Power Electronics

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Lecture 08 – Three Phase Rectifiers – I

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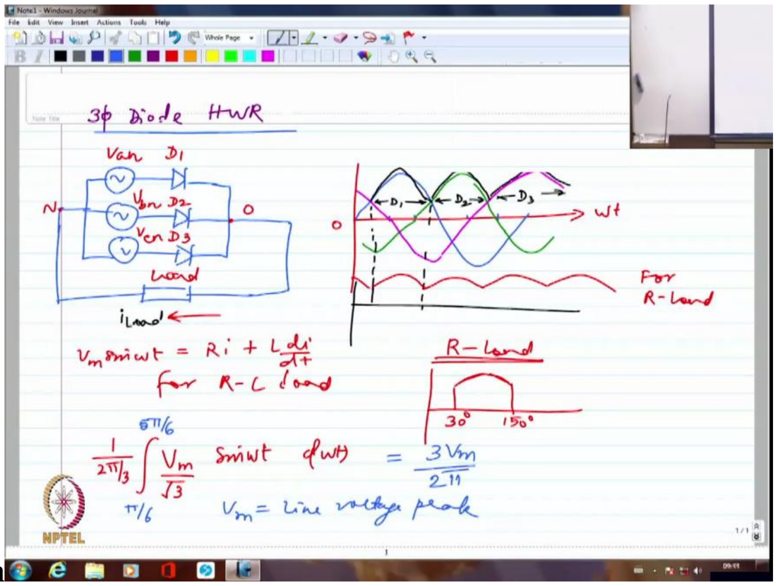

Vm

We said that we will have the three-phase supply A, B, C phases with the neutral and we are going to have 3 diodes which are somewhat like this and we are going to have a load between the neutral and the start point of the 3 diodes ,this is what we said and we had called these three as D_1, D_2 and D_3 respectively, this was V_{an}, this was V_{bn} and this was V_{cn}, we call this point as the neutral point and I may call this as some "O" it does not matter. So, we are going to have essentially the current flowing in this direction, this will be the load current which is unidirectional because either D_1 will conduct or D_2 will conduct or D_3 will conduct depending upon whichever is the most positive voltage at that point in time.

If I say that this is what is my "O" line and this is going to be my A phase; B phase will be phase shifted by 120 degrees like this and C phase is going to be phase shifted by another 120 degrees like this, this is how it is going to be. So whichever is the most positive that will conduct at any point in time, so if I say from here until here and I am just showing it as though it is exactly the same magnitude but I just want to differentiate between the blue colour, green colour and the black colour what I am drawing. That is the reason I am just drawing it as though they are two lines. So, this is how the load voltages are going to be and we said that normally I am going to have D_1 conducting from here to here, D_2 conducting from here to here and D_3

conducting from this point to this point, so each of them is going to conduct only for 120 degrees.

And if I assume that it is resistive load, I will essentially have the load current or like if I call this as i_{Load} , so i_{Load} is going to look somewhat like this. So, I have to just take this point here and this point here, so I will have essentially the load current showing up like this. This is how the current will be for R load, this is going to be for R load. Whereas if I am looking at R L load, only difference will be the peak will not coincide exactly with whatever is the peak of the previous one, so it is probably going to be shifted slightly, but by the time it is changing over from D_1 to D_2 it also depends upon what is the voltage across the resistance because we actually have to write the equation again ,

$$\frac{V_m}{\sqrt{3}} sin\ \omega t = Ri + L\frac{di}{dt}$$, for R L load

So, I have to look at whether L $\frac{di}{dt}$ will have to pitch in along with $\frac{V_m}{\sqrt{3}} sin\omega t$ to meet the needs of Ri. So if Ri happens to be higher at this point where it is supposed to switch over from D_1 to D_2, if by chance Ri happens to be higher, I am definitely going to have probably the D_2, the other one will not be taking over completely so I may have actually further the inductance forward biasing the outgoing device. So, we derive the expression for the voltage when we were talking about R load, when we talked about R load we basically looked at the voltage something like this, it actually went about like this, this is how the voltage was. So, if I look at this point, if I say this is ωt and this is 0, so this point is 30 degrees and this point happens to be 150 degrees because each of the devices conduct for 120 degrees. So, I am going to have essentially 120 degree conduction for each of those and that is the reason we wrote actually,

$$\frac{1}{2\pi/3} \int_{\pi/6}^{5\pi/6} \frac{V_m}{\sqrt{3}}\ sin\omega t\ d(\omega t) = \frac{3V_m}{2\pi},$$ V_m is the line voltage peak or line to line voltage peak, so this will be the expression for three-phase half wave rectifier with diodes.

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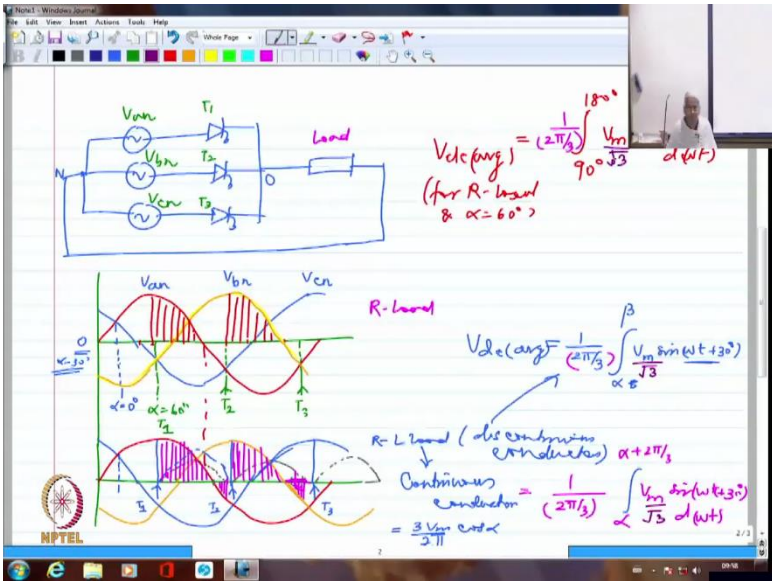

Now let us try to go for halfwave controlled rectifier, so I am going to have three-phase voltages somewhat like this and I am going to have one device here, second device here and third device here, this is the neutral point and here is the load, so this is the load and I am going to have this as the connection between these two, this point is "O". So, I would name these devices as T_1, T_2 and T_3, so this is V_{an}, V_{bn} and V_{cn} these are the 3 phase voltages. So, I should realise that had it been a diode, we had shown the conduction would start exactly at this point which is actually at 30 degrees, it is not at zero crossing of V_{an}, it is rather at 30 degree point of V_{an}. So, I should always calculate the delay angle with reference to where the diode would have conducted.

If the device had been diode where it would have conducted that happens to be delay angle equal to 0, so the reference will always become with respect to, we calculate it always with respect to diode. If the device had been a diode it is exactly starting at this point which is corresponding to ωt =30. If I say at my $\omega t = 0$ my sinusoidal voltage corresponding to A phase is having its 0 crossing. So, when I actually draw the waveform for this corresponding to α=30 or α=60, how do I specify that? I am just trying to emphasise that. So if this is one of the phase voltages so these are the 60 degree points and I am going to have the second phase somewhat like this which is very light, maybe I will at least use orange that may be better, and the third phase is here, this is how it is, all the 3 phases are here.

Now let me call this as V_{an}, this is V_{bn}, this is V_{cn} and this point I am specifying as α=0 degrees because that is the point at which D_1 must have conducted. Instead of T_1 if I replace that by D_1, it would have conducted at that point, so I am calling this as $\alpha = 0$, so I should calculate all my delay angles with respect to this particular reference. So, if I am talking about $\alpha = 60$ for example, this is what is $\alpha = 60$ because this is exactly 60 degrees away, so I should say this is $\alpha = 60$ and T_1 will be fired at this point if I want the delay angle to be 60 degrees. Again, the delay angle is incorporated to reduce the voltage, what I would get as the voltage, let us see how it gets decreased, so this is going to be $\alpha = 60$.

So, if I fire T_1 here, 120 degrees away from this I have to fire T_2 for symmetry because V_{an}, V_{bn}, and V_{cn} are phase shifted from each other by 120 degrees, so I necessarily need to, this is 30 degrees, this is 60, this is another 30. So here is where I have to fire T_2 and here is where I have to fire T_3, this is how I have to fire each of the devices. So, I have to go exactly by 120 degrees interval. And in this case that is why in three-phase converter, we will not give a firing pulse whose width is 180 rather we will give only 120 because we would not like to give the firing pulses to two devices simultaneously, we would generally like to give only one device at a time and T_1 will be given for 120 degrees, T_2 will be given for 120 degrees, T_3 will be given for 120 degrees with high frequency ANDing and pulse transformer, pulse amplification everything, the same kind of circuit will be adopted pulse width is 120 degrees, that is all is the difference.

So let us say, I am firing this at this point, so until now what was conducting I do not know but the moment I fire this, hopefully they should start conducting because I am in the positive half of Va, so I should be able to get forward biased, so it will continue definitely until this point for sure. After that hopefully we should have taken over provided it had gotten firing pulse, but I have not given the firing pulse to T_2 until here. I am giving the firing pulse to T_2 only until, only at this point. So, until here if nothing else is conducting between the neutral and “O”, between the two if I try to look at the voltages normally I am going to have this particular device T_1 forward biased definitely until here, so I should have this entire voltage coming up. But note that voltage is only for 90 degrees, it started with a peak and it has come until the zero crossing. So obviously it is there only for 90 degrees, we said that it has to conduct for 120 degrees, but it will not if I am talking about the resistive load.

So if I am talking about resistive load because the voltages and currents will be in phase with each other, the voltage hits zero at this point and after that the voltage will come out to be negative, obviously I cannot have current in the opposite direction, the device will not conduct in the opposite direction so at this point the conduction will cease to exist, it is stop at this point. So, I am going to have the next one which is again coming up, we will start coming up from here and again I am going to have this entire voltage coming up.

Student: Why using thyristor and changing the firing angle, is the current discontinuous?

Professor: I want to reduce the voltage, for some reason I want to control voltage. If I fire it at α=0, I could have used diode itself, why should I use thyristor? I use thyristor only because I want to have a control over the voltage. So now I am getting only for 90 degrees. So, when I actually calculate the expression or compute the voltage,

$$V_{dc(avg)} = \frac{1}{2\pi/3}\int_{90^\circ}^{180^\circ} \frac{V_m}{\sqrt{3}} \sin\omega t \, d\omega t \text{ (for R-load \& } \alpha=60^\circ)$$

Student: What if we have to give gate pulse at say α = 40°?

Professor: Yes, if you give gate pulse at 40 degrees it would have started conducting, this is α=30, this is α=40 slightly away, so it would have started conducting from here, so in which case this expression would also have changed. It would have started from 40 but whether it would continue beyond this we have to check, we would have given the firing pulse for b also somewhere here. So, until here device number one would have conducted, from here device number 2 would have taken over.

Student: Why we have given it as α=60?

Professor: I have just taken an arbitrary case, as simple as that. I am only taking an arbitrary case where I am showing the voltage to be discontinuous, voltage is also discontinuous, current is also discontinuous for R load, when I exceed probably α = 40, 50, how much? If I try to exceed probably this is 60, I hope I have not made any mistake, this is 60. So, this happens to be discontinuous. Only until 30 I will still have continuous because 30 means it would have started at this point and it would have come until here 120 degrees, again the next voltage would have started here it would have continued, it is just touching 0, it will just touch 0, anything beyond 30 degrees α will be discontinuous for R load.

We are talking about R load, we will have to look at how R L load is. So now averaging still I have to do it over 2π/3, please remember this because I am not getting any voltage, alright but every device is fired only for 2π/3 interval, so obviously I cannot average it over any other quantity, I have to average it over 120 degrees because every 120 degrees this particular pulse is being repeated. So, I have to average it over $\frac{1}{2\pi/3}$. So, this is what will be the value of voltage at this particular value of α that is at 60 degrees. So, at α=60 degrees for R load this is how it will be. Let us try to take a look at, current is very simple, current will be exactly the voltage wave shape because it is V/R that is it nothing more than that.

Let us try to look at it for RL load so this is for R load, let us try to look at it for R L load. So, let me again draw the three-phase voltages. So, this is how it is going to be, I am going to have the second voltage somewhat like this and third voltage somewhat like this. These are the three-phase voltages, I am firing again at α = 60°, I am taking as though we are firing at α = 60. So, this is α=0; so from here this is 30, this is 60 so I am going to fire at this point, this point and this point respectively. So here is where T_1 is fired, here is where T_2 is fired and here is where T_3 is fired. So, I am going to have initially if I look at the current, the current probably would start up from here in whatever way it rises depending upon R and L values, the current will start rising like this.

And at whatever point Ri = $\frac{V_m}{\sqrt{3}}\ sin\omega t$, if I say this itself is Ri for example, i and iR will be exactly similar only a scaling factor. So, if iR meets with the voltage at this point that is where the peak of the current will occur, so the current is going to start coming down. So if it comes down until here as shown as though the current is coming down until here, obviously the next phase current would start again similarly and it might reach the peak somewhere here and then come down until here Similarly I may have the third phase current rising and then coming down like this, so I have just shown the three-phase current. Please note that because inductance is there, even beyond the negative even beyond 180 degrees of V_{an}, the current could continue depending upon how much of energy is stored in the inductance.

So, I will have the device basically conducting even beyond the 180 degree point of the voltage which means that $\frac{V_m}{\sqrt{3}} sin\ \omega t$ corresponding to V_{an} will be connected to the load until this point until the 0 of the current. So, I am going to have essentially the voltage coming up until this point, all this voltage will come up completely. So similarly, I will have all this voltage until this point. So, all this voltage should come up. So, this particular point at what point the current becomes 0 I have to solve by the differential equation, there is no other way.

So, I can write in this case, the current is, $I_a(\alpha = 0)$ is the initial condition and β can be solved for again after deriving the complete expression for Ia or I, I should say in that I, if I say $I_a(\beta = 0)$, β can be solved for. That β is the final point where the current again becomes 0, it starts with 0, ends with 0. If I had larger inductance then I would have had the current probably go to even higher values and then I would probably see that it ends beyond if at all I allow it to end, it would have ended beyond where the next device is fired. In which case I will not have 0 point at all in the current, the current is going to be always non-zero. If I have a larger inductance, I would have had the voltage negative, portion of the voltage coming up until here, again it would have jumped to positive then again negative, positive, negative and so on.

So, if I say this is for R L load, I can have discontinuous conduction in which case my output voltage will be,

$$V_{dc(avg)} = \frac{1}{2\pi/3}\int_{\alpha}^{\beta} \frac{V_m}{\sqrt{3}} \sin(\omega t + 30)\, d\omega t$$

where V_m is the peak of line voltage.

I have to integrate between α to β and if I write this is $\frac{V_m}{\sqrt{3}}\ sin\omega t$ it is not correct. $\omega t =$ 0 corresponds to α=-30, so when I put the limits, I better be careful. I want to emphasise this, if I say α to β is my limit for the voltages, please note this is $\omega t = 0$ whereas α=0 is at this point, so this happens to be α=-30 .That point happens to be α-30, $\omega t = 0$ is same as α-30, so if I am saying actually from α to β. I am integrating the voltage, I am integrating V_{an} so V_{an} I cannot specify as $\frac{V_m}{\sqrt{3}} sin\omega t$ now, I have to write it as $\frac{V_m}{\sqrt{3}}\ \sin(\omega t + 30)$. I have to write it properly because there I am taking this as 0, or if you want to put it as ωt , I put this as α+30, you put it that way otherwise.

Student: Even β is defined with same as α.

Professor: So that is the reason why I would rather like to make the change here rather than making the change there. So, specify V_{an}, V_{bn}, V_{cn} properly with respect to α if I am taking the limit with respect to α. So, α = 0 is $\omega t = 30$ already, so that is the reason why I am twisting this expression a little bit because I would say it becomes $\omega t + 30$. If I try to look at α = 0 what is the value of this? It is $sin\ 30$ already, so it is not $sin\omega t$ where $\omega t = 0$, it is rather $\omega t + 30$ that is how we get it basically.

If it is continuous conduction, if I am going to have continuous conduction in RL load then I am going to have,

$$V_{dc(avg)} = \frac{1}{2\pi/3}\int_{\alpha}^{\alpha+2\pi/3}\frac{V_m}{\sqrt{3}}\sin(\omega t+30)\,d\omega t = \frac{3V_m}{2\pi}\cos\alpha$$

Student: Is the DC average expression only valid for $\alpha = 60$?

I have just specified Alpha, forget about any Alpha. So, I am going from α to β, let α be 40 degrees, 30 degrees, 50 degrees, 60 degrees, 70 degrees it does not matter but I am going from this to β. So, I am generalising it, I am deriving a generalised expression. I would like to again point out that α=60 we started deriving from 90, please remember the limits we set from 90. So that is why I said you could have set this as α+30 that is also fine, but this also then should be adjusted as β +30 because β is you are looking at it from α's point of view or $\omega t's$ point of view, better adjust that as well.

Student: V_m is peak of phase voltage or line voltage? (29:18)

Professor: V_m will be line voltage, everywhere we are taking that to be line voltage because you will normally get something like 30 degrees. So, Cos 30 is $\sqrt{3}/2$, so $\sqrt{3}$ will come and automatically that $\sqrt{3}$ and this $\sqrt{3}$ will get cancelled.

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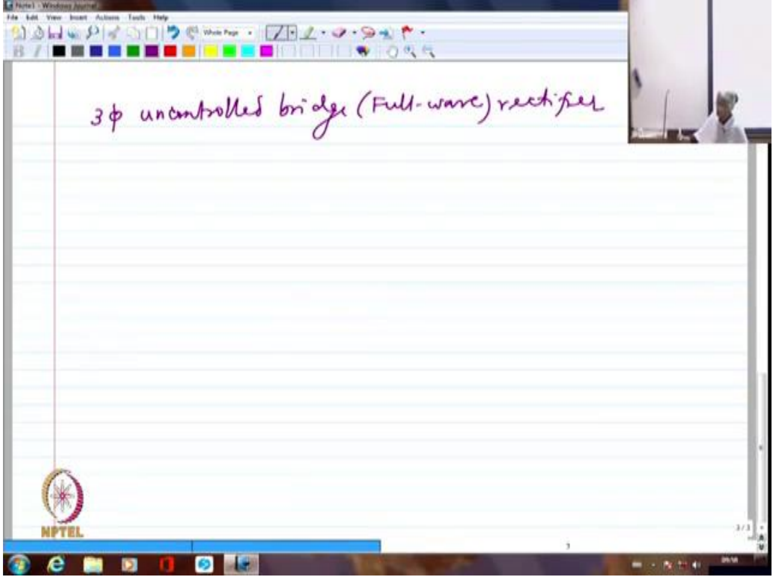

Now we are going to come to three-phase uncontrolled bridge full wave rectifier. Bridge has to be full wave, that is why that is redundant.

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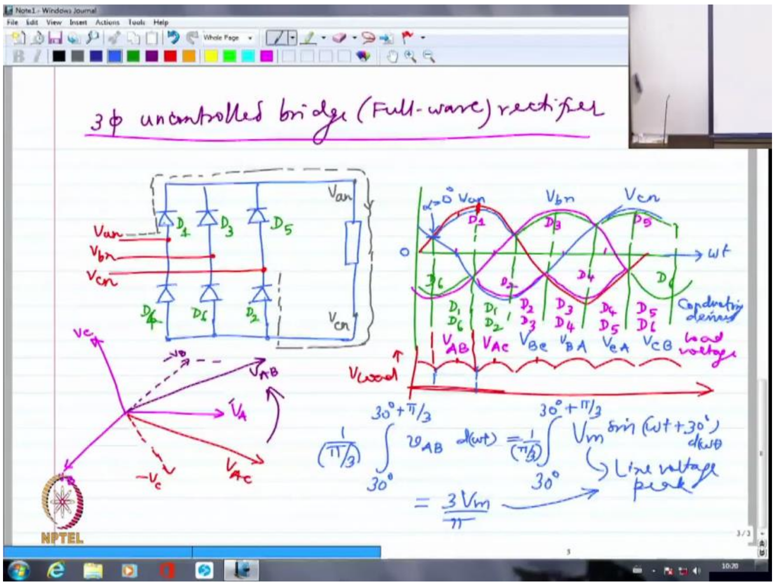

So let us try to look at three-phase uncontrolled bridge rectifier, uncontrolled six diodes are going to be used that is what it means. All of them are uncontrollable devices, they are going to conduct as soon as they are forward biased. So, these are the six devices, so this is going to be the load that is connected here, I am not going to number the devices right now because we will look at the conduction sequence and then number them. And then we are going to have one phase connected here, second phase connected here, and third phase connected here. I am not even showing the source. Assume that I am going to apply V_{an}, V_{bn} and V_{cn} here, let me draw the waves for the three-phase voltages.

So, let us say this is R, this is Y and this is B, so three-phase voltages I have drawn. So, let me name them also clearly V_{an}, V_{bn} and V_{cn}. Obviously, in the case of diode whichever is most positive that is going to conduct as far as the upper 3 diodes are concerned, whichever is most negative because the cathodes are connected to corresponding voltages, whichever is most negative at any instant of time that particular diode will conduct at that point in time. And please remember, I need at least one diode from the positive side and one diode from the negative side to conduct at a time so that there is a current, otherwise I will not have continuous current.

For example, if I assume that the current is flowing from here, it will flow through this, it will flow through this, it has to flow through the load, load direction is like this up to down and it might return through this which is C phase or it might return through this which is B phase. So, I need necessarily one diode from the upper side and one diode from the lower side from some other leg not in the same leg, some other leg to complete the path for the current, otherwise it will not work properly. So the voltage that is coming up in this particular case will be V_A will be connected at the top and V_C will be connected at the bottom, so I will have V_{AC}, if I say that this is V_{cn} connected here, this is V_{an} connected here when I have shown a path like this, what is coming up with V_{ac}?

Line to line voltages come across the load when I use a bridge rectifier, so bridge rectifier will give me definitely larger amount of output not just because both positive halves and negative halves will be transported but also because line voltages appear rather than phase voltages appearing across the load. So, let us try to take a look at the conduction sequence, so whenever I am going to have this voltage V_{an} dominating over any other voltage, for that duration A phase positive device will conduct. Let me name this as D_1. After that in the positive I am going to have this one conducting and after that in the positive this one will conduct. So, I know for sure that I am starting with $\omega t = 0$, at that point A is not the most positive, but A becomes the most positive 30 degrees away from that.

So, I assume that the diode corresponding to A phase positive is D_1, but D_1 cannot conduct alone, along with D_1 something else has to conduct so that something else is a negative device clearly. So I am going to call, if I call that this is D_1's conduction I would call this as D_2's conduction, I will call this as D_3's conduction, I would call this portion as D_4, I will call this portion as D_5, and I would call this portion whatever conducts as D_6 which is same as this D_6. I am essentially numbering the devices in the sequence at which they take over, so let us say D_1 takes over here, D_1 will be able to conduct for some time with D_6, sometimes with D_2. So, D_2 corresponds to C phase is negative, C phase is here, and this is B phase is negative I am calling that as D_6.

Then B phase takes over which is D_3 is D_6, this is D_4. So please note that I have written 135 for the positive leg's odd number and 426 for the negative devices which are even numbers and they have been exactly numbered in the same sequence of conduction as they will take over when they are diodes, they are uncontrolled devices. So, if I try to write what devices conduct at what time, let me divide this into every 60 degree interval, I have just divided them into 60 degree intervals. So here D_1 and D_6 conduct, here D_1 and D_2 conduct, here D_2 and D_3 will conduct, here D_3 and D_4 will conduct and here I am going to have D_4 and D_5 conducting, here D_5 and D_6 conducting and then again D_6 and D_1 which is the first interval. This is how they are going to conduct.

And by observing this you can directly say what line voltage will appear. D_1 belongs to A phase, D_6 belongs to B phase, so I should have V_{AB} appearing here. Here D_1 is A phase, D_2 is C phase, V_{AC} will appear, this will be V_{BC}. 3 belongs to B phase, 2 belongs to C phase, negative, so V_{BC}. And this has to be V_{BA} and this has to be V_{CA} and this has to be V_{CB}, this is how it will be. What I am writing here are the load voltages, so this is conducting devices, and this is going to be load voltage, and if you have to draw the waveform for the load voltages right, this is V_{an}, I hope you guys remember the phasor diagram. This is V_A, this is V_B, this is V_C. This is how we draw for phase voltages in the phasor diagram.

If I want V_{AB}, I have to take B on the other side, so it becomes $-V_B$. V_A and V_B added together, $-V_B$ added together is going to give me this as V_{AB}. V_A is first, then V_B comes, then V_C comes. So V_{AB} will lead V_{an} by 30 degrees. From the phasor diagram you can say that directly. Similarly, V_{AC} will lag V_{an} by 30 degrees, V_{AB} will lead V_{an} by 30 degrees.

So, if I say that this is what is V_{AB}, this portion is V_{AB}, V_{an} peak is reached at this point, V_{an} peak is reached at this point. This is the point at which V_{an} is reaching the peak, so V_{AB} should have reached the peak 30 degrees ahead because V_{AB} is leading. So, if V_{an} is reaching its peak at this point, V_{AB} should have reached its peak somewhere here even 30 degrees ahead, so somewhere in the middle of this I should have V_{AB}'s peak, somewhere in the middle of this I should have V_{AC}'s peak, somewhere here V_{BC}'s peak. So, this will be the waveform what I would get for the DC voltage of the load. What is the kind of DC voltage I get across the load it will be somewhat like this, I am trying to say that this is the point at which V_{an} reaches its peak, 30 degrees ahead V_{AB} should have reached the peak.

V_{AB} definitely has to be having a higher value than $\sqrt{3}\ V_{an}$, no doubt but I am basically saying that this is how the wave shape will look. So, this is V_{load}, this is without any control on the fully controlled rectifier, not full bridge rectifier, it is not controlled, it is uncontrolled full bridge rectifier. Three-phase bridge with diode will deliver this kind of a voltage if I am just having whatever kind of load it does not matter, I am going to get a voltage like this. Now let us try to get the expression, so I have to integrate from this point to this point right and I have to integrate $V_{AB}\ Sin\omega t$, whatever V_{AB}, so let me integrate from this point to this point V_{AB} $d\omega t$, that is what I need to do.

And as per this I may be able to say this is from 30 degree to $(30° + \frac{\pi}{3})$ because every 60 degree which is repeating itself please understand, 6 and 1 conducts for 60 degrees, 1 and 2 conducts for 60 degrees, 2 and 3 conducts for 60 degrees, 3 and 4 conducts for 60 degrees, 4 and 5, and 5 and 6 all of them conduct individually for 60 degrees each the pair, the pair conducts for 60 degrees. But if you look at the individual devices, 1 will join hand with 6, 1 will join hand with 2, so it will conduct for 120 degrees, 60 plus 60. 2 will join hands with 3, 2 will also join hands with 1, so it will essentially conduct for 120 degrees. Every device will conduct for 120 degrees individually, every pair conducts for 60 degrees, a particular combination conducts for 60 degrees.

So I should say this line voltage what is getting repeated as far as the magnitude is concerned, it will be the same whether I look at it here, , it does not matter because line to line voltage peak is the same and it is 30 degrees this side, 30 degrees this side of the peak. So, if I try to integrate V_{AB} it should be integrated if I assume this is ωt and this is ωt=0 point. It is starting from 30 degrees and it is going until 30 degrees plus 60 degrees which is 90, so 60 I have written as $\frac{\pi}{3}$ that is all, and it has to be averaged over $\pi/3$, this is what is my output voltage. If I say that V_{an} zero crossing is $\omega t = 0$, V_{an} zero crossing happens to be at $\omega t = 0$, how should I specify V_{AB}? V_{AB} is 30 degrees leading, so I should write that as $V_m sin(\omega t + 30)$. Output voltage is,

$$V_{load} = \frac{1}{\pi/3}\int_{30°}^{30°+\pi/3} v_{AB} d(\omega t) = \frac{1}{\pi/3}\int_{30°}^{30°+\pi/3} V_m \sin(\omega t + 30°)\,(d\omega t) = \frac{3V_m}{\pi},$$

V_m is line voltage peak. We are looking at V_{AB} being integrated, if I had taken V_{AC} being integrated, I should have started from what angle? This is 60, this is 30 so I should have started from 90, 90 to 150 that is what I should have integrated. But I should have written V_{AC} as V_m Sin $(\omega t - 30)$ because it is lagging behind V_{AN} by 30 degrees. If I am integrating V_{AB}, I better write plus 30 because it is leading V_{AN} whereas, if I write V_{AC} I better write $\omega t - 30$ because it is lagging behind by 30 degrees. So when you choose the limits and when you write a specific voltage, please be aware and sure what you are writing, what you are taking as the reference 0 and how do you specify each of the voltage waveform with reference to that 0, you have to be really thorough with that.

So, for that at least for me phasor diagram helps always, I always draw the phasor diagrams to understand which is leading, which is lagging, so that helps me really. And if I have to for example, look at the phase shift between these two, very easy to see it is 60 degrees, very easy.

So when you draw the phasor diagram it becomes much simpler normally. If you try to now integrate this, this will give simply $\frac{3V_m}{\pi}$ where V_m is the line voltage peak. For half wave rectifier it would have given you $\frac{3V_m}{2\pi}$, so this is $\frac{3V_m}{\pi}$, V_m being line voltage peak again. So, if I have all of them as diodes, again this is my α=0 point, later on when I put the controlled rectifier, I will always take this as α=0 degree point because that is where my D_1 is taking over naturally.

If I want diode to take over naturally, at what point it is getting forward biased that is what I have to check. So, I am going to get α=0 normally as the point again same as what we saw in the half wave rectifier. It is exactly 30 degree away from the zero-crossing point of V_{an}. Before we progress to fully controlled three-phase rectifier, let us try to compare slightly the single-phase case and the three-phase case.

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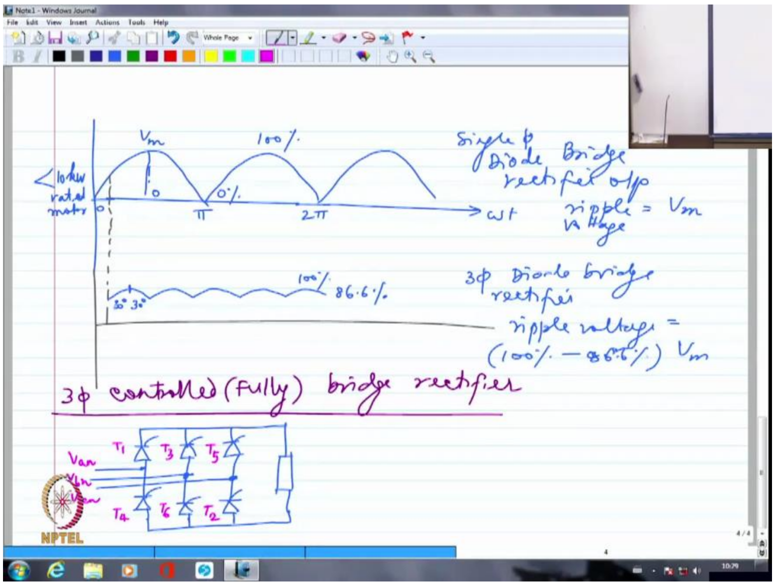

In single phase case when we drew the voltage waveform, it was something like this, it would go from the peak until zero like this, this is how it was in single phase case when I had just diode, full bridge diode rectifier which is uncontrolled. So, this is single phase diode bridge rectifier output, so this was ωt and this was π, this was 2π and this was 0, that is how it was. And the peak was like V_m and the minimum value was 0. So, the ripple in the voltage could go from 0 to V_m completely, uncontrolled I am talking about. If it is controlled, it can go to negative also that is what we talked about. So here the ripple happens to be just 0 to V_m which is quite a large value. So, if I apply this 2 for example at DC motor, although I will pacify the DC motor by telling it that I am applying $2V_m/\pi$ average voltage, the motor will groan because you are giving it oscillating voltage, the current will oscillate.

If the current oscillates, I am definitely going to have the torque oscillating, I hope you understand, the torque oscillates the speed will also oscillate, the shaft will vibrate. So, there will be a huge amount of ripple in the current, ripple in the torque, ripple in the speed, everything will lead to huge amount of vibration and noise. So single phase rectifiers are hardly ever used in a DC motor drive of very large capacity because of this reason. If it is a large capacity drive, the vibrations normally will not be tolerated so much if there is a small crack in the shaft; you know in a paper mill or textile mill or in a tire producing industry they are not going to tolerate even small vibration.

You will not buy such a cloth which comes out of the textile industry which is having all vibrations, so single phase rectifiers are known to have a huge amount of voltage ripples, current ripples, torque ripples, speed ripples, vibrations, noise and so on; so they are not generally utilised for large capacity DC motor drives. Maybe 5 kilowatt, 2 kilowatt, it is all because it may not be a very crucial industry as simple as that, but if it is a large motor for example, you think about a train, Madras still, one of the suburban train service runs with single phase rectifier, controlled rectifier but they put a large capacitor and so on, that is how they manage.

But whenever you are thinking of large capacity drives, if on the other hand if you look at the three-phase just now we drew it, so it started from about 30 degree point, the voltage waveform started from about 30 degree point and it went up to 90, so it was something like this, this is how it was, 6 such pulses within one single cycle because every pulse corresponded to 60 degrees .So, I am going to have essentially pulses like this, so this is the peak and the entire thing is 60 degree which means this is 30 degree and this will be another 30 degree. On either side there is 30 degree from the peak, the peak corresponds to 90 degrees which is $sin\ 90$ which is 1.

On one side it will be $sin\ 60$, the other side it will be $sin\ 120$, $sin\ 60 = \frac{\sqrt{3}}{2}$, so the ripple will be only from root $\frac{\sqrt{3}}{2}V_m$, $\frac{\sqrt{3}}{2}$ is 86.6 percent, so the ripple is going to be from 86.6% to 100 %, whereas the ripple here is from 0% to 100%. What I mean is ripple, what I mean by ripple is what is the maximum and minimum, the difference between the two that is called as the ripple that is present in any DC voltage. From a battery it will be steady, the ripple is literally 0, there is no ripple at all, where as if it is from a rectifier there is bound to be ripple. And when I have ripple, the minimum the ripple is, it will be closely you know emulating or copying a DC voltage.

So, I would like to have as much as possible you know a steady DC, and at least close to a steady DC. So, this is essentially the output of a three-phase diode bridge rectifier. So, here ripple is equal to V_m ripple voltage, so here I am going to have,

$$\text{ripple voltage} = (100\% - 86.6\%)\ V_m.$$

So, in that sense I will have my three-phase diode bridge rectifier almost copying a DC voltage pretty much. So, this is definitely much more suitable for running a DC motor drive as compared to what I would do with a single-phase rectifier. So generally, this is always used for less than 10 kilowatt rated motor, it is never used rather for beyond 10 kilowatts. Whereas, three-phase may be used in many cases where I have very large capacity drives like 500 kW, 700 kW, such motors are also run with the help of three-phase rectifier.

Now let us go over to three-phase controlled rather fully controlled bridge rectifier. So obviously I am going to use 6 thyristors, all of them will be thyristors. If I use 3 thyristors and 3 diodes then I will call them as semi-controlled, we will look at that as well but first we will start off with fully controlled. So, I am going to have a circuit somewhat like this. So, this is A phase, this is B phase, and this is C phase; so this is V_{an}, V_{bn}, V_{cn} and I am going to call this as T_1, T_3, T_5 and T_4 you always add 3 that is it, T_6 or subtract 3. If I have 1 at the top, I will have 4 at the bottom, if I have 3 at the top 6 at the bottom, and 5 at the top 2 at the bottom. So, this is going to be the configuration of a fully controlled bridge rectifier three-phase. Obviously here also the current will flow from up to down and I will like to have a control over the output voltage, so I might like to vary the firing angle.