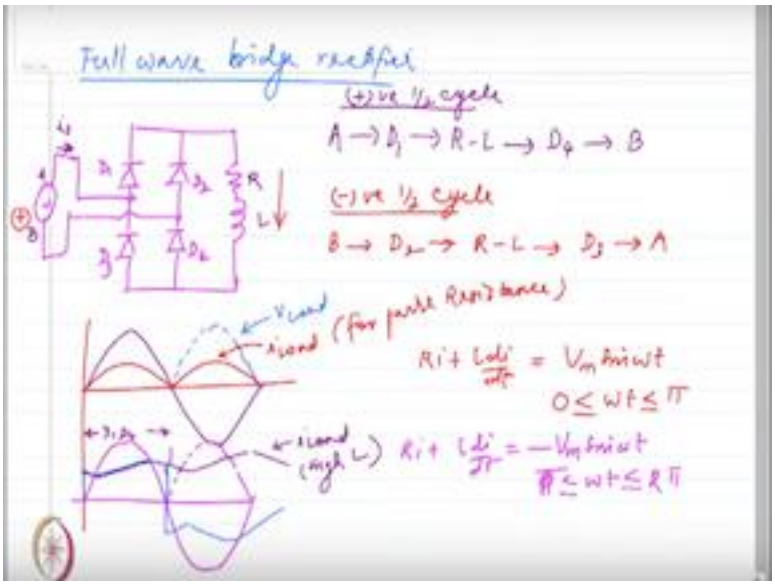

So we had started on that in the last class, full wave bridge rectifier. So we mentioned that this circuit will consists of four diodes and whatever load it is, RL load, R load, and this is going to be connected to the AC source. So we said that we would number this as D_1, D_4, D_2, D_3 and here is the AC source, so I am calling this as A and this as B. During positive half cycle A will be positive and during negative half cycle B will be positive. And we said that the path will be from A to D_1 to RL and then it will go to D_4 and back to B, so this is during positive half cycle and during negative half cycle we start from B because this will be positive now. So, B it will go to D_2, from D_2 it will go to R and L, so again the current will flow only from up to down and then it will go through D_3 and then back to A.

This is the path, so we drew the wave form also if you may recall in the last class, so this is going to be the sinusoidal wave form and I told you that it will start up from 0 current and slowly build up, that what we said. So once it builds up and the minimum values are almost remaining the same and similarly maximum values are remaining almost the same, we are going to call that as the steady state.

So if it is a purely resistive load, I am going to have the rectified wave form somewhat like this, the voltage wave form will be somewhat like this, this is the rectified voltage wave form and current will exactly follow whatever is the voltage wave shape. So I am going to have essentially the current wave shape somewhat like this, this is how the current wave shape is going to be, so this is i load for pure resistance. If it is a purely resistive load, it will touch obviously because the voltage is touching 0, the current also has to touch 0, whereas if it is inductance obviously the current will not touch 0 because it would have already accumulated enough energy, the inductance would have accumulated energy.

So it will give back some of its energy and because of which the current will definitely be retained above 0 value because we are going to have always,

$$Ri + L\frac{di}{dt} = V_m sin\omega t \, , 0 \leq \omega t \leq \pi.$$

Whereas if I am going to have, $Ri + L\frac{di}{dt} = -V_m sin\omega t, \pi \leq \omega t \leq 2\pi$ because it is the reverse of the voltage that is being uploaded when I have D_2 and D_3 conducting.

This is how it is going to be. So always the inductance will find at least some amount of energy to be stored as long as I am going to have $V_m sin\omega t$ or magnitude of $V_m sin\omega t$ being greater than Ri. If it is greater than Ri, always inductance will try to store energy.

If it is less that Ri, it is going to be the shortfall is going to be met by the inductance stored energy, that is how it is going to function. So you will never see that the current really touches down to 0 value. That is what is going to happen in this case.

If higher and higher inductance values are seen, you would see that if this is the voltage that is the supply voltage the rectified voltage is somewhat like this. I am going to have actually the oscillation in the current is really really minimized, so I may have something like this, then it may increase again decrease again increase, decrease and so on.

You can see that the current will essentially see very minimal oscillations if I have larger and larger value of inductance. Higher the inductance value the ripple in the current will decrease because the inductance acts like a filter, whenever there is a shortfall in the energy it is going to supply back, so the amount of energy supplied back is going to make the current fall or current rise really minimal. That is what is going to happen.

So this kind of wave form that is the load current wave form is going to be true for high L, larger value of inductance. This is how the current is going to be. Now because I will have D_1 and D_2 conducting, D_1 and D_4 conducting during this portion I will have a current flowing in this direction. Whenever D_1 and D_4 are conducting we had already said from A it will flow to D_1, so the current direction is this way.

So during positive half cycle I am going to have the current exactly flowing from here to the load, so if I say this is what is the supply current direction normally I take, then I am essentially going to have the current, whatever I mark here in blue until this portion. This is going to be the current during positive half cycle whereas during negative half cycle I have to have exactly the opposite of the current, like this.

So I would see that if I look at the current on the AC side, on the AC side if I try to look at the current I am going to get exactly the current whatever I have got in the load, exactly being reproduced as it is until the positive half cycle. In the negative half cycle, whatever is the load current I am having just the opposite of that, negative of that coming up as the supply side current.

So I will have positive current and negative current equally visualized on the supply side. So there is no question of any saturation of transformer. If I put a transformer on this side it will have equal amount of fluxing and defluxing. So there is no question of transformer just accumulating the flux and then getting saturated, it will never happen.

So you will not see any saturation in the case of a full bridge rectifier. This is one of the major advantages of full bridge rectifier. In most of the applications we may be using transformers because we might have to bring down the voltage to the required level. That may be done with the help of a transformer.

So, generally whenever you use a transformer, you look for such a configuration where you will not have saturation. So full bridge rectifier is a good apparatus for being used along with a transformer.

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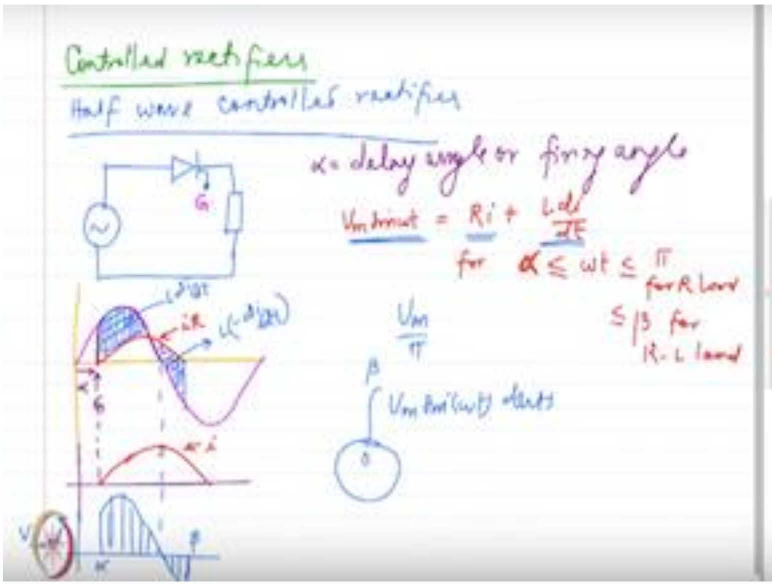

Let us now go to controlled rectifiers. In controlled rectifiers I should be able to determine at what point I want the device to conduct, which means I have to use a controllable device. If I am using a controllable device I should be able to give a gate pulse, a firing pulse only at that instant when I want that to control.

I will be able to get a variable DC voltage, whenever I have a diode rectifier I do not have really the liberty to control the output DC voltage whereas whenever I have a controllable device like thyristor, I will have the capability to control the output voltage. So let me start off with half wave, half wave controlled rectifier.

I am looking at a similar circuit, only thing is I am going to replace this diode by a thyristor, that is all is the difference. This is a half wave configuration but I am going to replace this particular diode what we had put earlier with a thyristor and I am going to show the load like this, it can be resistive, it can be RL, either way is fine. So this is going to be the controlled rectifier configuration.

If I actually have my sinusoidal voltage somewhat like this. I can choose to make this device conduct by giving a gate pulse at any point in time but clearly for a SCR to conduct I have to two conditions being satisfied. One is it has to be forward biased, the second one is I have to give sufficient gate pulse and of course after giving that the current has to exceed the latching current value, only then it will continue to conduct. So I may choose to probably fire it somewhere here maybe which is like 35-40 degrees, so I am going to give the gate pulse only at this point, I will not give the gate pulse before that.

So if I give a gate pulse at this point, let us say this is the angle normally specified in all the textbook as α. α is the angle of conduction or at which I am going to give the pulse to the thyristor. So this particular angle is delay angle or firing angle. We call this as delay angle or firing angle. The delay angle is the angle at which I am giving the gate pulse which is delayed from 0 degrees, so the conduction is delayed by so many degrees, whatever is the delay angle I am actually doing the design for. So this α is known as delay angle or firing angle.

This is completely under my control, I can always have a firing circuit or the controlled electronic circuit which I can design to give it at any angle, α such as 30 degree, 40 degree, 90 degree, before 180 degrees of course. If I try to do it beyond 180 degrees clearly this device will be reversed biased.

I am essentially planning to make this device conduct not from 0 degrees but beyond 0 degrees, so I will give the firing pulse only at a later time than 0 degree. So, if I give it a 0 degree, it would have started conducting here, there will not be any difference between a diode and an SCR. But if I delay the conduction obviously it is not going to start conducting at this point because I have not opened up the gate, so it will start conducting only from this point.

So at this point it is going to start conducting and I am going to get this as the output voltage. Had it been resistive load I would have gotten the voltage only until here because the current would also stop exactly at that point. Whereas if it is R and L load I will have the current starting from this point, I should again show at this point the current will start but the current cannot jump to a large value right away because it is RL circuit.

So the inductance current cannot jump from 0 value to a large value right away, so the current would slowly start rising, it will rise and until what point it will rise depends upon again what we wrote as the equation if you may recall, $V_m sin\omega t = Ri + L\frac{di}{dt}$,this will be the governing equation. And this is true for then I am going to start from α originally we wrote 0 for diode but now I am going to start from α until π depending upon whether it is R load.

If it is RL load I may have beyond π also. So this is going to be until the conduction takes place maybe π for R load, maybe until β for RL load. So the current will start like this and then it will probably die down at some point depending upon where exactly the current starts falling, how much is the stored energy in the inductance and so on and so forth.

So if I try to draw the voltage corresponding to this, I may have some voltage wave form somewhat like this. The same current I am drawing with multiplied by R, if I try to only look at the voltage across resistance, so this is going to be i R, this is i for example. So whatever is the leftover voltage here, the difference between these two that happens to be V_L, this happens to be $L\frac{di}{dt}$ or V_L, whatever is the voltage across inductance because I am essentially writing that $Ri + L\frac{di}{dt} = V_m sin\omega t$, and this is $V_m sin\omega t$, and this is iR, so obviously this has to be $L\frac{di}{dt}$.

Student: What will happen to the source voltage in the negative half cycle?

Professor: It will be reversed. See, if I am writing $V_m sin\omega t$ it is still $V_m \ sin\omega t$, only thing is $\omega t >$π. So, automatically it becomes negative, I do not have to reverse it forcefully. So, I am going to have now after this iR is somewhere here, so if I try to look at iR and $V_m \ sin \ \omega t$ difference here, this happens to be the V_L value which is in the negative direction now.

Because we are having essentially $V_m \ sin\omega t < iR$, so $iR - V_m sin\omega t = -V_L$ now because of which I am going to get this as the negative inductance voltage or I can say instead $\frac{di}{dt}$ is becoming negative.

So the current is falling during this portion, so $L\frac{di}{dt}$ happens to be negative because the inductance is not trying to give back its energy, until I was increasing or $\frac{di}{dt}$ was positive inductance was storing the energy. Then once it has reached the peak and $V_m \ sin\omega t = \ iR$, there is no more energy that can be given to inductance.

So now inductance is pitching in and it is trying to give back some energy, so it joins hands with the voltage source to make sure that the resistance needs are met, that is what happens. So this area if I say $L \times -\frac{di}{dt}$ and these two areas have to be equal to each other because inductance cannot really hold back any energy with its own self.

Student: Will the current touch down zero?

Professor: I may go to 0 at this point. At this point I will go to 0 because it is starting from 0, I shown it as though it is starting from 0 because it is a half wave rectifier. In the full way rectifier case it can be different, in the diode we saw that current never touches 0. Only in the pure resistive load it touches 0, so in this particular case, it is touching down to 0 value because I am not applying anymore voltage, here my thyristor gets reversed biased.

So if I try to look at the output voltage corresponding to this, I will have the output voltage somewhat like this, I had to have the output voltage somewhat like this until the current really becomes 0. So this entire thing is going to be my output load voltage. This is going to be my load voltage. So it starts fromα but it goes until β. So atαI am going to have again the current to be 0, at β also I will have the current to be 0.

So I have to essentially solve the complete differential equation, look at the regular the particular integral and then I should be able to say at what point, that is initial condition will be i of α equal to 0 and the final condition β can be solved for by putting in the same solution for i, i of β equal to 0 and solve for β

Student: By delaying the firing, output voltage decreases, then why would you delay the firing?

Professor: I want to control the voltage, if I do not give a delay, I will not be able to control the voltage.

Previously in diode rectifier case, I was starting the conduction right from here, so I got only a value of $\frac{V_m}{\pi}$ for a resistive load, this was a constant and in the case of inductive load I had to start form $\int_0^\beta V_m \sin(\omega t)\, d\omega t$.

So this point is not controllable. Whereas here I may be able to control that, so I would be able to control how much voltage output I am getting. So this is essentially for controlling the output voltage. You are not controlling the voltage, you are either giving a gate pulse or do not give a gate pulse, that is it.

If you give a gate pulse you are going to see that the device starts conducting, if you do not give a gate pulse it will not conduct it, that is it. So let us now try to take a look at, now that we have seen at least half way rectifier, let us now go to the full bridge controlled rectifier.

Student: How is the SCR forward biased even after the source voltage becomes negative i.e. at $\omega t > 180°$?

Professor: If you are going to have the inductance forward biased this thyristor or SCR even after the positive half cycle is over, you are still having this device connecting the source to the load. So, whatever is the source voltage, it will appear across the load, but we are looking at the overall voltage across this, we are not segregating iR and $L\frac{di}{dt}$. We are putting it together. So these two are exactly in parallel, so whatever is the voltage here will appear here.

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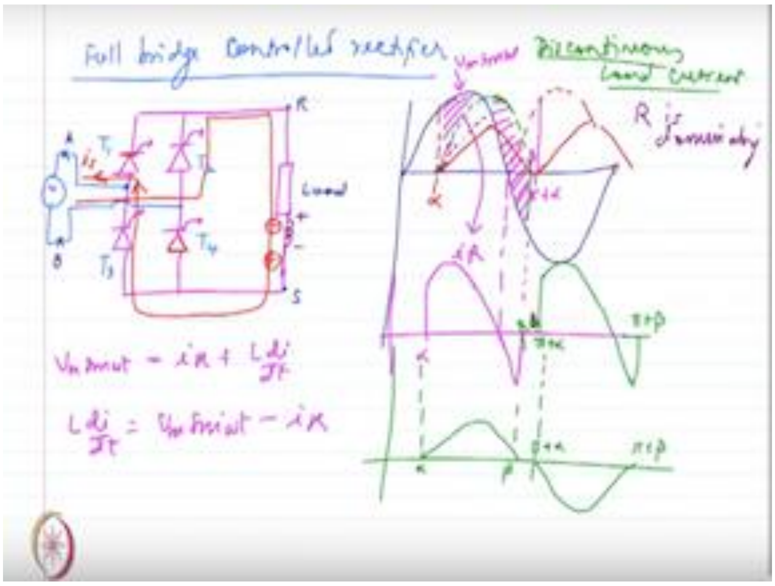

Let us try to take a look at fully controlled bridge rectifier, so I am going to have again four devices but all of them are going to be thyristors, so this is going to be connected to a load, and I am going to have the AC supply connected here. So let me again name these things, this is T_1, this is T_4, this is T_2, this is T_3, and let me name this point as A and this point as B and I am going to have this as the load, maybe I can say R and S, these are the points.

So let me first of all start with drawing the voltage wave form, this is my voltage wave form,. I do not want T_1 and T_4 to conduct at this point because I want to have a control, so which means I have to delay the triggering of this particular device by some angle α. So I am going to trigger T_1 as well as T_4 simultaneously. Both of them will be triggered simultaneously, I will give a gate pulse for both of them simultaneously.

So I might have had the current carried over from the previous half cycle, that is very much possible or I may be starting from 0 depending upon how exactly the circuit is working, whether resistance is dominating, whether inductance is dominating, depending upon that I may start off with 0 current or I may start off with some finite value of current, very clearly if I am starting from rest, the current would start from 0, it cannot start from some finite value. If I am starting from rest the current will definitely start off from 0 value.

So let us say the current has started off with 0 value, maybe it is going like this, and then it is reaching some maximum value somewhere and then it is going to probably come down, because I am essentially having T_1 and T_4 conducting still. They are going to conduct still until I give a pulse for T_2 and T_3. So T_2 and T_3 pulses I may give only at this point because if I want to be symmetrical, I have to give it at $\pi+\alpha$, very clearly, I cannot have them to be completely unsymmetrical.

If I try to make them unsymmetrical, I will have the positive half cycle voltage may be much higher than the negative half cycle voltage or vice versa. The moment I have positive half cycle higher than negative half cycle or something I will not have even kind of voltage being applied repeatedly, similar kind of voltage being applied repeatedly. So I would normally fire if one of them is fired, if 30 for example, 30 degrees the other one will be fired at 180 +30, 210 degrees.

So I will always have them fired symmetrically, so if it is fired symmetrically let us say in this particular case I have shown as though the current has reached 0. Then again the current have to start and it might probably reach the same value and then again come down. This is how it is going to be if it is highly resistive very small inductive circuit, the inductance is really really small, not good enough to sustain the current for much longer.

If the inductance is really strong enough, it would have shown sufficient energy to pull along the conduction for even from $180°$ to $180° + \alpha$. Even during that time it would have pulled along, so if the inductance is not sufficient enough, I am definitely going to have only a smaller amount of stored energy because of which it will not be able to pull along for too long. Just to show this I can show it somewhat like this, maybe I am going to have iR drop to be very very high, like this I should show. iR drop is very high so I am going to have may be the inductance voltage only this much, only this much is the inductance voltage.

Actually I have not drawn it very well, so I should have on the other side the negative of the inductance voltage should be this much. i R minus whatever is the supply voltage, $V_m\ sin\omega\ t = i\ R + \ L\frac{di}{dt}$. So I should say $L\frac{di}{dt} = \ V_m\ sin\omega t - i\ R$. So this is, $V_m sin\omega t$ and this I have shown as iR, so whatever is the difference that is inductance voltage, so inductance voltage is the shaded portion. This shaded portion should have been equal to the other shaded portion, one is $-V_L$, the other one is + V_L, I have not shown it exactly the same but that is how it should be.

Whatever V_L is accumulating, inductance is accumulating as energy the entire thing has to be given back right away, so that is what is making the current continue into the negative half cycle side as well. So if I try to look at the voltage during this kind of a conduction I am going to have essentially the voltage actually coming out somewhat like this, it would start at α and it is going completely like this and it would go until if I may call this angle as β it will go until β.

This is how the voltage wave form is going to be for 1 half cycle, it starts from α and goes through π and goes into the negative direction until β. Now again for the next half cycle it will start from π+α, so if I may call this as π+α, the next one is π+α, again it will go through this and it will go until here which is π+β.

So I am going to have this kind of voltage wave form repeated. This is across the load.

Student: Why are you firing at π+α?
Professor: Because I am firing this at α. Why are we firing that at α? Because I want to get the control over the voltage. Let me try to now get what is the average voltage but you want it to be symmetrical, now if I draw the current wave form it will be symmetrical. If I try to draw the supply current wave form, I will have this to be the current on the supply side and this to be

the negative half cycle of the current on the supply side, they are exactly symmetrical. So it is starting at α, ending at β, it is starting here at π+α and ending here at π+β, supply side current.

Student: Based on inductor will α have a limit?

Professor: Based on inductor will α have a limit, no, it does not have to, we look at that, continuous conduction case we will see, this is discontinuous. The current is discontinuous on the DC side. The load side current is discontinuous. What we mean by discontinuous is it is touching 0, so we call this as discontinuous load current.

So this will happen when R is dominating, when R is dominating over L this is going to happen, So, when I have R dominating over L, the inductance stored energy becomes really really minimal because the inductance stored energy becomes minimal I would not have the inductance sustaining the current because the inductance has to supply the energy. If it does not supply the energy, the current will not be sustained.

Please understand the moment this point is crossed, π is crossed I will not have T_1 and T_2 anymore forward biased by the supply. The supply cannot forward bias it. So only way to forward bias the device is if I have an inductance here then instead of having plus here and minus here when it was absorbing energy, now when it is releasing energy it will become plus here and minus here. L $\frac{di}{dt}, \frac{di}{dt}$ has reversed its direction, current has started falling, because current is falling I will have essentially plus here and minus here and look at this plus this plus is connected to the anode here, so because of which T_4 will get forward biased.

Similarly, this minus is connected to T_1's cathode. So obviously T_1 and T_4 can get forward biased if inductance voltage is sufficient enough to forward bias these two devices. That is the reason why we are having the conduction possible through T_1 and T_4 and remember only when T_1 and T_4 conduct my i_s is flowing in this direction. When T_2 and T_3 conduct the i_s will flow in the opposite direction

The supply current will reverse its direction if I am switching over the conduction from T_1 and T_4 to T_2 and T_3, because T_2 and T_3 will always have the current flowing like this, you are looking at this is the way current is going to flow, T_2 and T_3 if the current is flowing, this is how it will flow, which is in the opposite direction. It cannot flow in this direction like what I showed over here.

Shall we go over to continuous conduction? So that let us see whether we have understood the discontinuous conduction properly. This is discontinuous conduction; the current is starting from 0. If by chance I did not have such a high iR drop, maybe resistance is small, in which case I am probably going to have my iR drop, I am just drawing it arbitrarily, it may be somewhere here only, only this much. This is what is iR drop, in which case it gets much more energy to be saved in the inductance, if iR drop is smaller I will have $L\frac{di}{dt}$ component to be much larger, so it will save much more energy in the inductance.

You think about it this way, if I had 10 ohm resistance with a 400 volt supply, I would have gotten only 40 amperes of current, so $\frac{1}{2}Li^2$ if I try to calculate i^2 will be only 40^2. If I use only 1Ω resistance then I would have 400 amperes of current. So, $\frac{1}{2}Li^2$ will be become $\frac{1}{2}L(400)^2$, so obviously I am going to get much more energy stored in the inductance. So lesser the resistance I will have more energy stored in the inductance, clearly. So if I am going to have much more energy stored in the inductance, why would the current end here? The current can definitely sustain itself for longer.

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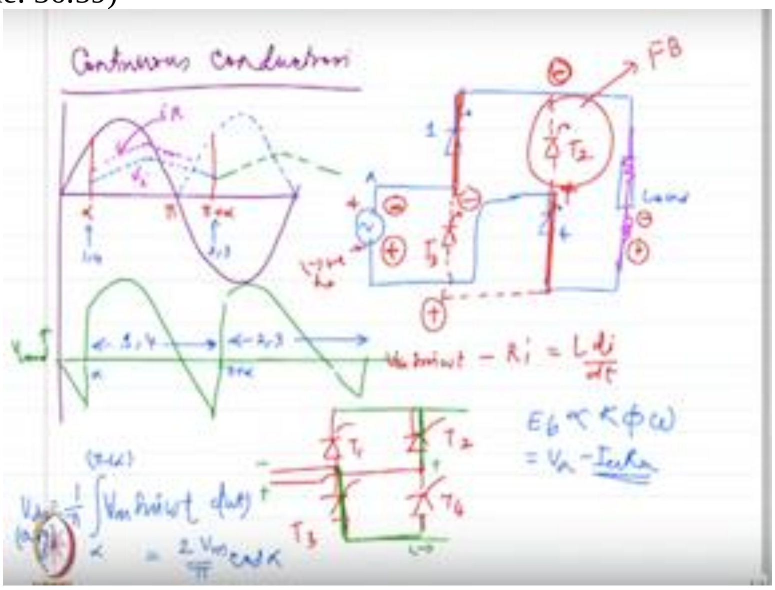

So let us try to look at that kind of a wave form which is corresponding to continuous conduction. So I am going to have the voltage wave form like this. And I am saying continuous conduction which means the current cannot start from 0, it has to start from something other than 0, a higher value, of course it would have gone through initial transience, it will start from 0, inductance would have accumulated more and more energy and so on and so forth and ultimately it would reached the steady state where i minimum and i maximum are at some fixed values, that is the way it is going to be.

So let me draw the other half cycle also inverted or rectified. Let me choose again a firing angle, some α and let me say this is (π+α). Now the current is starting from some non 0 value, it is starting from some non 0 value. So it is going to increase maybe until some point I do not know and then it will start decreasing. It is not linear, obviously it will be exponential and RL circuit, at this point again I am firing the next two devices.

So at this point I am firing 1 and 4, whereas at this point I am firing 2 and 3. So when I fire 2 and 3, let me probably again draw the circuit so that it is, this is 1, this is 4, here is where I am having A, and this is the AC source with positive half cycle like this and then it is going to go through the load, it is coming through 4 and then it is going to return like this. This is what it is, this is corresponding to 1 and 4.

At this juncture I am going to have, here anyway 2 is sitting but it is not conducting. Similarly, I am going to have 3 sitting here and that is also not conducting. Both of them are sitting here. Now until here it is very clear. Until π it is very clear, I will have definitely 1 and 4 conducting. After that let me write the equation again $V_m sin\ \omega t - R\ i = L\frac{di}{dt}$.

So, wherever I am going to have Ri probably is equal to this, so at that point I am going to have the current start declining. So, wherever iR is equal to the supply voltage, the current will start declining after that point, so the current starts declining at that point.

Now when the current starts declining I am going to have, if I show this as separate inductance and separate resistance, I am going to have very clearly plus here and minus here. So the inductance stored energy is going to aid whatever is the supply voltage as long as it is still in positive half cycle, because in positive half cycle I am going to have plus here and minus here, so this plus comes in addition to the source, both of them comes additive, they become additive as long as positive half cycle is persisting. So, during positive half cycle this plus is actually added to this plus and minus of the voltage, so together they are able to forward bias the overall devices although iR drop happens to be quite high. Both of them together essentially make up for the forward biasing of the devices.

Now as it comes beyond π still I have to retain the conduction in the same direction. The property of inductance is to retain the current direction as much as possible by virtue of its stored energy. So this will now strive hard further to forward bias these two devices still despite the fact that the voltage supply has gone into the negative half cycle. So the voltage supply have gone into negative half cycle, alright but the inductance stored energy still is going to dominate over iR drop and this supply voltage, both of them to sustain the conduction you know despite the negative half cycle, being you know there. So I will have the current containing but it is still declining. The current is still declining, so the inductance is still having some amount of stored energy definitely but at this point I am trying to fire 2 and 3 because I have come to $(\pi+\alpha)$, automatically 2 and 3 will be fired. When 2 and 3 are fired, which one is more conducive for conduction, that is what we have to check, whether 1 and 4 are more conducive for conduction or 2 and 3 are not, I have to check, nature will check basically.

So what happens is something like this: 1 is conducting which is like a short circuit, 4 is conducting which is also a short circuit. So because of these becoming like short circuits and now I have come into negative cycle, which makes this as positive and this as negative, so this is the negative half cycle.

Now because this is a short circuit, this positive is applied automatically here and because this is a short circuit this negative is applied automatically here. This is positive, this is automatically applied here and that is negative, through device number 1 it is automatically applied to the cathode of device number 2 so that device is forward biased. So what happens is because of the existing conduction this negative is applied here, this positive automatically comes here. So this device is forward biased.

Similarly, if I try to look at this particular device, this negative comes here and this positive comes through the short circuit of this here, so this device if I may call as T_2, this as T_3, both T_2 and T= are forward biased because of the conduction of the previous thyristors. Now I have two thyristors forward biased and I apply a gate impulse, immediately they will take over, why not, the moment they take over, they kill the other two thyristors.

You apply the same logic, the moment these two take over, those two will become short circuits. Once we take over they are short circuits, if they are short circuit I am going to have this plus applied through this to this terminal. So I am going to have and let me draw this again. So, I am going to have, these are the four devices, this is T_1, this is T_4, this is T_2, this is T_3, this is negative half cycle, so I am going to have plus here and minus here. This is negative half cycle.

Now I am going to have, I am not unduly bothered about the load, T_2 has taken over, I have given it pulse, T_3 has taken over, I have given it a pulse. Now this is plus, so automatically I am going to have plus here, this is minus, this minus is going to be connected through this to the minus here. T_4 gets reversed biased.

So the two devices which help the T_2 and T= to getting to conduction that became sinusoidal for those two devices. So T_1 and T_4 help T_2 and T_3 to getting to conduction but after getting into conduction T_2 and T_3 quench them. Turn it off, that is what happens.

So, this particular current transfer from T_1 to T_4 to T_2 to T_3 that has taken place because of the supply voltage reversal automatically. The supply voltage reversed, from the positive half cycle to negative half cycle, so if I had fired it anywhere, here also T_2 and T_3 would have taken over without any difficulty. But I chose to delay it by α, $(\pi+\alpha)$, that is the reason why T_2 and T_3 are taking over much delayed but the moment T_2 and T_3 take over, T_1 and T_4 go off because they are reverse biased by virtue of the supply voltage. The supply voltage is the one, which is coming across those two devices to turn them off.

So this line voltage, which helps the commutation or turning off of the thyristor is known as the line commutation or natural commutation. The other one what we discussed earlier with LC circuit and diode and so on, that we forced, we told the circuit that according to this design you are going to have a reverse voltage at this point in time. Here we do not have a control, it is at 50 hertz so 10 millisecond it will be in positive half cycle, 10 millisecond it will be in negative half cycle.

So I do not have any control over when it reverses or something, so the moment the voltage reverses it is ready for being turned off but I chose the moment when I turn on the other two devices because of which they went off but I did not do anything further. I did not deliberately apply a negative voltage, turning it on automatically the negative voltage comes across the device, so I do not have to do anything special. So it is natural commutation or line commutation, yes.

Student: T_1 and T_4 will be reversed and that will be based on whether the voltage across the inductance or the supply voltage inductance.

Professor: If I am having inductor voltage and supply voltage like this, they are opposing each other, agreed, but I did not even draw any load, please note, even without any load I am able to simply apply only the supply voltage across T_1 and T_4, forget about the load. There is no responsibility of the load here at all; I have not even shown the load here, you see because these two terminals are directly connected across T_1 and T_4.

This is for negative that is connected to the anode directly and this is positive, that is directly connected to the cathode. The load does not come into picture at all here. So when there is continuous conduction, I assume the devices to be short circuited, whichever device is conducting that is short circuited. So the load does not really come into picture at all here when I am talking about the commutation in continuous conduction. The load is completely this side, I have not even drawn it and it does not matter.

Student: But it will because whatever voltage is across the inductance, that is the positive side of the inductance.

Professor: But that does not matter because the supply voltage is coming across the device, the load does not come into the circuit at all now. When I am talking about the forward biasing or reverse biasing the load is completely an isolated separate circuit. I may form the loop probably through T_1 and T_4 or I may form the loop through T_2 and T_3 but this is a separate loop in itself. That is a completely separate loop. So this is an independent loop, completely. So whenever I have continuous current I do not have to worry about what the load voltage is, absolutely, I do not have to worry about it at all.

All I need to worry is only whether I am able to fire a particular device. To fire a particular device it should be in the corresponding half cycle. If I have to fire 1 and 4 here, it has to be in the positive half cycle. If I have to fire 2 and 3, the firing has to be done only in negative half cycle, otherwise I cannot really do that. So now if I look at the voltage for this, the load voltage, I am talking about load voltage, so this current will repeat itself, this current will repeat itself. If I try to look at the load voltage, I should have from α, until (π+α), again (π+α) to (2π+α) and so on and so forth.

This is how the load voltage wave form will be, obviously I am having 1 and 4 conducting through and through, until here. 2 and 3 conducting through and through until here. So I should be able to write the expression for average voltage.

Output DC voltage average, $V_{dc(avg)} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m sin\omega t d(\omega t) = \frac{2V_m}{\pi}\cos\alpha$,if I vary α, I am going to get different values of voltage. When α=0 I will get maximum, so that full voltage comes across the load and when I am going to have higher and higher values of α, lower and lower values of DC voltage will appear.

Applications: If I want lower value of armature voltage to get a lower speed in a DC motor drive, I can increase α, I want to have a controlled rectifier feeding a DC motor drive. The DC motor drive's speed is dependent upon how much armature voltage I am applying. I hope you remember at least some amount of machine, $E_b \propto k\emptyset\omega, E_b = V_a - I_aR_a. I_aR_a$ drop is very very small, so I can say V_a is approximately equal to E_b and $E_b \propto \emptyset\omega$

So if I keep the flux as a constant as I increase voltage ω will increase, as I decrease voltage ω will decrease. So I can always obtain whatever speed I want, you know according to voltage that I apply. So vary α smoothly, you will be able to get variable speed. This is one of the typical applications of the converter that is being applied for speed control. It can be battery charging, I can control the current that is going into the battery.

If I want very quick charging I have to really impress upon the battery a huge amount of current, lot of research is going on in battery charging because of electric vehicles. So there normally it takes 6 hours to 8 hours to charge a battery of the vehicle. Two wheelers that is the major problem, the maximum distance you can go is 40 kilometers. So you go 40 kilometers and after that you have to wait for a charging station and charging station these days will take at least currently it will take 6 to 8 hours to charge a battery.

So you cannot really think of going anywhere until completely the battery is charged. So power electronics research is going towards increasing the rating of these rectifiers, which charge the battery. So you want to push 300 amperes, 400 amperes of current in one go. Can we do that, whether the battery will be able to withstand it, whether our rectifier will be able to deliver that much, so a lot of research is going on towards that particular area. So this is one of the applications of rectifiers.

So we will look at RLE load, which we have not seen as yet, which is like a DC motor drive because back emf will be there and after that we will go over to semi-controlled and uncontrolled and so on. Semi-controlled and with freewheeling diode and so on.