Power Electronics
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Lecture 07 - Single-Phase Controlled Rectifiers-II

We looked at half controlled and fully controlled with R and R L load, I will recapture that a little bit so that we will have continuity.

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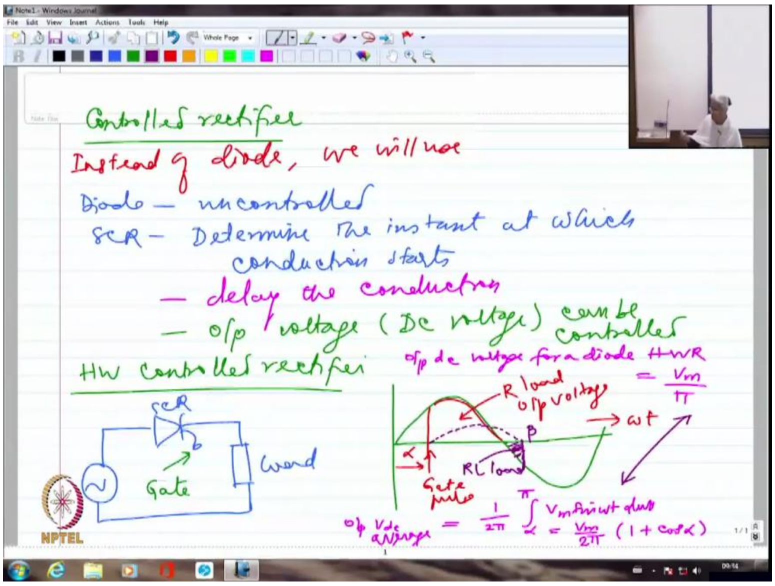

We started with controlled rectifier, and what we said was instead of diode we will use SCR. A diode will conduct whenever it is a forward-biased, there is no control over its conduction duration. So, diodes are uncontrolled devices whereas for SCR, you would be able to decide or determine the instant at which conduction starts. So, we would be able to delay the conduction because of which the voltage will get varied. We essentially intend to delay the conduction so that output voltage can be controlled. So, in whichever application we require different values of voltages as per the requirement, then controlled rectifiers could be used.

Initially, we showed a half-wave controlled rectifier. Just quickly recapturing, so we are going to have a thyristor here, this is the power supply and this is the load. So, we are supposed to give the gate pulse, here is the gate pulse that we need to give. So if we are looking at a pure resistance load, if this is what is my sinusoid, then it was a diode, we were talking about the entire positive half conducting from here to here. Whereas, if I am going to have a thyristor, I am going to turn on this SCR, so this is the gate pulse that I am giving at an angle α, this is ωt. So, at an angle α I am essentially looking at this device being fired.

So, I am going to have this as the voltage provided; it is a resistive load. So I would say this is R load output. If I am talking about resistance load the output voltage will be like this.

Output, $V_{dc\,average} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m sin\omega t\; d(\omega t) = \frac{V_m}{2\pi}(1 + \cos\alpha)$

Whereas if I had had a diode, I would have gotten this integration from 0 to π because of which we got $\frac{V_m}{\pi}$, so $\frac{V_m}{\pi} > \frac{V_m}{2\pi}(1 + \cos\alpha)$ provided $\alpha > 0$.

We are delaying the firing essentially to get a variation in the output voltage. So, I would say output dc voltage for a diode HWR $= \frac{V_m}{\pi}$, so compare these two to find out how the controllability is in one case versus others. Whenever I am going to have an SCR, I will have reduced voltages, provided I am delaying the firing. I am talking both the cases about same R load. Whereas with RL load it is not going to be so simple because the current can start from here and then it can extend for longer because of which even this portion would appear.

So this will appear only for RL load, not for R load and I should know at what point the conduction is being completed which is β, so I have to integrate between α and β, and β has to be solved for, by first of all solving for current, after solving for current the initial condition will be I (α)=0 and again I have to put I (β)=0 to solve for β in that expression. So, this is the difference between what we had as uncontrolled rectifier and what we have as controlled rectifier.

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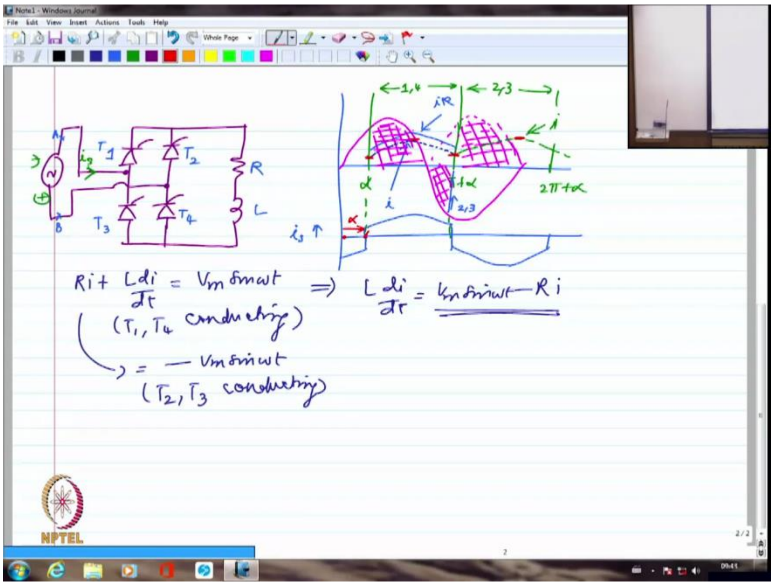

Just to recall what we did as the second portion of this rectifier circuit where we had 4 thyristors and we had an RL load and we looked at two cases; one of continuous conduction the current is continuous and another case of discontinuous conduction, both we had taken a look with the source that is being connected is a single phase AC source. And most of the time the sources that we consider are generally of 50 or 60 hertz because these are all power frequency rectifiers, power frequency AC to DC converters. So we will normally assume that the frequency of operation is very slow, so the devices will have sufficient time to turn ON and turn OFF. That is the reason why we use thyristors which are very much slow compared to IGBTs or MOSFETs and so on, we are not going to use any of them.

So, in this case we numbered this as 1 and 4 and we call this as T_2 and T_3, and we call this point as A and this point as B, and we said this is an RL load. Just do iterate, we essentially drew different waveforms that is the supply voltage, load voltage, supply side current and load side current, these are the things we drew. So if I am looking at the supply voltage somewhat like this and if I am going to assume that I am firing 1 and 4 at firing angle of α then I have to fire the other two at π+α so that it will be symmetrical, I will have symmetrical way of firing this. So now if I assume it is continuous conduction, the current can never be 0 it has to be at least some value.

So, if I say that it is starting from some value, so maybe it is starting off with some value, so from here it is going to start increasing like this, it is increasing and at some point it will start decreasing. Let us write the equation again $R\,i + L\frac{di}{dt} = V_m sin\omega t$ if I am having T_1 and T_4 conducting, if these two are conducting I am going to have $V_m sin\omega t$ directly applied across the load. Whereas I am going to have this will be equal to $-V_m sin\omega t$ if T_2 and T_3 are conducting because just the opposite polarity is connected right across the load, that is the reason.

Now if I am going to have $L\frac{di}{dt} = V_m sin\omega t - R\,i$, we already said when these 2 are equal to each other the current is going to reach its maximum value or minimum value because of which let us say at this point it reaches the maximum and from here it is going to start dropping down.

Correspondingly I can draw probably the voltage waveform which is iR somewhat like this, so at this point it reaches the peak and at this point it starts declining, so this is iR whereas this is going to be i. Now I am going to have at this point I am firing 2 and 3, at this point I am firing 2 and 3. So until now $V_m sin\omega t$ was directly connected as it is, so I am going to have this entire voltage coming up as the load voltage on the whole that is how it is going to come up. And then I am going to have this portion again coming up, this portion is going to come up. So, I am going to have this shaded portion as the DC voltage or the load voltage that comes up when I am having continuous conduction. So, the current you can see is oscillating between some peak value and some minimum value, so it is going to repeat itself again, I have to have this repeating again.

So, this is going to be the current waveform, so if I try to look at what is the current waveform that I see from here which is the supply side current. Whenever 1 and 4 are conducting, I am going to have a positive current that is flowing in this direction, I say that this direction is the positive flow of current. Whenever 2 and 3 are conducting because it is conducting during the negative half cycle this will be plus and this will be minus, so because of which the current is going to go in the opposite direction. So, I should say the conduction duration I can write it somewhat like this, from this point to this point 1 and 4 are conducting. From this point until again if I call this as $2\pi+\alpha$ I am going to have 2 and 3 conducting.

So during this portion if I try to draw the current, it might just increase like this and then decrease like this, this is the current corresponding to 1 and 4 and this is the current corresponding to 2 and 3 and this happens to be the supply current, this is how the current is going to be. So abrupt rise and abrupt fall is going to take place as per as the supply side currents are concerned. But they are exactly shifted, if you try to look at the supply side current, it is exactly shifted from the voltage zero crossing by an angle α whichever is the delay angle, that is how it is going to be shifted.

So I will have the phase shift between the voltage and current to be actually α because voltage had the zero crossing here whereas the current is having zero crossing here, so I will have the shift that is coming up between positive going zero crossing of the voltage and positive going zero crossing of the current and negative going zero crossing of the voltage and negative going zero crossing of the current. The shift is exactly the same because I have done symmetrical firing.

Student: Why the current is not starting from zero?

Professor: We are not starting with transient, I told you that if you start from transient it will start from zero, inductance will slowly accumulate energy, we are talking about the waveforms in steady state. In steady state and I am considering continuous conduction, if it is discontinuous conduction it will start from zero. So, if you look at the discontinuous conduction, it would have started from zero, if it is continuous conduction it will not start from zero especially in steady state. When you are talking about transient, yes it will start from zero, but when you are talking about steady state, all the minimum values will be at the same level. Similarly, all the maximum values will be at the same level, when that happens that is when you call it as steady state.

Student: Are we assuming that in the transients we use diodes? (15:20)

Professor: No not at all, even in the transient you have to start with thyristor only because you are not changing the circuit, you are starting off with dead position of the circuit, it is dead completely dead. You are applying a voltage, the current will start from 0 at α whichever α it is, at that α the current will start slowly increasing. It is R L circuit so the current cannot jump, so it will slowly increase. As it builds up you are going to see that inductance stores energy, so at whatever point, $V_m \, sin\omega \, t = \, R \, i$, the current has reached its maximum, there is no more energy to supply to the inductance, then the current will start declining because of which inductance will be able to pitch in.

So it pitches in until the next pair of devices are fired, the moment the next of devices are fired if the current has not still touched down zero then it is already having a head start. So, like that it builds up energy, that is what happens.

We are talking about at a given α, at a particular supply voltage with a given circuit how it slowly attains steady state and in steady state how the waveforms look, this is what we are talking about. Now, if I have an RLE load which is like a DC motor drive, for example which is already running, so it will have a back EMF and if it has the back EMF you are going to have definitely that back EMF opposing the current, back EMF will not aid the current, if it aids the current it will go to infinity literally. So, I will have essentially this as the circuit.

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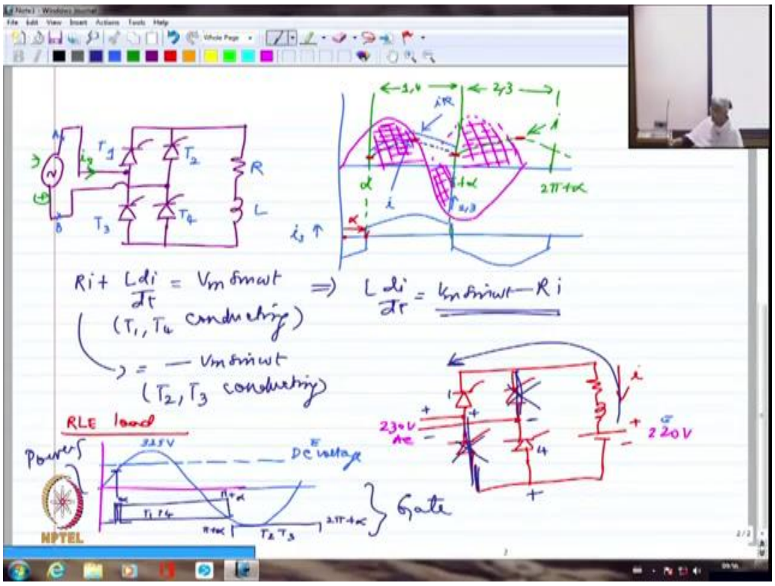

I am going to have the four devices here and I am going to have R, I am going to have L and then I am going to have this. So now I have put the source such that the positive is here which means it is definitely going to oppose the flow of current or it is as though a battery is getting charged, the current is in this direction. So, I am going to have plus here and minus here, so the battery is trying to accumulate energy.

Now, if I am having 230 volts AC here, maybe this is a 220 volts battery for example, I am just arbitrary taking some values. 230 volts RMS, 325 will be the peak roughly, so I am essentially going to have a voltage waveform somewhat like this. This is 325 and what I am having here is about 220, so probably this is going to be my DC voltage, this is E.

So if I try to fire for example at this point, if by chance if it happens to be a continuous conduction then ,why should you not consider the inductance voltage at all while you are looking at whether it is trying to forward bias, the supply voltage will forward bias the devices or not? But the load inductance is completely isolated. If I am trying to look at the whole thing as though, let us say I am trying to fire 1 and 4, and these two if they are already conducting if they are already carrying a current continuous current, in that case I can consider them as short circuits.

And I am considering positive half cycle which means plus here and minus here, so I would say plus is connected here clearly and this is minus and through this device which is short-circuited this is going to be connected to minus, so this is plus and this is minus. So, obviously device number 1 is forward biased irrespective of whatever is the voltage that is there in the inductance or anything it does not care. Same way I can say if I consider device number 4, this is minus because this minus is directly connected here and this is plus and this is a short-circuit, so this will be automatically plus. So, no matter what this device is forward biased irrespective of whatever happens here, from supply voltage itself I can say this particular devices forward biased, no matter what.

So if I talk about continuous conduction even in this case and even if my DC voltage is higher than whatever is the supply voltage at the instant of firing, it does not matter the devices will get fired, no matter what the devices will get fired.

On the other hand, if I am not having the conduction, let us say it is not continuous conduction, if no current is flowing this is an open circuit, this is also an open circuit.? It has to be open circuit. If it is open circuit, I have the supply voltage connected here which is positive but I have this plus also coming into picture here, this plus will come here because it is open circuit voltage, I have to look at open circuit voltage. When there is no current essentially whatever is the voltage here there is no drop, nothing here, so this voltage will appear right there. So, if that voltage appears here, I have to have a tug of war between these two whether this is dominating or that is dominating.

If I am going to have the voltage that is here that is dominating over this positive, then it is reverse biased. On the other hand, if this is going to be smaller, I will have this forward biased, the same thing holds good for the other device as well.

So there are two cases we have to consider, if I am having already continuous current then I do not have to bother about what is happening in the RLE, I can directly say if it is positive half cycle I will be able to fire 1 and 4, if it is negative half cycle I will be able to fire 2 and 3. Whereas if I am not having continuous current in fact, the current has to start from 0, at the instant of firing I have to compare basically what is the voltage here and what is the voltage coming up from the supply and I have to compare the two and if the supply voltage is dominating only then it is going to get fired. That is all the more reason why we never give a single pulse normally for a thyristor, we get a train of pulses.

We generally make a pulse almost for 180 degree duration because I would know that from here to here this device can conduct and from here to here the other device can conduct, so this is for T_1, T_4, this is for T_2, T_3, so this is from α to almost $\pi+\alpha$ and this will be from $\pi+\alpha$ to $2\pi+\alpha$.

So if it does not get a chance to fire here, at least let us give it a chance to get fired whenever it is possible for it to conduct, so thyristor circuits as the rule are never given one single pulse of a very short duration, never ever. So if I am going to have actually an AC supply being supplied to a thyristor circuit, I necessarily need to give a long duration pulse, but the continuous long duration pulse normally I do not give for SCR because I use a pulse transformer, please correlate the two. I connected a pulse transformer to isolate the gate from power, these all these things are in gate, all these things are in power.T_1 and T_2 whatever I am giving is in gate T_1, T_4, T_2, T_3 all these pulses are in gate and gate pulses if I try to give continuous pulse, I need to give a wider pulse .

But if I give a wider pulse directly, the pulse transformer will get saturated which I am using for isolation, so I necessarily need to AND it with high frequency that is what we did. You remember, we ANDed it with high frequency and then we made the amplification and after the amplification in the collector we had connected a pulse transformer, that is what we had done, so please correlate these two. We are having a pulse given here, so if I am having one pulse here it is not going to allow the SCR to fire especially under discontinuous conduction, so I might have to give it a chance fair chance to conduct by giving a wider pulse.

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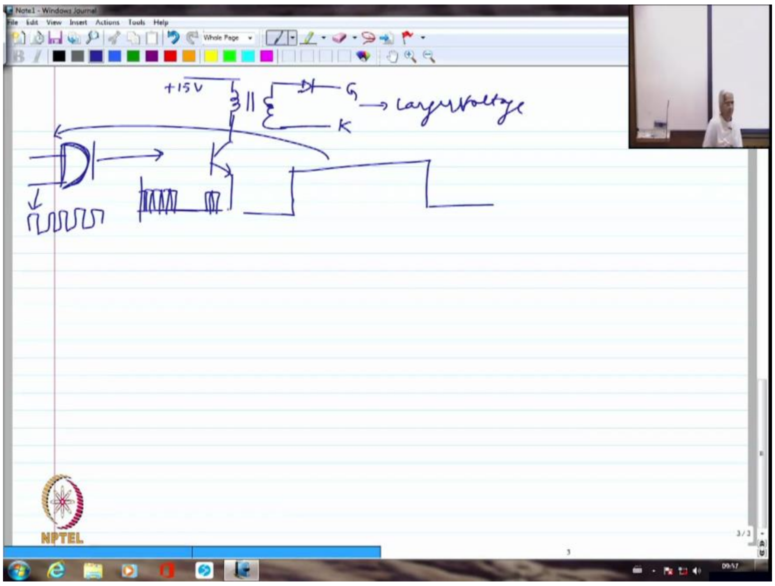

But if I give a wider pulse because that is the norm for the thyristor normally, if I give a wider pulse directly if you may recall we had said that the pulse has to be given basically to an amplifier. In the amplifier I had given a pulse transformer in the primary which is connected to the amplifier and secondary was directly connected through a diode to the gate and cathode this is how I have shown. So this is all 15 volts or 5 volts all the electronics, microelectronics whereas gate and cathode clearly is connected to larger voltage, larger power levels (larger voltage and larger current). So, I want isolation between the two that is the reason I am using a pulse transformer, the pulse transformer will isolate the ground of the microelectronics side from the power side.

But because I am using a transformer, I cannot afford to give a pulse which is continuous like this, it will saturate. That is the reason what we had done was to use an AND gate, an AND gate we had used with here we had given a clock kind of pulse, high frequency pulse and here we had given this pulse. So, what you will get here will be a train of pulses like this and then it will be 0 again, a train of pulses like this.

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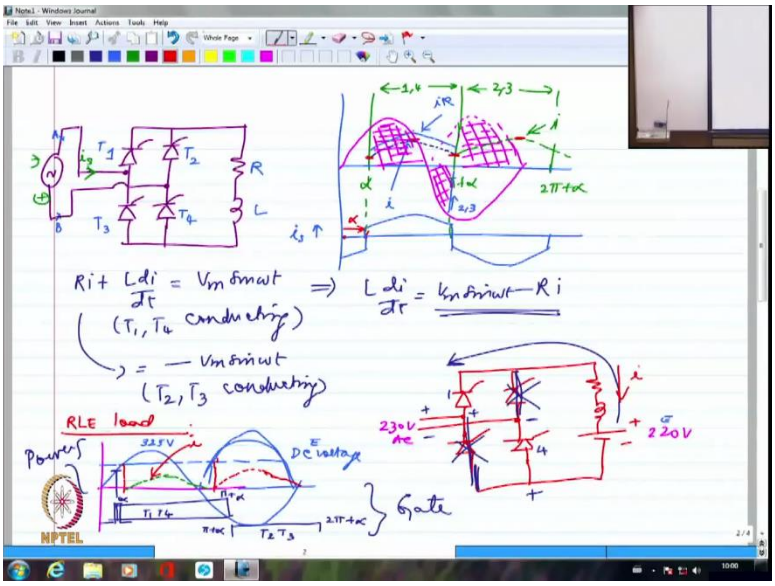

Student: Why pulse width is for 180 degrees though conduction is less than that?

Professor: It will not get ON absolutely but generally what we do is as a rule, all the single-phase converter circuits will receive a pulse of 180 degrees, that is a standard design. Although it is not going to be really work, even if I try to fire it beyond this it will not work but we generally make it like a standard practice. So, all the single-phase SCR control circuits will have a pulse width of normally 180 degrees. When we come to 3 phase we will see it will be 120 degrees, as a rule single phase circuits will have a pulse width for the thyristor phase control circuits, they will always have 180 degree pulse width. Whereas 3-phase control circuits with thyristor will always have 120 degrees pulse width, we will look at it why as to.

So in this case if I assume discontinuous conduction, it will start conducting only from this point although I had tried to give a firing pulse at α but I will see the conduction starting only from this particular point, the current will start rising from here, and it might just end up coming down something like this. It is possible, it depends upon R, L and E values especially R and L values now because I know exactly where E stands, so this is the way the current is going to be. Obviously in the other half cycle again I am going to have this as the other half cycle and I am trying to fire it somewhere here and then I am going to have essentially the current starting only at this point and then it is going to probably go again like this.

It will be of course symmetrical because I am not changing anything, R, L, E everything remains constant so I will have one pulse which is corresponding to T_1 and T_4 conduction this is the current, this is the other current which is corresponding to T_2 and T_3 conduction, so this is going to be the current i , this is discontinuous.

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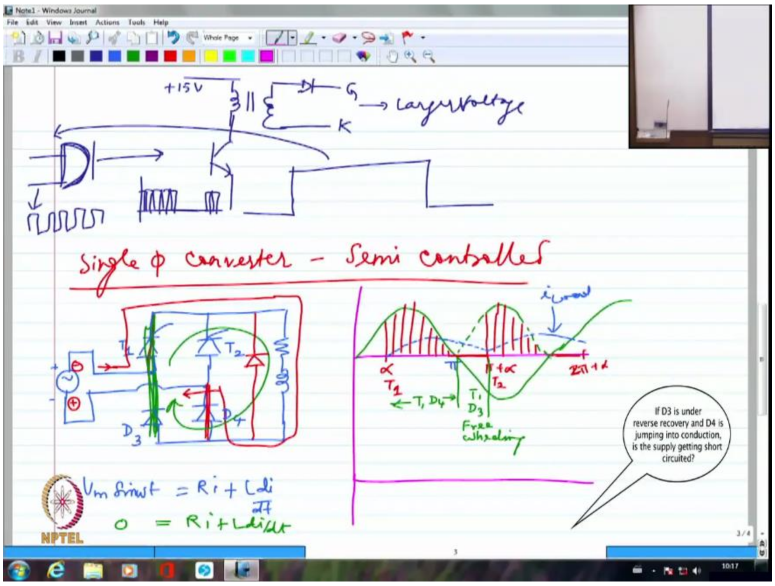

Now let us try to look at the last type of single-phase converter which is semi-controlled. We said uncontrolled when we had all 4 diodes, we said fully controlled when we had all 4 thyristors, we can call it as semi-controlled when we have two diodes and two thyristors. So, we are essentially going to have let us say two thyristors like this and then two diodes like this. I can even draw in one like both of them thyristor, in the other like both of them diode, there is nothing wrong, but I want to be uniform over 3 phase and single phase. So in 3 phase if I am talking about semi-controlled, I have to have 3 on the top probably or at the bottom probably as SCRs and in the top if I have assumed SCR, at the bottom I should have all the 3 as diodes. So, this is semi-controlled converter and let me talk about this with R L load.

So, let me call this as T_1, let me just adhere to the same 4, so I would call this as D_4 and this is T_2 and this is D_3 and I am going to have the power supply connected here. Let us see now what happens, I do not have to fire D_3 or D_4 clearly, they are uncontrolled devices but I necessarily

I have to fire T_1 and T_2, otherwise they are not going to conduct. So, the tone for the conduction is going to be completely set by the thyristor, at least to start with the conduction will be dictated by when I am giving the pulses to the thyristor. So, let me draw the waveform also and simultaneously let us try to see how the whole thing is going to work. So, this is my power supply and when I am inverting it or I am rectifying it, I am drawing the other side also like this, right. I am firing say this T_1 at some value α then obviously I have to fire T_2 at π+α for symmetry.

So only one device I am firing obviously, so this is T_1 and this is T_2. When I am having T_1 fired, T_1 and the conduction path is somewhat going to be like this, this will go like this, this will come through D_4 because D_4 hopefully is forward biased you can check it and then I am going to have the current flowing like this, this is how the current will flow. From the power supply will go through T_1, load, D_4 and back to the power supply, that is how it is going to be. So, we are essentially going to have a current like this, that means let us say my current probably would increase slowly depending upon the same equation,

$$V_m sin\ \omega\ t =\ R\ i +\ L\frac{di}{dt},$$

So, the same thing holds good when $V_m sin\omega t = R\ i$, I am going to have the peak being reached, same thing holds good.

So, the current has reached a peak somewhere here and then it will start falling. What happens at this point I have to check, I am talking about the point here that is π, the current has been flowing, if the current is flowing I am going to have this almost as a short-circuit. So, if this is a short-circuit and this is reversing its voltage because ωt is π already, so I will have plus here and minus here when I am talking about negative half cycle. This plus is connected through D_4 to D_3 here, this minus is connected here, whether I like it or not plus and minus are connected now in such a way that this diode gets forward biased.

D_4 is conducting because of that the supply voltage comes now across D_3, until π the supply voltage was reverse biasing it, the moment it crosses π and it comes into reverse half cycle, I am going to have essentially D_3 getting forward biased. The moment D_3 gets forward biased it is not going to keep quiet; it will start conducting so D_3 will start conducting. The moment D_3 starts conducting, now look at this if D_3 is conducting it becomes a short-circuit, D_3 jumps into conduction because of D_4 because D_4 was the one which was instrumental in making D_3 forward biased. But the moment D_3 gets into conduction, now this is a short-circuit so I can say that this is plus, that plus goes here, and this is anyway connected to minus, so D_4 sees that that itself is reversed biased.

The moment D_3 gets into conduction, D_4 gets reverse biased because D_3 is a short-circuit, this minus comes to the anode of D_4 and this plus comes to the cathode of D_4, so D_4 completely is switched off. So I am going to have because of this uncontrolled nature of the diodes, previously I was having a clear you know distinction between the conduction zone and the non-conduction zone whenever I give a gate pulse only then it will start conducting, whereas here the diodes jump into conduction the moment they are forward biased, and the forward biasing and reverse biasing happens because of the supply voltage as long as the current is continuous. If the current is not continuous this diode would not have been conducting, the diode is not conducting I cannot talk about the short-circuit and so on and so forth.

So, whenever I have a semi-controlled converter especially in the lower portion of the lead then the negative half cycle almost the control goes for a toss, it is something like that. Whereas, what now is going to happen is both these fellows conduct together, D_4 has gotten into conduction, T_1 is already conducting, nobody to turn it off.

Student: If D_3 is under reverse recovery and D_4 is jumping into conduction, is the supply getting short circuited?

Professor: D_3 has gotten into conduction, T_1 is also conducting so this entire leg is conducting, happily circulating a current only through the load and the two short-circuited devices, as simple as that. So, the source is completely eliminated, the source is out of circulation, it is not there in the picture at all. So, if I look at it from here to here it is going to be T_1 D_4.

Student: How is T_1 forward biased?

Professor: T_1 is already conducting. If any thyristor device is conducting, to turn it off you have to follow two conditions in sequence; the first and foremost condition has to be the current has to be less than holding current, that is not happening so T_1 will not care, it will say as long as I am having the current I will continue. The moment it conducts, if you forget about the fact that it is not ideal, it will have a resistance definitely and the current is flowing in this direction that will make this slightly positive, that slightly negative. So, it is forward biased by virtue of its own voltage drop.

It is connected to the negative terminal, but you have to look at this also, at what terminal see potential difference we have to look at, we cannot look at only anode potential. With respect to the cathode whether it is more positive that is what we have to check. So, if the current is already flowing, that is a small voltage drop of 0.7 V or 1 V or whatever that will always be plus here and minus here because thyristor can never conduct in the opposite direction obviously. So, I will have basically from π until π+α, T_1 and D_3 will conduct together and this is simply going to circulate the current like this. Source current does not exist during that duration, source is completely isolated, this particular duration is known as the freewheeling duration, it is simply freewheeling the current through the two devices which are connected continuously in series, so this duration what we have is freewheeling.

Now, if you look at again the current probably would come down but not as fast as what it was coming down for the fully controlled converter. In fully controlled converter, this negative portion of the voltage was appearing, that negative portion of the voltage was a huge drain on the inductance stored energy. Please remember, this is still the equation, when I have freewheeling this will become, $0 = R\,i + L\frac{di}{dt}$.

if I neglect the drops across the two devices. So, there is nothing which is actually coming up as source voltage whereas in fully controlled converter this negative portion of the voltage was appearing.

Because there is a negative portion of the voltage that is acting like a drain on the inductance stored energy, definitely the current could have fallen faster because it is essentially draining the energy of the inductance. But now the current will not fall as fast, so it is kind of pretty rare to see discontinuous conduction in semi-controlled converters, you will see very rarely discontinuous conduction in semi-controlled converter unless I make my α very large. So, I make the α very large, the conduction itself starts very late so there will not be much of stored energy and so on. But for smaller α you will hardly ever see discontinuous conduction with RL load, you will not see.

If it is only R load, I do not think it makes any difference, only the inductance stored energy is really creating all this magic. So, if you do not have inductance in the load then all these things are not valid arguments at all. So, if I try to draw the other portion of the current, I should again draw it as though it is increasing and decreasing and so on, this is how the current will be. So, this is the DC current or I_{load}, load current. Now if I try to draw the load voltage until here, I am going to have the load voltage coming up like this completely, but the moment the shortcircuiting happens I will have 0 voltage. Again, I will have this voltage appearing; again, I will have 0 voltage until $2\pi+\alpha$.

So, whatever I have shown here is the load voltage without any negative portion of the voltage, there will not be any negative portion as far as the load side is concerned. So, whenever I have a freewheeling diode or freewheeling kind of duration coming into picture, I am going to have 0 voltage. Sometimes, we tend to put an explicit freewheeling diode even though these two can very happily do the freewheeling, there is no problem, but we put the freewheeling diode sometimes to reduce the voltage drop. Although we say ideal devices will not have any voltage drop, instead of having two devices having the voltage drop if I have only one single device having the voltage drop then the current can even pull along for longer duration.

You understand because R times i whatever is the forward resistance of this and forward resistance of this, whereas here there is only one device whose forward resistance needs to be considered, so sometimes we might explicitly put a freewheeling diode just to reduce the drop. What is happening across two devices is a higher drop, I want to reduce the drop so I might put just one device across this. So now let us look at the supply current waveform.

Student: It seems like inductance was low.

Professor: Inductance was not low.

Student: If this inductance is low, there can be a case in which this can become discontinuous.

Professor: But that is why I said in a reasonable value of inductance if I compare semi-controlled, if I compare fully controlled, semi-controlled has a better possibility of having continuous conduction. I am comparing those 2. Similarly, if I have a much larger α, even for a high inductance I might get into discontinuous conduction, it is very much possible.

Most of the times what happens is we assume everything to be ideal devices and do the analysis completely and 20 millisecond is a vast compared to the kind of microsecond durations that are involved in turning ON and turning OFF. If you say that D_3 is jumping into conduction even that will take some time, by then D_4 would have recovered. So fortunately, in semi-controlled converter when we operate it in actual practice, we hardly see the supply getting short-circuited.

If this is in reverse recovery and this has already jumped into conduction you are going to short-circuit the supply. If you are going to short-circuit the supply, then it is not really good for the supply normally and one more thing we have not consider for all the analysis which I will finally consider. None of the sources are ideal sources, we always consider this to be a very ideal source, there is always an impedance. You have transmission line, you have transformers, you have everything, all of them are going to have some impedance or the other. As long as D_1 and D_4 are conducting I am going to have the supply voltage directly connected to the load.

So, supply voltage comes right across the load, so that is why this is the supply voltage and I am going to have the load voltage same as supply voltage from α to π. After π current is not 0 but these two devices are conducting, the load voltage is this entire thing, so this entire thing is short-circuited by two devices, that is the reason why I get zero voltage. And after that I am again going to have the supply voltage from $\pi+\alpha$ to 2π, from 2π to again $2\pi+\alpha$ it will be 0 voltage because the other two devices will be short-circuited. Now if I look at the supply current so from here it is T_1 and D_4, so I am going to have exactly whatever is the DC side load current the same thing will come. It is exactly the same waveform what I have drawn, I have taken as it is.

But from here to here the supply is isolated completely, the supply is not in the circulation, only it is going through the two devices through the load, that is it. So, I will not have any supply current during this portion. So, this is starting from α until π, again in $\pi + \alpha$ I am firing the device which is corresponding to T_2, so T_2 and D_3 will take over. Whenever T_2 and D_3 are taking over the current will flow exactly in the opposite direction, so I am going to have the same current what is same as supply current and then it is somewhat like this. And then here is where is 2π, at 2π the current ends and 2π to $2\pi+\alpha$ it will circulate only through the load, there is nothing returning to the supply.

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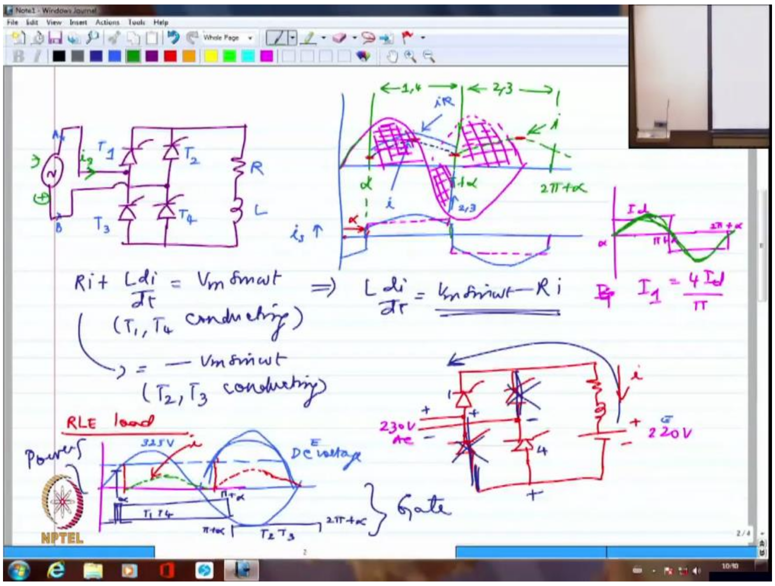

I will go back here a little bit to talk about the power factor, somewhere I talked about power factor. This is one I talked about power factor somewhere here or at least the zero crossing of voltage and zero crossing of current I was talking about at this point. So, if I actually look at fully controlled converter's supply side current, when I did not have any of these rectifiers if the supply voltage is sinusoidal, the supply current will be sinusoidal. R, L, C whatever you connect it will be good there is no problem. The moment I connect a power converter and I intervene with the switching of one device, switching off of another device and so on and so forth, the current wave shapes get completely modified, they are far from being sinusoidal.

If I have a very high inductance almost the oscillation will be negligibly small, so if I try to look at the entire current it will look as though this is like a current like this and this will be a current like this. If I neglect the ripple, the current will look completely like a rectangular current like I will have a square wave or rectangular whatever you may call it, you will have essentially a current wave shape like this. It is not at all sinusoidal that is what I am trying to get it. So, if you derive the fundamental for such a current wave shape, I am talking about a current wave shape somewhat like this, so it is starting from α, it is going until π +α and this is 2π+α.

Maybe let me call this as I_d, the DC current that is the magnitude of the current. For this if I try to derive the fundamental component and then other harmonic components using Fourier expansion then I would see that the fundamental component I_1 let me call that as fundamental component which is corresponding to 50 hertz.

$$I_1 = 4I_d/\pi,$$

This is the peak of the fundamental, and fundamental is normally sinusoidal in nature because Fourier expansion essentially tells you that any periodic waveform can be expanded into several sinusoids consisting of the fundamental, second harmonic, third harmonic, fourth harmonic until nth harmonic.

So if I try to look at the fundamental it is a sinusoid in its own and it is going to have the peak value as, $I_1 = \frac{4I_d}{\pi}$. And if I try to draw the fundamental corresponding to this, it may look actually something like this. So I am going to have a fundamental exactly coinciding with the Zero crossing of the square wave, so if I look at the square wave versus the sinusoidal waveform both of them will have the Zero crossings coinciding everywhere, positive going, negative going and so on and so forth.

Please note the current that was flowing in the supply which is far from being sinusoidal was shifted from the original voltage by α if I am firing the thyristor converter at a firing angle of α. So, this is the phase shift between the current and the voltage, and if I look at this current and the fundamental current, both of them are actually not phase shifted, they are in phase with each other. So, I can say the fundamental current and the fundamental voltage are shifted from each other also by an angle of α.

So this particular angle is generally known as the displacement power factor angle, the displacement power factor angle is the angular difference or the displacement between the fundamental component of the voltage and fundamental component of current, so that is actually going to play a vital role in deciding what is the kind of power factor I can anticipate in my circuit because this is essentially pushing the current behind. That angle is telling you how much the fundamental current is being pushed behind. So, if this is the way the current is being pushed behind when I calculate the power, generally we say $\int VI$ over a cycle and average it over the complete cycle. So obviously wherever the voltage and current are not in phase, I am going to have some reactive power that is what is manifesting itself as reactive power.

So, whenever I am going to have a displacement power factor other than unity I will have a good amount of reactive power content in my circuit. I cannot help but have some amount of reactive power content.

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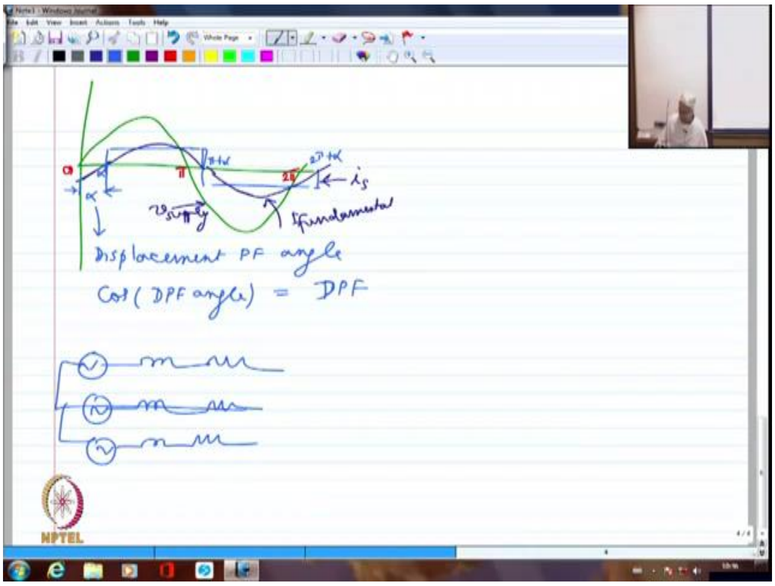

Just to reiterate this again, let me draw the waveforms of the fully controlled converter's voltage, so maybe this is the voltage of the fully controlled converter, the current might start at α, so it may be α to π+α and it may come from π+α to 2π+ α. So, this is α, this is π +α and this is 2π+ α and I am going to have this as 0, this as π and this as 2π. So, if I am drawing the fundamental current corresponding to this, I have to draw the fundamental somewhat like this. Now to scale, so I am just trying to establish the 0 crossing that is it, so it is going to be somewhat like this, this is how the fundamental current is going to be. So, this is $i_{\text{fundamental}}$, this is without incorporating any of the ripples, I have neglected the ripples, and this is the V_{supply}.

Now whatever is the displacement between the fundamental voltage and fundamental current between these two, this angle this is α in this case this is called as displacement power factor angle and cos of displacement power factor angle is known as displacement power factor,$\cos(DPF\ angle) = DPF$. So, I will have essentially this contributing towards rather requirement of reactive power, so the thyristor converters in general have a couple of issues or a couple of problems. One problem is always the converter circuit even if I connect the simple resistance in all probability, I will ask for some amount of reactive power, the circuit will demand some amount of reactive power. So, it is going to demand certain amount of reactive power because the displacement power factor is not unity.

And second problem is the currents are far from being perfect sinusoids, there are large and large number of harmonic contents that is present in the current. So, if I have lot of harmonic content present in the current imagine my source which is a sinusoidal source, alright but I am going to have some impedance, resistance and so on in the transmission line. If it is a 3 phase, everywhere I will have some transmission line impedances. All these things are going to carry this harmonic current, so R multiplied by the harmonic content of the current will give me some harmonic voltages whether I like it or not, so there will be a lot of harmonic voltage generation.

Although my generator is trying to generate purely sinusoid, I have generated all these harmonics. So, whenever I connect an induction motor or anything which requires sinusoidal supply, they are all going to get all these harmonics voltages also injected into them which is not good for the induction machine because we analyse the induction motor assuming it is all sinusoidal supply. The moment there is a non-sinusoidal supply, I may have fifth harmonic, seventh harmonic, third harmonic, eleventh harmonic, so I will have different revolving magnetic fields. One rotating at $5\omega_s$, another rotating at $7\omega_s$, another rotating at $11\omega_s$, so many things all of them are going to confuse the induction motor. So, this essentially is a prelude to power quality.

I am not going anymore into this, but I am trying to say that power electronic converters are a big menace, they create power factor problem, they create harmonic problems. And the solution also line for electronics ultimately, so we create the problem we also eliminate the problem ultimately with power electronics, I will not go into anymore that. If I am talking about square wave that is the current actually drawn by the converter which I cannot eliminate, because of that I will have harmonic currents. And if I have harmonic currents and if I have R and L multiplied by the harmonic current will give me the harmonic voltage drops. So, although I generated sinusoid, now I am going to have some harmonic voltages maybe negative, maybe positive whatever that is generated in the transmission lines which is ultimately is going to reach the motors and so on which I am connecting in the power grid.

And these are not 1 kilowatt, 2 kilowatt, power electronic converters most of them may be megawatt level especially when I talk about the DC motor driver or AC motor driver or HVDC transmission and so on and so forth, everything will be incurring so much of harmonic content into the entire system. So we are will not dwell on this but on the whole DPF that is Displacement Power Factor, Displacement Power Factor angle, power factor and so on are extremely important in terms of the overall performance of the thyristor rectifiers.

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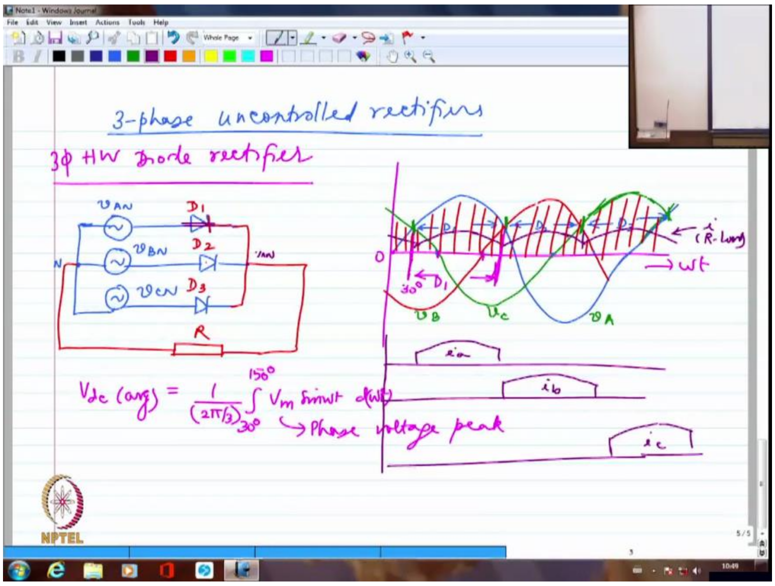

So much so for single phase, let us now try to look at 3 phase uncontrolled rectifiers. Let me again start with the simplest of configuration which is the half wave diode rectifier. So let us say I have 1, 2 and 3 phases, these are the 3 phases so let me call this as V_{AN}, this is probably neutral and this is V_{BN} and this is V_{CN}, 3-phase voltages which are 120 degree shifted from each other and I am assuming balanced voltage is obviously, all of them are having the same magnitude, peak magnitude is the same. So, I am going to have one diode here, second diode here and third diode here. Let me call this as D_1, this as D_2, this as D_3, and then finally from the neutral I am going to connect the load which is also connected to the star point like this.

So what I am converting is AC to DC of course, and DC is connected between the neutral and the star point of the 3 phases which are connected after the device. So, I have to see at what point D_1 will conduct, at what point D_2 will conduct and at what point D_3 will conduct. Let us first of all start off with a simple resistance load R load, so let me first of all draw the three-phase voltage waveform. So this is the sinusoid, so let me divide this into 120 degrees interval I mean 60 degree intervals, so obviously my second phase is going to be somewhere here and the third phase is going to be something like this, these are the 3 phases. Now let me name them, this is V_A, so the second one is V_B and this third one is V_C.

Whichever is the diode which is having the maximum positive voltage hopefully that will conduct, we will come back to the logic as to why that should only conduct. So, during this portion the maximum positive is with this particular phase, during this portion the maximum positive is with red colour waveform, during this portion the maximum positive will be with green, whatever is the maximum positive let us say that conducts. So, from here to here I am going to have D_1 conducting, from here to here I am going to have D_2 conducting, from here to here I am going to have D_3 conducting.

Let us say now D_1 is conducting, when D_1 is conducting it is as good as a short-circuit. When D_1 is conducting, if I try to look at the voltage across D_2 and D_3, V_{AN} will come here at this point because D_1 is conducting. So, this voltage will be V_{BA}, this voltage will be V_{CA}. Because on one side it is connected to a source, on the other side it is connected to V_{AN} through this conducting diode. The diode is conducting so the entire V_{AN} is applied to the load because this point becomes V_{AN}. So, the voltage across this will be V_{BA}, the voltage across this will be V_{CA} and if I try to look at V_{BA} or V_{CA} because A is the maximum, V_{BA} as well as V_{CA} have to be negative. There is no other way, the maximum is A, rest of them are all smaller. So, $V_B - V_A$ or $V_C - V_A$ all of them have to be negative, there is no other way. So, both these diodes are automatically reverse biased.

Whenever I am going to have D_1 conducting and if its voltage is the maximum at that point, automatically other two diodes are eliminated, they are not going to be able to conduct anymore. Whereas at this point because D_2 now has the maximum value of voltage, again the same logic holds good, D_1 and D_3 will automatically be eliminated because beyond this point D_2 will get automatically forward biased, because it gets forward biased it will jump into conduction and once it jumps into conduction you are going to have the other two diodes eliminated automatically. So, I am going to have the voltage for a simple diode rectifier whether with R load or RL load it does not matter, if it is a diode rectifier I am essentially going to see that the voltages that come up are this entire thing. I am going to get this entire thing as the voltage that is coming up across the load.

If I try to look at the load voltage, this entire shaded portion comes. So, whenever D_1 is conducting I am going to have the entire V_{AN}, whenever D_2 is conducting I am going to have the entire V_{BN} and similarly I am going to have the entire V_{CN} whenever D_3 is conducting. And please note this is repeating itself every 120 degrees, V_{AN} comes up for 120 degrees, V_{BN} comes up for 120 degrees, V_{CN} comes up for 120 degrees. So, I have to essentially get the value of voltage by integrating from this point until this point, when I integrate between these two points that is where D_1 is conducting.

If I try to integrate the voltage waveform for just 120 degree which is sufficient enough, I do not really have to integrate it for the entire duration, so I can simply say, if I assume this to be 0 of ωt this point is 30 degree because I told you that already I had divided everything into 60 degree interval, so this point is 30 degree. And 30 degree is $\frac{\pi}{6}$, so I have to essentially integrate the voltage. So if I say V_{dc} or $V_{load\ average}$ will be equal to 30 degree to 150 degrees and I have to write, $V_{dc(avg)} = \frac{1}{2\pi/3}\int_{30°}^{150°} V_m sin\omega t\ d(\omega t)$, where V_m is phase voltage peak

So, this is going to be the kind of expression I will get for a 3-phase half wave rectifier with diode, so it is uncontrolled rectifier. This is just for the sake of continuity again, this is hardly ever used anywhere because you should know how a half wave rectifier works and then we will go to full wave, that is the reason I am kind of discussing this because this hardly have any applications hardly ever. Look at the current now, if it is like a resistance load, I am going to have the current somewhat like this. This will be the current, so it will go like this and again it will jump up like this, same 120-degree duration again I will have the current like this. So, this will be the current for R load, for R load the current will be exactly following whatever is the wave shape of the DC voltage, load voltage.

But A phase will conduct only for this duration, B phase will conduct only for this duration and C phase will conduct only for that particular duration. So, we are utilising each of the phases in a very limited manner. We are going to have A phase current flowing only for 120 degree, so if I try to the current waveform for A phase, I will draw only like this, that is it, this is A phase current. And if I try to draw the current corresponding to B phase this is going to be B phase current, and again if I try to draw the voltage current waveform corresponding to C phase, this is going to be C phase current.

No negative half cycle currents and the currents are far from being sinusoidal anyway, so this really gives rise to again huge amount of harmonic content and without any negative half cycle which means saturation of the transformer could be very well seen in this particular kind of rectifier. So, this rectifier is really problematic because of these reasons. And one more thing is without neutral I cannot work in this particular rectifier, and most of our industries will have only 3 phases coming in. You will hardly ever see a neutral; three-phase will directly come to any industry.

If the neutral is not there you cannot use this kind of a half wave rectifier, so this kind of half wave rectifier is hardly ever used in any of the industries.