Power Electronics
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Lecture 10 - Three Phase Rectifiers -II

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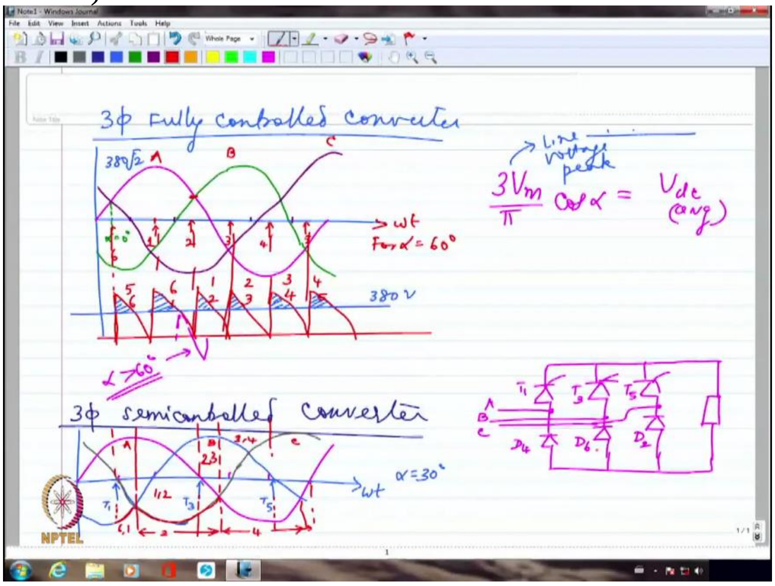

So we had stopped at the point of three-phase fully controlled converter. This is where we had stopped and I think I had drawn the waveform corresponding to α=30,α=60, α=75, and then maybe 90, I said positive and negative sides will be exactly equal to each other due to which you will have 0 voltage. So if you may recall, let me again draw only corresponding to α=60, then we will go over to semi-controlled converter.

So this is my sinusoid. So, this is R or A phase, this is the second phase and this is going to be the third phase, So these are the 3 phases. So this is the three-phase waveform and we said that this is going to be α=0°. So if we are talking about α=60 we said this is where I have to fire 1 and then 2, then 3, then 4, here will be 5. So obviously, just the previous one will be 6. 6 would have been fired here for α=60. So this is for α=60. So this is ωt, this is for α=60 degrees.

So this is A, this is B and this is C. I can again write the interval somewhat like this. So these are the intervals that we are writing here. So this is going to be 5 1 6, this will be 6 and 1, this is 1 and 2, this is 2 and 3, this is 3 and 4, this is 4 and 5. This is how each of those devices pair up with the other one and then conduct. So this we are assuming again continuous conduction but of course if it is a resistive load, even if it is a resistive load, I would have gotten a waveform, so I am going to look at 6 and 1 conducting.

So I have to get V_{AB}. Please note that V_{AB} becomes 0 here and V_{AB} is clearly positive before that. So I am going to have essentially, this is touching 0, again this will touch 0, this will touch 0, this will touch 0 and so on. This is how the waveform is going to be. If it is a resistive load, I would not have anyway 0 current interval persisting for longer because it might touch 0 even if it is R load. It will touch 0 again, it will jump up. The current will jump up.

So the 0 interval is not really finite, it is just, it touches 0 and then again jumps up. So this is the way the voltage is going to be. So we said, as we increase the firing angle further, I am probably going to see that this gets delayed further and maybe I will have some negative portion and so on. So, this is for $\alpha > 60$. Whatever I have drawn for the purple or pink color, whatever I have drawn, that is corresponding to $\alpha > 60$.

So you are going to have essentially some portion of positive voltage and some portion of negative voltage, both of them and you might have an average voltage equal to 0. We derived the expression that $\frac{3V_m}{\pi}\cos\alpha = V_{dc(avg)}$ where V_m is line voltage peak. Line voltage is line to line voltage.

Any equipment that is available in the market, if it is a three-phase equipment, the specifications are always given in terms of RMS values of line voltages and RMS values of line currents. If I say 415 volts, 50 hertz, obviously 415 volts refers to the RMS value of the line to line voltage. Any three-phase equipment, the specifications are always like this.

And similarly, if I am talking about a motor or a generator, the power rating that is given, 5 kilowatt, 6 kilowatt, whatever, that is the output, not the input. That is the output. So please remember these things, being an electrical engineer you should know at least this much for sure. So this is the kind of waveform you are going to get for three-phase fully controlled converter. I think in the exam what I had asked is the question was, this is connected to the DC link with a battery and a resistance.

So a battery is sitting there and maybe that is 380 volts, maybe this peak is $380\sqrt{2}$. I have chosen the numbers in such a way that if it was $415\sqrt{2}$, I have given a battery of 415 volts. If it is 380 $\sqrt{2}$, I had given a battery of 380, it will make my life simpler to solve all of them. That is the reason I had changed the numbers here and there. Firing angles, I changed slightly of course. So if I have something like this, obviously the resistance will conduct only for this duration. Why would it conduct for any other duration?

The devices will be forward biased only when the battery voltage is subdued as compared to the voltage that is coming up across the DC link. Otherwise, the devices are not going to conduct. And we are assuming ideal devices, of course. So if at all you had to put down the assumption, you should say ideal devices. That is all. Anyway, we have done all the analysis using ideal devices.

So this will be the voltage across the resistance and the same will be the current across the resistance as well. So if you want to calculate the current, you could have done it in 2 ways. Some people have calculated as RMS, people who have done until here, they have calculated whatever is the $V_m \sin \omega t$ value minus the battery value divided by R, the whole square and integral of, that is where many people have gone wrong, from what degree to what degree. It will conduct only for 15 degrees. It will not conduct more than that if you actually calculate.

So it just calculates, I mean it is starting at 120 and it is going until 135. That is how it will be. So if you had done it and you had calculated the RMS current value, that is fine. Otherwise, if you had calculated V_{dc} average with the complete thing and then minus the battery voltage divided by R as the I_{dc}, I have given still full weightage. No problem as long as you have calculated I_{dc} like that. And then of course, whatever is the I_{dc} multiplied by the battery voltage will be roughly the power transferred to the battery.

Battery voltage may be slightly fluctuating but we are ignoring that because we are saying that it is a 380 volts battery or 415 volts battery. We are ignoring whatever is the oscillation in the battery voltage. So much so for fully controlled converter, I have still not gone for $\alpha > 90$. We will take it up after we do the semi-controlled converter for three-phase. So now I am going to venture into three-phase semi-controlled converter. So three-phase semi-controlled converter basically will have 3 SCRs and 3 diodes.

So I am going to have 1, 2, 3, I am assuming that the positive devices are SCRs and I am going to assume that the negative devices are diodes. And then, I am going to connect it to the load on the DC side and I have to give three-phase supply. Some people have drawn the supply like this and that to DC. So here, you are going to have the three-phase supply .So this is A, this is B, this is C. Let me call this as T_1, T_3, T_5, this is D_6, this is D_4, this is D_2.

Please note that the negative portions go uncontrolled. Because I have diodes, so the diodes are going to conduct whenever they are forward biased or whenever it is the maximum negative. So wherever I have maximum negative, that particular device will conduct for that 120 degree duration. I will not have any control over the negative side conduction. Whereas positive side conduction, I have control. So let me first of all take the three-phase waveforms.

So this is my sinusoid and this is the second phase and this is going to be the third phase. So let us say I am looking at α=30. So if it is α=30, I have to fire T_1 here. So, I am talking about α=30and this is of course ωt, That is what is $\alpha = 30°$point. So if this is T_1, I am going to have, this is where T_3 will be fired because T_2 is a diode here, so I will skip firing that, I cannot fire that because it is a diode.

So I am going to have essentially T_3 here and T_5 here. This is how different phases are fired. Now if I say that whatever is the maximum negative, that is what will conduct, now during this portion, from here until this portion, right, this portion corresponds to let me write the phases, this is A, this is B, this is C. This is B phase negative and B phase negative is D_6. So here 6 and 1 will conduct.

For this duration, 6 and 1 will conduct because 1 has been fired here. 6 will conduct for this duration because that is the maximum negative. Whereas here, I will have corresponding to 2, the conduction will correspond to 2 because I am going to have maximum negative corresponding to C phase. So this entire portion will correspond to 2. This entire portion will correspond to 2 and this entire portion will correspond to 4 because this is corresponding to the maximum negative.

The maximum negative portion until here. Maximum negative of A phase takes place until this point. So I am going to have no matter what, 2 will try to join hands with whatever is the other device that is conducting. So please note that 6 and 1 conduct only for 30 degrees, not more than 30 degrees. So this 30 degree conduction portion will correspond to 6 and 1. From here to here, it is 30 degrees.

From here until 2 ends up or 3 takes over. So from here until this point where 3 will take over, that will correspond to the conduction of 1 and 2. 1 and 2 are going to conduct for this duration. So let me just try to write the duration. So this is the duration for which 6 and 1 will conduct and this is the duration for which I am going to have 1 and 2 conducting. So this is going to be the duration for which 3 and 2, 2 and 3 will conduct. Whereas this is the duration for which I am going to have 3 and 4 conducting.

Please note, each pair is not conducting for 60 degree duration. This is a much smaller duration. This is only 30 degree and between these two, the duration is 120 degrees. So if 30 degrees is gone here, rest of 90 degrees is coming. Then I am looking at 1 and 2. So when 1 and 2 are conducting, they are conducting for 90 degrees whereas when 6 and 1 are conducting, they are conducting only for 30 degrees.

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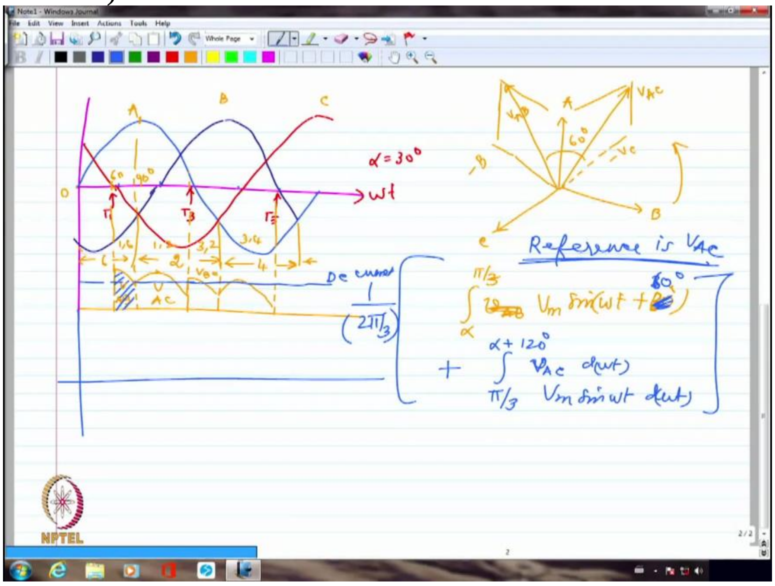

Let me again redraw the waveform here so that we will be able to draw completely the line currents and so on and so forth. So this is my one of the phases and this is the second phase and this is going to be the third phase. So, I am talking about this is ωt, α=30degrees. So we said that here is where we fire T_1, this is T_3, this is T_5. So, we said that for this entire duration, let me probably draw the duration itself.

From here to here, I am going to have, this is corresponding to A phase, B phase, and C phase. So this is going to be device number 2. This is corresponding to device number, this is A, so 4 and this is going to be 6. So I can right away say which device is joining hands with which other one. So I should be able to say that from here to here, I am having 1 and 6 and from here to here I am having 1 and 2. So this is 1 and 6 and this is 1 and 2. So earlier also, we talked about this. A phase zero crossing is here, A phase peak is here.

And this point is 30 degrees ahead of A phase peak which means that is same as A, B peak because V_A and V_{AB} are shifted from each other by 30 degrees and V_{AB} is leading. Please recall the phasor diagram. If this is A, this is B, this is C, I am going to have AB, so this is minus B. So I will have V_{AB} somewhere here. So V_{AB} is 30 degrees ahead of V_A, then I am assuming that anticlockwise direction of rotation.

So I should say that at this point, I should be having V_{AB} peak. So I would have had V_{AB} peak and I must have seen that it is coming down. But after that, V_{AC} would take over because this is V_{AB}. After this, V_{AC} would take over. 1 and 2, V_{AC} has to come up. So when V_{AC} is coming up, again if I look at V_{AC}, so this is $-V_C$. So if I draw, this is V_{AC}. V_{AC} and V_{AB} are phase shifted from each other by 60 degrees.

So if I am having AB peak here, AC peak will happen after 60 degrees. So this is only 30 degrees. So it must have, see it must have been going up like this so that the peak happens exactly after 30 degrees from the point where V_{AB} ceases to be the DC link voltage. So I have the peak of V_{AB} here, peak of V_{AC} will be shifted from the original peak of V_{AB} by 60 degrees. That is what I am trying to get it. So because of which, I am going to have V_{AC} peak coming up after 30 degrees from the beginning of V_{AC} waveform itself.

Now from here, it is going to come all the way like this probably. How much it comes down, we will have to find out because this is totally 90 degrees. That is what I said. This is 30, this is 90. So this is 30, it should not be in the middle. So it is 30 and then 60 degrees, it must have come down. So this is the way I am going to have V_{AC}. Now again the next one what I will have is, this is 3 and 2. So that will be V_{BC}. So it will be a repetition, again.

So I am going to have something like this. Then I am going to have until here, 3 and 4 for this duration. So, I am going to have again some peaking up here and then it is coming down like this and so on. So this is the kind of waveform I am going to get for single phase semi-controlled converter when I am looking at $\alpha=30°$. And for this if I have to write the expression for the voltage, I should say from α until what point? That we have to check.

Because if I say I am integrating V_{AB} from α until the point V_{AC} is taking over. And V_{AC} is taking over where two must have been fired. 2 must have been fired when it is like a diode converter with α equal to 0, So 2 will be fired normally at α+60. 2 will be fired at α+60. So I should basically say that if I say I am doing from α until say it is not α+60, I should say if this is this is 0 and this is the point which is 60 degrees and this is taking over exactly at 90 degrees.

So I have to just integrate between α to $\pi/3$. I can write V_{AB} as V_m sin $(\omega t + 60)$.

$$\int_{\alpha}^{\pi/3} V_{AB} = \int_{\alpha}^{\pi/3} V_m \sin(\omega\, t + 60)$$

If I am taking basically V_A as just a second, you are starting with α and we are going until 90 and then we are integrating.α is actually ωt = 30 degree point. So that is the reason why you are saying that I have to make this α+30. π / 3 should be π/ 6.

Student: $\pi / 3$?

Professor: $\pi / 3$. So in which case I cannot write this as ωt + 60. It should be ωt + 30. We are taking reference as V_{AN}, V_{AN}. Everywhere we are taking reference as V_{AN}. So with respect to that, we are saying from α, whatever. We are starting from α. So actually my reference is V_{AC}.

Then if I am taking V_{AC} as the reference, then this becomes π/3, not π/2. So we are taking here reference to be, so reference is V_{AC}. We have written. so we are taking basically 60, 60. Oh, I corrected and still wrote 30. We are looking at V_{AC} as the reference. So we are firing at α with respect to V_{AC} 0 crossing.

From α, how far it has continued? It has continued until the natural point of conduction of 2 and natural point of conduction of 2 is α+60. But we are taking basically V_{AC} as the reference and we are taking a diode in the negative side. So it should have started conducting exactly at 60 degrees away from the point of α=0 which is V_{AC} 0 crossing. So V_{AC} we have taken as the reference. So, we are always calculating the α from V_{AC} and from there, how far 2 will conduct? I mean, 2 will not conduct.

How far 2 will not conduct? 2 will not conduct only until 60 degrees point, 60 degree point of V_{AC}. So this is one portion, this is only this portion. We have one more. So here, it has to again start from π/ 3, And I have to say clearly T_3 is fired at α+120 degrees. So I do not have to worry about it at all. T_3 is fired exactly at α=120.And I am going to integrate V_{AC} dωt. Now, our reference is V_{AC}. So I can simply write V_{AC} as V_M sin ωt.Our reference is V_{AC}. So I can simply write this as V_m sin $\omega t d(\omega t)$. Now the entire thing has to be averaged over 2 $\pi/3$.

Reference is V_{AC}

$$\frac{1}{2\pi/3}\left[\int_{\alpha}^{\pi/3} V_m \sin(\omega t + 60) + \int_{\pi/3}^{\alpha+120^\circ} V_{AC} d\omega t\right];\ V_{AC} = V_m \sin\omega t$$

Student: 2 π.

Professor: 2 π/3, not 2π. 2 π/3 because this will repeat again. I will have 6 and 1, 1 and 2 and after that, I am going to have 2 and 3 for a short while, then 3 and 4 for a longer duration. And so on and so forth. So we will have different kinds of outputs whenever I have different firing angles. We will look at one more firing angle at least and then we will decide exactly how the output changes. So in this case, if I try to look at the supply current, maybe I have a huge inductive load, RL load and the current is ripple free.

Let me assume the current is ripple free, it is a straight current. So if I try to draw the DC current, maybe I am going to have a DC current like this. So this is the DC current. So if my DC current is somewhat like this, I have to see what happens on the AC side, how the AC side currents are changing?

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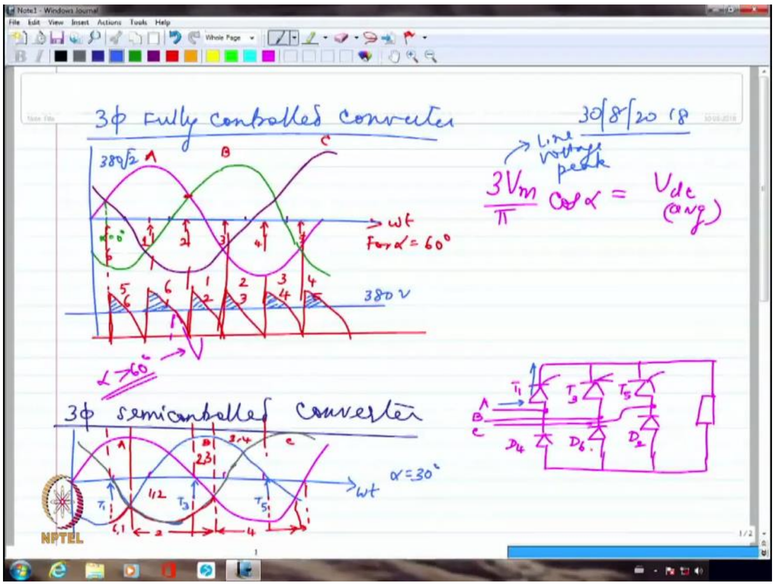

So please look at this circuit. So, if I have A, so if 1 is conducting, device number 1 is conducting, A phase current is positive. If device number 4 is conducting, A phase current is going to be negative. So, I have to look for wherever 1 is conducting, I will have correspondingly that particular current to be, A phase current to be positive. So let me take a look at this.

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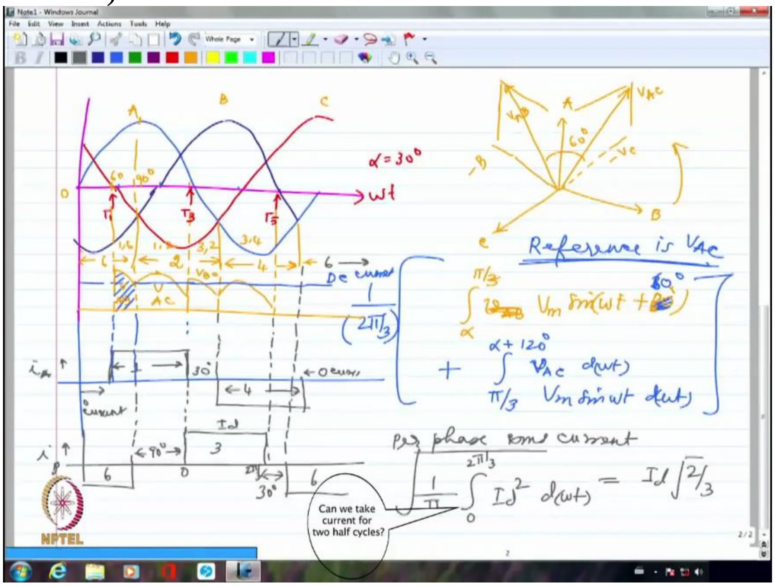

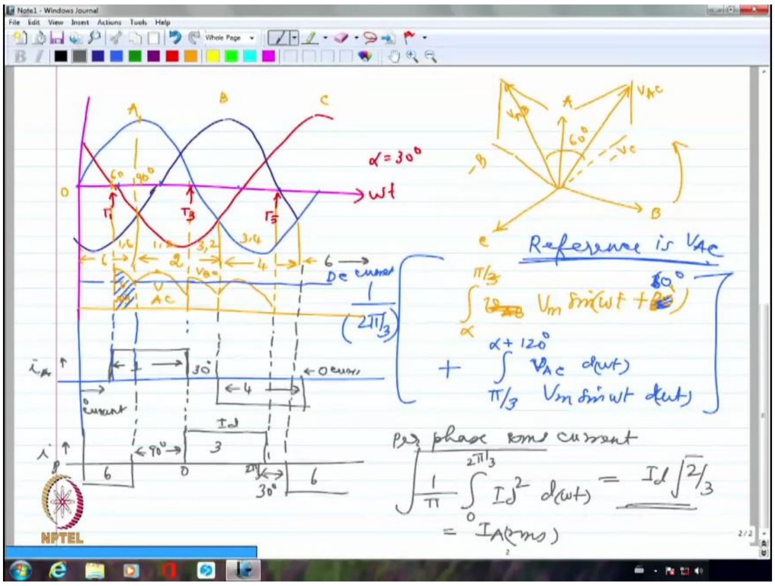

I am going to have, here device number 1 is conducting. So, I am going to have clearly A phase current coming up as positive until here. This is A phase current and please note, it is for 120 degrees. This is A phase current whenever 1 is conducting and if I try to look at the other side of the current wherever 4 is conducting, so this is going to be 4 whereas this is going to be 1. And in between, I have only 30 degrees, not 60 degrees. In the other fully controlled converter, because we had symmetrical conduction of each of the positive and negative devices, I had 120 degree current in the positive, 60 degree of 0 current interval, again 120 degrees current in the negative, against 60 degrees of 0 current interval.

So it was separated very nicely by 60 degree or symmetrically. Whereas here, if I try to look at, for this entire duration 6 is going to conduct from here to here. So I am going to have 0 current here, this is 0 current until I am going to have 1 coming up, along with 6. So this is all 0 current. So the 0 current interval will continue for almost 90 degrees once the negative half cycle of the current is over because as we said, 3 and 4 conduct for some time and after that I am going to have 4 and 5 conducting for probably a longer duration.

Or 5 and 6 conducting for a longer duration, 90 degrees duration. So that is going to essentially make A phase completely not having any current. So similarly, if I try to look at for example, B phase current. B phase current is going to be somewhat like this. I am going to have B phase current positive here whenever 3 is conducting. So this is i_A, this is i_B. Whenever 6 is conducting, so 6 is conducting here. So I am going to have 6 conducting here and this interval is only 30 degrees.

But 6 is probably going to conduct again here and this interval will be 90 degrees. So I am going to have the positive current duration for 120 degrees and negative current duration for 120 degrees but they are not separated symmetrically from each other. On one side, they are separated by 30 degrees, on the other side they are separated by 90 degrees. So if I try to find out what is the RMS current, if I say this is Id, per phase RMS current if I try to calculate. It conducts basically for 240 degrees inclusive of positive and negative and it does not conduct for 120 degrees. So it conducts for two-thirds of the duration and it does not conduct for one-third of the duration. So I have to essentially say, I have to probably integrate it from about if I say this is 0 and this is 2 π/3 for example, so I should say 0 to 2π/3 Id^2 $d\omega t$ and I have to divide this by π because I am talking about half a cycle, RMS current.

I am trying to calculate the RMS current. Positive and negative halves are exactly symmetrical. So it is sufficient if I do it only for half a cycle. And I have to take a square root, that is it. So this will come out to be Id $\sqrt{2/3}$

Per phase RMS current,= $\sqrt{\frac{1}{\pi}\int_0^{2\pi/3} Id^2}\ d(\omega t) = I_d\sqrt{2/3}$

Student: Can we take current for two half cycles? (32:43).

Professor: So I could have done that and then I could have divided this by 2 π. Rather than that, I have taken only half the cycle. I could have done this as Id^2, from 0 to 2 $\pi/3$, another Id^2 from say 2 π, if this is 2 π/3, this is 150 degrees whatever it is. 150 to 270, I could have taken it like that. But rather than that, if I just integrate for half the cycle, that is more than sufficient because they are symmetrical.

Student: If the load is purely resistive, can we make an approximation?

Professor: No, when you have purely resistive load, you just cannot make this approximation. So for purely resistive loads, it is not easy to calculate the current unless you are given exact numerical values. If you are given exact numerical values, you will be able to calculate by integrating and substituting the actual DC values and so on and so forth. Otherwise, you cannot. But this is basically for the case where there is a large amount of inductance, highly lagging load. Let us now try to take a, this is true even for a three-phase fully controlled converter. I am sure you realize that because if I am going to have you know 120 degree current in the positive half cycle and 120 degree current in the negative half cycle and in between 60 degrees duration, it does not matter.

Whether it is 60 degree or 30 degree, I am going to get the RMS value like this. So this is going to be I_{ARMS} or I_{BRMS} or I_{CRMS} irrespective of whether it is a single phase or three-phase fully controlled converter. But semi, I mean three-phase semi-controlled or fully controlled converter but three-phase semi-controlled converter, when we go for a little larger values of firing angles, they are going to behave a little differently.

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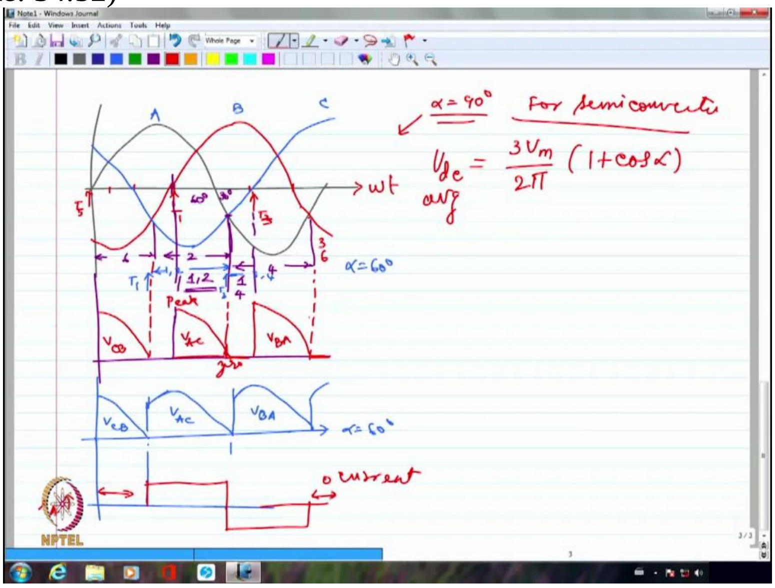

Let us try to take a look at that. So let me probably take again three-phase waveforms. So these are the 3 phases. This is A, this is B and this is C. Let us take maybe not 60, 60 maybe, shall we go 90 or a little more than 90 maybe? So let us say, we will go for 90 degrees, let me check for alpha equal to 90 degrees what happens. Let me take it for α=90. So which means, this is actually my α=0. So I am going to have this is α=90.

So this will be where T_1 will be fired, this is where T_2 will be fired. This is where T_3 will be fired. T_3 and T_5. This is for the case of α=90. Now if I try to look at it, again I am going to have clearly for this duration, I will have 6 conducting. There is no opportunity for 1 to come in touch with you know 6 at all because 1 is actually being fired here. So 1 and 6 are not getting in touch with each other at all because when you have fired 1, 6 has already ceased to be the most negative device.

So 6 will never join hands with 1. So what I will have is here I am going to have, for this duration it is 1 and 2 and for this duration, I am going to have, from here to here, it is going to be 4.So I am going to have actually 1 and 2 conducting for this duration. From here it is going to start and it will conduct until here, 1 and 2 will conduct for this duration automatically. After that, what happens? When 1 and 2 are conducting, it is V_{AC}.

After that what happens is here 1 and 4 conduct and 1 and 4 are in the same leg. They are not in two different legs. So it will freewheel. Obviously freewheeling will take place when I have 2 devices which are in the same leg conducting simultaneously. So semi-controlled converter will get into freewheeling the moment you have the 2 devices together conducting in the same leg. Because one of them is diodes, you do not have a control over preventing its conduction.

So I am going to have actually if I try to draw the waveform, for this I have to draw 1 and 2 and please note this is 0 crossing of V_{AC}. Here A and C are crossing with each other, so because of which it is 0. V_{AC} will be 0 at this point, And it is starting to conduct here. And how much is the duration? This is 60 degrees, and this is 30 degrees. So totally 90 degrees I am getting 1 and 2 conducting. So that means it should start from the peak and come down to 0. So I should have essentially this as V_{AC} part of the sinusoid.

So it is starting from the peak and ending up in 0. And when it is freewheeling, I am going to have 0 voltage clearly. And after that, I am going to have 3 and 4 conducting. When 3 and 4 are conducting, it is V_{BA}. So I am going to have again V_{BA}. And then after that, it is going to be 0 because if I say that 4 is conducting until here and 3 is continuing until this point, so 6 has already started. So there will be 0. 3 and 6 will conduct for some time.

And after that, I am going to have 5 and 6 conducting. If 5 and 6 are conducting, I am going to have V_{CB}. So I am getting all sorts of different varieties of waveforms when I am looking at semi-controlled converter. But actually if you try to derive the expression for each of the cases, you would see that it will be $V_{dcavg} = \frac{3V_m}{2\pi}(1 + cos\alpha)$ This is what you will get irrespective of whatever is your α. This will be the V_{dc} average for semi-converter.

Student: If α=60 degrees, how will be the waveform?

Professor: No. It will probably come from here itself because you would have fired T_1 here. So you would have had 1 and 2 continuously conducting for the entire 120 degrees. If I had fired, if I say α=60, for that I would have fired T_1 here. So I would have had 1 and 2 continuously for 120 degrees. I will never have 0 current interval. 0 voltage interval. Then I will have T_3 actually fired here. T_3 will be fired here. So I will have 3 and 4.

But what I will get as the waveform will be something like this. It will go like this and then it will come down. So this will be V_{AC}. This is for α=60. Because I have fired it at 30 degrees ahead, so there is no question of short-circuiting by 2 devices. So this is V_{AC} and then you will have again V_{BA} and similarly, you will have something like this and then coming like this. So this is going to be V_{CB}.

One major thing here will be please note, in α=60 degree case, I will have 1 conducting here because of which I will have a positive current here and A conducting here, that is 4. So there will be a negative current here. Please note there is no gap at all between the positive and negative current, And 120 degrees, it is dead. This is for α=60. So for this 120 degrees it will be 0 current completely.

Whereas here whenever there is freewheeling, the supply is completely eliminated or isolated. The supply is not going to care about what happens to the load because only between the load and the freewheeling leg, there will be current.

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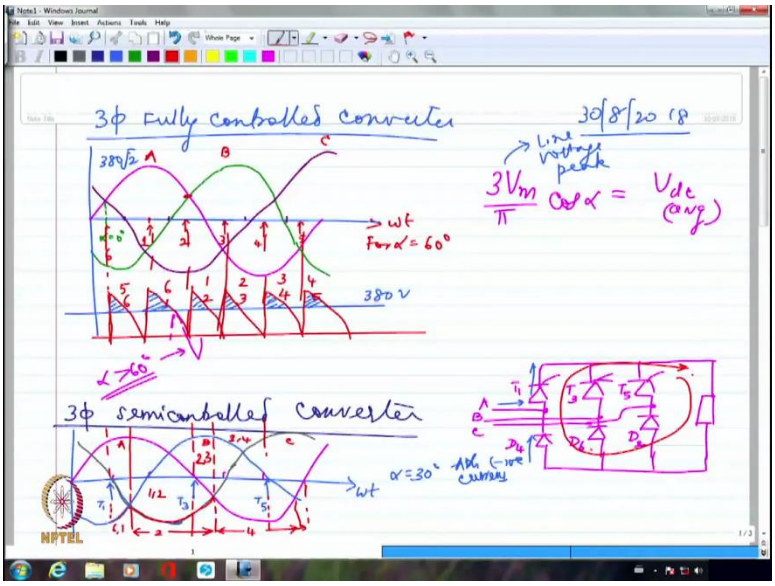

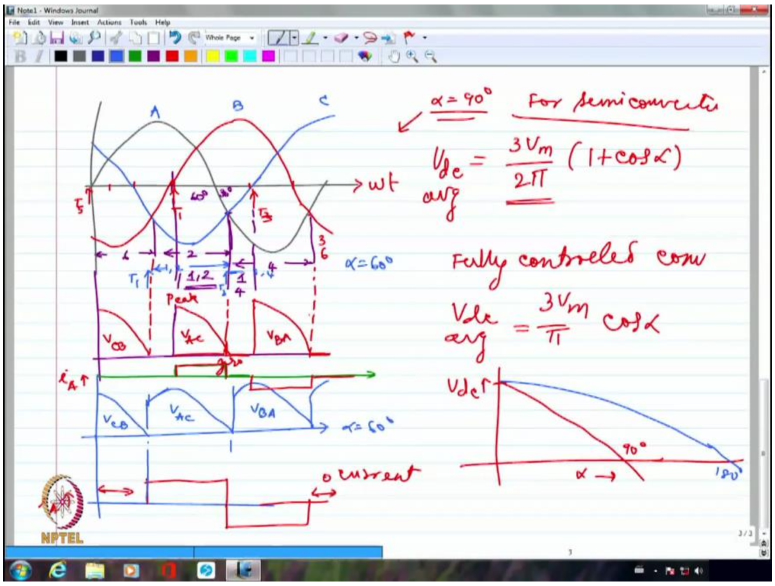

So if I am having for example, these 2 are freewheeling, I am going to have simply the current going like this. There is nothing that is going through the supply. It is just going round and round in this. That is it. So the supply will be deprived of any current or it will not carry any current during the freewheeling. So if I try to look at the current here in this particular case, I would see that for example, during V_{AC}, I will have a positive current.

I will have 0 current during this time and I will have a negative current during this time. This will be i_A. So I am going to get positive current for only 90 degrees here. Negative current again only for 90 degrees. So 90+90 (180). Rest of 180, it will be dead. No current at all. So in this case, that $\sqrt{2/3}$ will not work. So semi-converter is a pain basically for analysis. It is not very easy to analyze semi-converter in general. It is going to be really difficult.

Unless you are given clearly the firing angle and clearly what kind of load and so on and so forth, it becomes kind of difficult but one major advantage of the semi-converter is of course if I compare with fully controlled converter,

$V_{dc(avg)} = \frac{3V_m}{\pi} cos\ \alpha$ is the expression for fully controlled converter.

I am sure from these 2 you can realize that I will get more value for this particular case.

Clearly semi-controlled converter for a given α, other than 0 will yield a higher value of voltage. If I for example take α=90 degrees, here it is 0 whereas if I take α=90 degrees in the other case, it will be $\frac{3V_m}{2\pi}$.

So if I try to actually plot what is the value of voltage I get with respect toα, so if I say that if this is my α and this is the V_{dc} .I will have the V_{dc}, basically Vdc average I will be getting a higher value for the semi-controlled converter. Whereas for the fully controlled converter, I will get much lower value because of the fact that I have 1+cos α expression in my semi-controlled converter whereas I have only α expression for the fully controlled converter.

At α=0 degrees, both of them will have the same value. At α=0 degrees, both of them will have the same value but as I see the fully controlled converter, I am going to see that it probably goes like this and then it goes into the negative direction. What do you mean by negative direction we are yet to discuss which we are slowly migrating to. So the voltage will go into negative direction if I go far this is α=90degrees if I say. Whereas if I am talking about a semi-controlled converter, it will still be positive even until α=180, at α=180 degrees only it will become 0.

It cannot become really 0 before that. So I am going to have essentially this becoming 0 only at 180 degrees.

Student: If $\alpha > 180$ then?

Professor: You will not be able to have the line commutation at all. It will not go off. I do not know whether you guys have understood that because we have repeatedly said in the single phase case also, one new device comes in, the old device is actually reverse biasing the, I mean old device is getting reverse biased by the new device. That is the reason why it is going off. So α=180 is theoretical limit. Practically, I might have to do it a little ahead of time.

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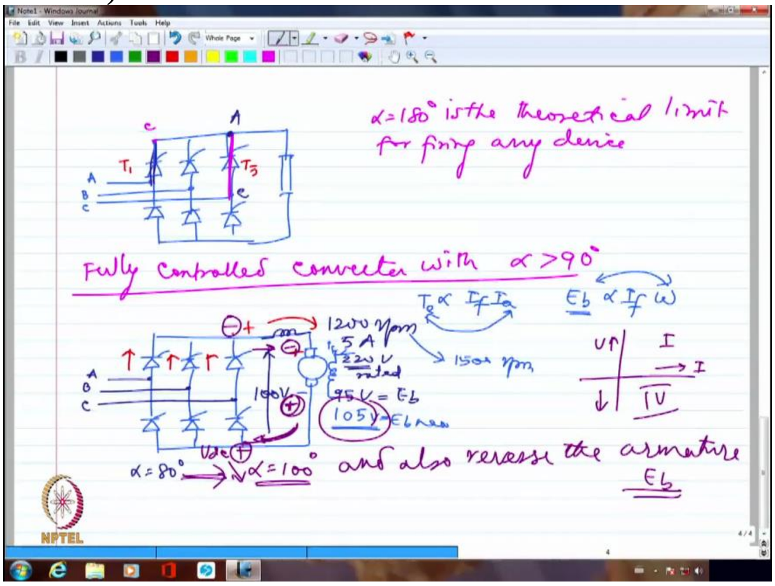

What I mean is, if I have a fully controlled converter, let me probably talk about commutation again. So these are the fixed devices. So if I am having T_1 fired and T_5 is going OFF, let us say I am firing T_1. When I am firing T_1, this is A, this is B, this is C. This happens to be a short-circuit. Already, this is conducting. So, whatever is this C, that C comes here. I am going by the same logic, whatever we talked earlier. So for me to fire T_1, V_{ac} has to be positive. If V_{ac} is not positive, I will not be able to fire T_1.

And V_{ac} 0 crossing is α=0.So obviously at α=180, V_{ac} will start going in the reverse direction. So, I will not be able to fire T_1 if I want to fire it after α=180 degrees. So α=180 degrees is the theoretical limit for firing any device because after that, it is going to get reverse biased. I am looking at basically the previous device which is conducting, that is bringing in some line voltage. And the new device which is going to get in, it is going to have a phase voltage on the other side.

So the line voltage which is coming across the device has to be positive. If that is not positive, there is no way you can fire that particular device. So α=180 degrees is the theoretical limit that we generally set for making sure that the device gets into conduction. But this is assuming that the forward voltage drop is 0. If the forward voltage drop happens to be 2 volts, 3 volts, then I cannot go until 180 degrees, I have to push it a little ahead, maybe 179, 176 degrees because I need at least that much of voltage across the device so that it is having some forward biasing voltage across it.

This is one thing. Second thing is, the moment this gets into conduction, this becomes a short-circuit. So now this A will come here. Once A comes here, we have to see whether V_{ac} is able to reverse bias the outgoing device. The outgoing device has at least some turn off time, it may have 50 microseconds, 100 microseconds, 120 microseconds whatever. So for that duration, I have to make sure that it is reverse biased and recombination takes place. So that is also true only if α is until 180 because if α is beyond 180 V_{ac} we said will be negative.

If V_{ac} is negative, I am going to forward bias 5, device number 5. So there is no way device number 5 will get recombined or it will not turn OFF. So normally, I am not going to be able to operate any of these converters beyond α=180 degrees. We will be able to operate it from α=0 until α=180 degrees. That is the limit. Beyond that we will not be able to operate it unless, maybe we have some other commutation circuit, some other thing which we are not discussing, that is not under the purview of this course.

So we are only talking about natural commutation or line commutation where the supply voltages which are going from positive half cycle to negative half cycle, automatically turn OFF the device. Now let us try to see what it means to be $\alpha >$90 because I told you that there is a negative voltage that is coming up but we said, AC to DC conversion, DC means unidirectional and we are talking about negative voltage. It does not make much sense.

So we have to first of all understand what we mean by the negative voltage, where is it applied, how is it going to be useful in any of the applications. So let us say fully controlled converter with $\alpha >$90. I cannot help but I have to take some kind of active load like a motor. Otherwise, we will not be able to really say from the DC side whether we will be able to feedback the power. DC side, only resistance, it will not be able to feedback any power.

Inductance, it is a passive element. It may store some energy but it will again not be able to generate anything. So let us take a DC motor drive. So let us say I have a fully controlled converter. And I am going to have a DC motor drive connected. So according to what α I am working at, I will get different values of voltages across the DC motor's armature because of which I will be able to look at a different values or speeds in the DC motor.

Voltage is essentially going to decide what is the speed and current is going to decide what is the torque. So $T \propto I_f I_a$ and $E_b \propto I_f$, if I forget about flux, $E_b \propto I_f \omega$.So obviously I can say, the voltage is going to decide the speed and T is going to be decided by the armature current under constant excitation. Now I have the three-phase voltages here, A, B, C.

Let us say, my machine is probably working at α=80 degrees, very large α .And I have a large armature inductance. So maybe the current is continuous and it is working at certain speed, maybe I can say 1200 rpm, 1500 rpm, whatever and it is drawing probably a 5A current and maybe it is a 220 volts DC motor drive.

So I am having, not really 220 volts, currently I am getting less than that. Because I am working at α=80 degrees, maybe I am going to get much. So this is rated. So maybe I am going to have only say 100, 120 volts, whatever this is the voltage I am having. Average, everything is average. Now let us say, this machine is fitted into a vehicle and it is moving down the gradient. Maybe you are in a hilly region and it is moving down the gradient.

If it is moving down the gradient, the speed will automatically increase. Whether you like it or not, the gravity is going to aided, the speed will increase. If the speed increases, originally it was working at 1200 rpm and back EMF would have been less than 100 volts. Maybe back EMF would have been 98 volts, 95 volts, whatever. But now the speed is going from 1200 to 1500 rpm let us say. It is just going quickly.

So I will have definitely this back EMF instead of originally whatever was the 95 volts back EMF, now it may become 105 volts or 110 volts because of increase in the speed. So from 1200, let us say the speed has become 1500 rpm. If the speed increases, the back EMF is going to increase. If the back EMF increases from 100 volts, no way I will be able to push the current into 105 volts. I will not be able to really push the current into 105 volts compared to what my 100 volts is.

So I necessarily need to do something and I want to control the speed. So I might incorporate something called breaking in this particular case. So if I want to incorporate breaking or whenever I want to even stop the motor drive or whatever, even when it is moving down the gradient, I might like to stop it eventually at some point. So if I have to stop it, in that case only way I can do it is to feed the power that is being generated in this machine.

I am calling this as a machine now, not motor. I have to feed the power that is generated because of downward movement of the machine which is working like a kinetic energy generator. So the machine will essentially start generating power. Can I feed it back to the mains? That is what I have to check. If I can feed it back to the mains, nothing like it. Because I am not wasting the energy.

The downward movement because of gravity is also being converted into electrical energy and I am feeding it back to the mains. Nothing like it if I can do that. That is being done in Delhi Metro very regularly. Delhi Metro uses regenerative braking most of the times. So if I do that, for that one thing I need to do is if this is my field current, I must have had my back EMF somewhat like this.

And when from this plus, the current was moving to this plus, this was actually working like a load and this was working like a source. Now I want to this the other way round and I know for sure that these will conduct current only in this direction. They are set in stone. I cannot do anything. So only thing I may be able to do is if I want to make the power flow direction reversed, I do not want the power to flow from the AC side into DC side, I want the power to flow from the DC side into AC side. I cannot reverse the current.

Only thing I can reverse is voltage. I would be able to reverse the voltage in this case. So what I can do is to reverse maybe the field current or reverse the armature first, so this will become plus and this will become minus with the same 105 volts, let us say. And I got this 100 volts as the voltage when I had a firing angle of 80. I will get the same 100 volts as minus 100 volts if I have a firing angle of hopefully 100 degrees because 90 if both sides were essentially the same, only thing is one is minus cos α, the other one is plus cos α.

Cos 80 will be equal to magnitude-wise cos of 100. Both of them should be equal to each other. So all I need to do is, to make this α shift from 80 to 100 and also reverse the armature E_b. E_b reversal can be either done by field current reversal or E_b reversal can be done by armature terminal reversal itself. Of course armature terminal reversal is not a joke because it will be carrying a huge current. You have to disconnect and reconnect.

It is not very easy but it is being done. It is being done in, not in Delhi Metro. Delhi Metro, this is not being used. It is a little different way of regenerative braking but in Chennai, in some of the portions, they use it. Old suburban train service where they are still using DC motors, good old DC motors. Whereas what we use here, most of them are induction motors.? So if I make α=100 degrees, now imagine I am going to have plus here and minus here for the V_{dc} after α becomes 100 degrees.

Now I have reversed this as well, I have reversed this as well. Now from here to here, the current will flow. The current direction has not reversed, the voltage has reversed. Because the voltage has reversed and the current direction has not reversed, you are essentially looking at instead of the AC power being fed to the DC motor drive, we are having the DC generated power from the machine being fed to the three-phase supply.

I have only thyristors which can conduct only in one direction. So I cannot afford to change the current direction. I cannot change the current direction even if I want to. So only way I can really reverse the power flow is by reversing the voltage and voltage can be reversed by making $\alpha > 90$. And when I make $\alpha > 90$, just to make sure that it will be in a position to feed, I have to make this plus and minus of the motor drive also conducive. Otherwise, it will not work. That is what is dual converter.

We will come to that also definitely. So he is saying that, why cannot we have another converter in the opposite direction? Complete, full converter, we have to have in the opposite direction. Only thing, you will be increasing the cost. If you are okay with increasing the cost, yes, by all means. So when we have two such converters, we call it as a dual converter. When we have only one converter, we call that as a two quadrant converter.

This we call as 2 quadrant converter because I will be able to have current only in one direction but voltage can be in both directions. So fully controlled converter is a 2 quadrant convertor. It will operate in both first and fourth quadrant. This is true only in fully controlled converter. Semi-controlled, very clearly the voltage cannot reverse. We said that already. So if I want regenerative braking, I cannot implement regenerative braking with semi-controlled converter because no way I can reverse the voltage.

So power flow can never be in the opposite direction. So although the semi-controlled converter gives me a higher voltage, maybe the control is somewhat simpler because only 3 devices have to be controlled but basically, it is not used in some applications where I am looking for regenerated power. Typically electric vehicles we will never use this kind of where regeneration cannot happen because electric vehicles especially in the case of vehicles stop and go traffic, you will stop every now and then and you want to regenerate that power and you want to maximize the battery going for longer.

So we will never use generally semi-controlled converter in any of those applications where we are looking for regeneration. Whereas, we will use normally fully controlled converter if we want to save on cost. If you do not mind you know spending a little bit more money, we will go for something called dual converter.

Student: When we reverse the polarity, and so the net voltage that is being, so that we have armature resistance, so when the current suddenly want to increase…

Professor: When you?

Student: When we change the polarity.

Professor: Polarity. Simultaneously, you will do this also. You will never do it only one. You have to reverse the polarity of this plus make $\alpha>90$ both have to be done simultaneously. Simultaneously. So whatever is the changeover switch which is reversing, his question was, if you only reverse this by chance you have still not done the alpha greater than 90, then they will become additive.

It will become like plugging, what you guys have studied in electrical machines, Reverse current breaking or plugging where you are going to have essentially the machine basically looking at huge amount of voltage coming up because its back EMF comes in addition to whatever is the applied voltage. So you will never do that because if you do that, you will be damaging the machine. So you will normally do both simultaneously. So all these things have to be done with time precision, very clear precision of time.

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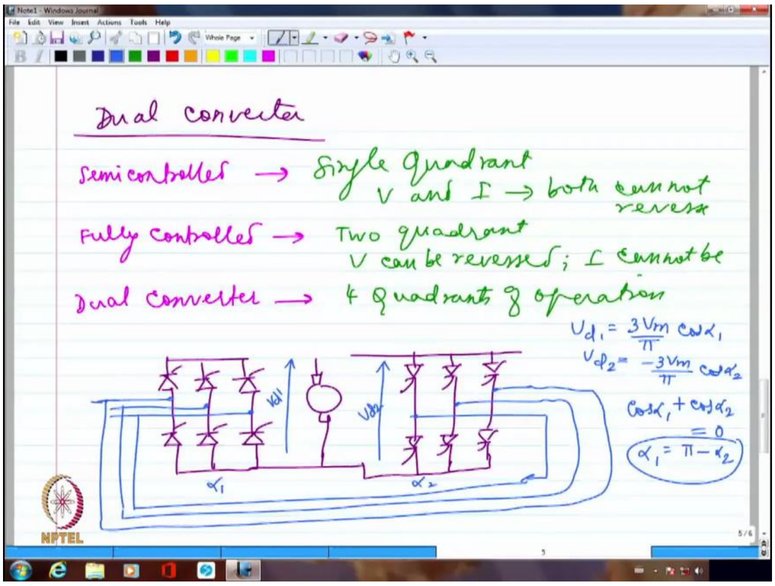

So we talked about so far semi-controlled or half controlled, semi-controlled is definitely not the same as half wave. So semi-controlled is only meant for single quadrant, that is V and I both cannot reverse. Whereas if I talk about fully controlled converter is 2 quadrant operation is possible because I am going to have V can be reversed, I cannot be, Whereas dual converter, what we are going to discuss now. This actually corresponds to all 4 quadrants of operation.

So you can have voltage as well as current, both reversed. So we are actually looking at one fully controlled converter here and another fully controlled converter here. And then I am going to have a three-phase supply. The same three-phase supply will feed this as well. So I can simply draw the three-phase supply and then it is all connected together. I should show it as though this is connected here, this is connected here and this is connected here.

So three-phase supply is the same for both of them. One is in the forward direction, the other one is in the reverse direction. So I am going to have a load connected here. Let me show it as the DC motor, that is it. I have not connected the positive side deliberately because if I am trying to fire both the converter simultaneously. What I want is this voltage whatever comes up here, if I call this as V_{d1} and if I call this as V_{d2}, I want $V_{d1} = V_{d2}$ average value.

If the values are not equal, then if I try to connect them together, I will have a flashover. So I have to have $V_{d1} = V_{d2}$. So, I should say, $Vd1 = \frac{3V_m}{\pi}\, cos\alpha_1$ if I may call this as converter 1 and firing angle α_1, this is converter 2, firing angle α_2. So $Vd2 = -\frac{3V_m}{\pi}\cos\alpha_2$ because I am just specifying V_{d2} in the opposite direction. I am not showing this as plus and this as minus. I am rather showing this as plus and this as minus

I am showing that as the voltage rise. So, it has to be $-\frac{3V_m}{\pi}\cos\alpha_2$. These 2 have to be equal to each other. If I do not want flashover, these 2 have to be equal to each other which means

$$\cos\alpha_1 + \cos\alpha_2 = 0, \text{ This will give me the solution, } \alpha_1 = \pi - \alpha_2.$$

So if I am firing one of them at 70 degrees, I should fire the other one at 110 degrees. That is what it means. So I have to fire both of them simultaneously but at different firing angles.

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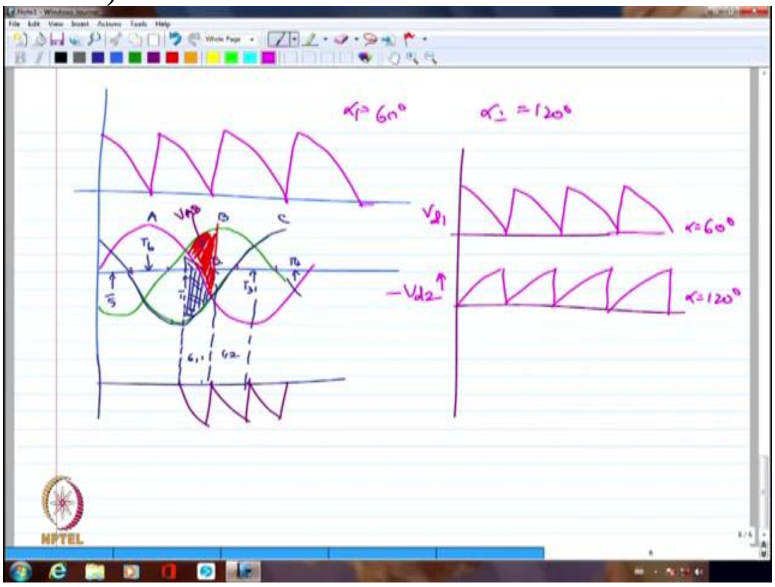

So if I try to do that, for example, let us say I am firing one at α=60, we all now have at least I hope you guys have gotten familiar with this α=60 degree waveform. This is α=60 degree waveform, normally. If α=120, what kind of waveform I have to get, I have to check. Let me draw that also. So α_1 is fired at 60 degrees, so alpha 2 has to be 120 degrees.

So if I try to draw the waveform corresponding to α_2=120 degrees, let me just draw the three-phase waveform again. The frequencies I have drawn are different, does not matter. So I should have drawn with a different color. So these are the three-phase waveforms. So this is A, B, C. Where is α=120? This is 30, this is 30, this is 90, this is 120. So this is where I have to fire 1. That means I have to fire 2 here, 3 here, 4 here and 5 here and 6 here.

This is α=120. So for α=125 if I am firing, here I have to get basically during this portion from here until here, I should be getting 6 and 1 conducting and from here until here, it will be 1 and 2 and so on. When 6 and 1 are conducting, it is V_{AB}. So let me try to see what is the kind of

V_{AB} I am going to have. Here is my A and here is my B. This is A and this is B. B is here, B is higher than A.

B is higher than A because when I am, so this is the kind of voltage I am going to get. This is the voltage I am getting. What I have shown, that is essentially the kind of voltage that I am going to get. And showing V_{AB} between A and B whatever is enclosed, I am just shading that. That is the voltage I am getting, V_{AB} but I am having actually A here and B here. So I am going to have, no, I have done V_{AC}. B is here. So this portion, let me probably just this red one, this is V_{AB}. This is V_{AB}. What I have shaded originally was V_{AC}. That is what I was wondering, How come I am getting positive voltage?

So V_{AB} is negative voltage. B is higher than A. So this is V_{AB}. So V_{AB} is negative voltage. So I am going to get some voltage like this continuously. Please compare that voltage with this voltage. Average value will be the same because I am inverting this. This is reverse, it is connected reverse because V_{d2} is connected with positive terminal to the bottom and negative terminal to the top. So I exactly reverse connection I am making.

So I will have one of the voltages like this, the other voltage, so I can draw the 2 voltages if one of the voltages is like this. This is V_{d1}, the other voltage will be somewhat like this. If I try to draw the same thing, I am going to have something like this. This is $-V_{d2}$ or $+ V_{d2}$. So I am talking about what is the V_{d2} value and what is the V_{d1} value. 2 converters, voltages.

Average values will turn out to be the same. This is for α=60 and this is for α=120. But instantaneously, the voltages are not the same. Look at the value, this is at minimum, that is at maximum. Here, this is at maximum, that is at minimum. So I am not going to have the instantaneous values of voltages of converter 1 and converter 2 to be the same at all. They are different. They are different. So if I try to tie them up directly, there can be a huge current circulating through the two converters.

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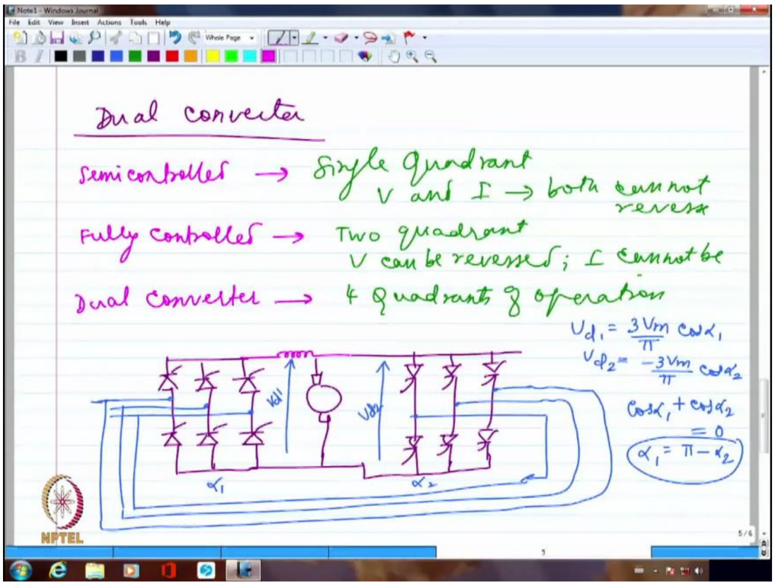

That is the reason why normally I am going to have generally a reactor with a small resistance also. Current limiting reactor, that is what we put so that $\frac{di}{dt}$ is also minimized, inductor is always going to minimize $\frac{di}{dt}$ and the resistance will also minimize the current that is circulating through the entire two converter configurations.