Power Electronics
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Lecture 12 - Commutation Overlap-II and AC-AC Converter-Introduction

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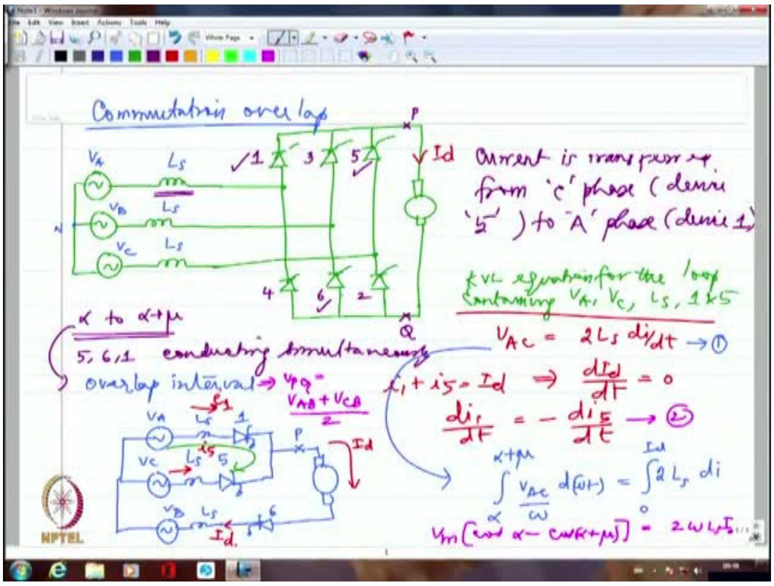

Commutation overlap

Current is transferred from 'C' phase (device '5') to 'A' phase (device 1)

KVL equation for the loop containing V_A, V_C, L_s, 1 & 5

$V_{AC} = 2L_s\, di/dt \rightarrow$ ①

$i_1 + i_5 = I_d \Rightarrow \frac{dI_d}{dt} = 0$

$\frac{di_1}{dt} = -\frac{di_5}{dt} \rightarrow$ ②

$\int_{\alpha}^{\alpha+\mu} \frac{V_{AC}}{\omega}\, d(\omega t) = \int_0^{I_d} 2L_s\, di$

$V_m[\cos\alpha - \cos(\alpha+\mu)] = 2\omega L_s I$

α to $\alpha+\mu$

5, 6, 1 conducting simultaneously

overlap interval $\rightarrow V_{PQ} = \frac{V_{AB}+V_{CB}}{2}$

I had started on commutation overlap. So, I said that this will come into picture when the source inductance is not negligible. If I am going to have a perceivable value of source inductance and if the current is continuous if the current is not continuous, then also there is no question of the current getting transferred from one phase to another, right? So, we are looking at two things simultaneously. One is the DC link current has to be continuous. For every 60 degrees it should not touch down to zero.

And the second thing is that the source side inductances of perceivable value. So what we actually drew out something like this, I have a three-phase sources maybe coming up from the grid, maybe I use a transformer to step it down and the transformer's leakage reactance I am representing in the form of source inductances, I am neglecting the resistance because that does not play a vital role in making sure that the current continues.

So, this is the source inductance value, I am assuming that all are balanced, so I am assuming them to be L_s and this is and this is V_B and this is V_C with respect to the neutral of course, this is the neutral supply-side neutral. Right, now this is connected to the fully controlled converter. So, I am showing as though there are three sets of devices, it could be diode even then you will see commutation overlap but I am just taking thyristor, that is it. And we are going to have a load on this side which has to be at least RL because the current has to be continuous. Let me probably show it as a DC motor drive, it does not matter because that is also equivalent to having RL and E, all three of them in series.

Now this is A phase connection, this is the B phase connection, and this is the C phase correction. Let me write down the same numbers as what we write down normally 1, 3, 5 and 4, 6, and 2. And I call this point as P and this point as Q if you may recall. And we were talking about the current getting transferred from device number 5 to device number 1 because I am firing one at a firing angle of α. So, the current is getting transferred from C phase or device 5 through A phase which is actually device 1, this is what we said.

So when it is getting transferred we said that as long as we did not consider the source inductance, abruptly the current could get transferred, that is what happened earlier. But now the current cannot get transferred abruptly because L_s will not give up the current. It has some stored energy, it is not going to be able to give up the current. And if it is not giving up the current, we are going to have both 5 and 1 conducting simultaneously as far as the positive side is concerned. And in the negative side of course, I have assumed that 6 is already continuing to conduct.

So initially the combination was 5, 6, now the combination should have been 6, 1 but because 5 and 1 are conducting simultaneously I am going to have all three devices conducting simultaneously. So, I am going to have from α to $\alpha + \mu$, this is the duration I am going to have 5, 6, 1 conducting simultaneously. And we call this interval this interval is called the overlap interval because I am having an overlap between A phase and C phase which I should not have had if the source inductance effect was not perceivable. So, this is what is the overlap interval.

So, we first of all drew the diagram which is the equivalent circuit. If you may recall, we first drew V_A, we drew L_s and then we drew as though 1 is conducting. Similarly, we had V_C we had L_s and we had 5 conducting. Both of them together is connecting to point P. And then we drew this load and then from here we drew the reverse conducting that is this device which is device number 6 and then we had L_s and then we had V_B and this is how the current was flowing. So if I try to draw the current flow, this is the current flow direction and this is going to be I_d or DC link current whatever is being carried and this is going to be again I_d.

So obviously there is no variation in this DC link current assuming that may be the motor drive is operating at a particular torque value, so the armature current will not change. So, I am going to have I_d to be a constant. So, I can say I_1 if I may call this as i_1 and this as i5, I should say $i_1 + i_5 = I_d$ and we also said because $\frac{dI_d}{dt} = 0$ we are going to have, $\frac{di_1}{dt} = -\frac{di_5}{dt}$ Right, we wrote a few relationships, so I am trying to recall those things. One more thing we wrote was to actually draw the KVL equation here, this was the KVL equation that we wrote from which if you may recall we got, so KVL equation for the loop containing V_A, V_C, L_S and then 1 and 5, we wrote that as well and then that actually resulted in

$$V_{AC} = 2L_s \frac{di}{dt} \tag{1}$$

This is one more thing we wrote. V_A-V_C we wrote and then $L_s \frac{di_1}{dt}$, the other one was $L_s \frac{di_5}{dt}$ and because

$$\frac{di_1}{dt} = -\frac{di_5}{dt} \tag{2}$$

we wrote that as $V_{AC} = 2L_s \frac{di}{dt}$, this is what we wrote.

From which we also said from here we wrote that

$$\int_{\alpha}^{\alpha+\mu} \frac{V_{AC}}{\omega} d\omega t = \int_{0}^{I_d} 2L_s di$$

Because at α I fired device number 1 and until $\alpha + \mu$ I had both the devices conducting simultaneously. So, this is equal to, we wrote this as 2 multiplied by L_S multiplied by *di* and of course we had to divide this by ω because we wanted to do it *dωt* rather than *dt*. And I should have integrated this from zero to I_d because the current was increasing from zero and it reached I_d this is what we wrote.

So, we wrote, so this is one equation which is of importance. This is another equation which is of importance and the third equation what we got from here was that V_{AC} we could have written as $V_m \sin \omega t$ because α is our reference so V_{AC} zero crossing is our reference, that is why we are able to integrate α to $\alpha + \mu$. So, we wrote this as

$$V_m \left[\cos \alpha - \cos(\alpha + \mu)\right] = 2\omega L_s I_d \tag{3}$$

I think we wrote what is V_{PQ} during the overlapping interval. So, we calculated first of all what is V_P, so V_{PQ} we wrote which is the DC link voltage, we wrote as

$$V_{PQ} = \left(\frac{V_{AB} + V_{CB}}{2}\right)$$

$\left(\frac{V_{AB} + V_{CB}}{2}\right)$ is the average of just 5, 1, 6 conducting and 6 and 1 conducting and then their average we took, and this is what we called as the DC link voltage. And we also got the expression for the difference in the DC link voltages between when there is no overlap and when there is overlap, right.

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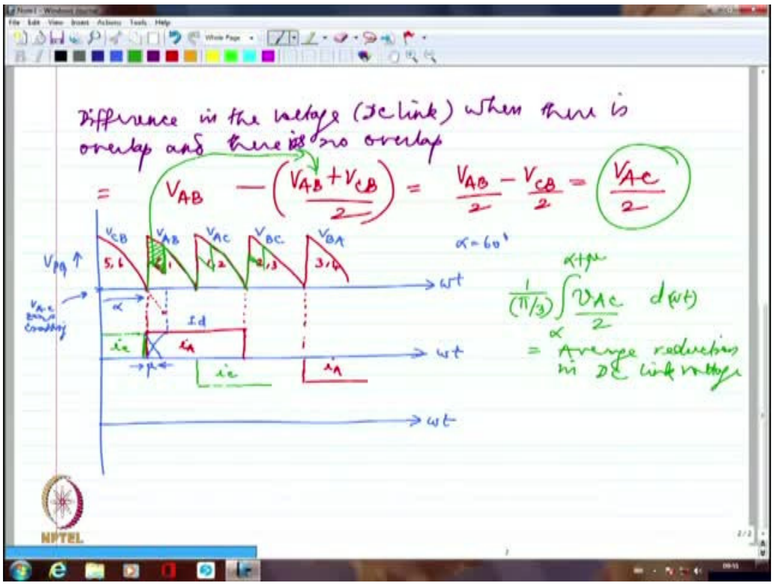

Difference in the voltage (DC link) when there is overlap and there ~~is~~ no overlap

$$= V_{AB} - \left(\frac{V_{AB} + V_{CB}}{2}\right) = \frac{V_{AB}}{2} - \frac{V_{CB}}{2} = \boxed{\frac{V_{AC}}{2}}$$

$\alpha = 60°$

$$\frac{1}{(\pi/3)} \int_{\alpha}^{\alpha+\mu} \frac{v_{AC}}{2} \, d(\omega t)$$

= Average reduction in DC link voltage

So, we should say that the difference in the voltage difference in the voltage, that is the DC link voltage when there is overlap and there is no overlap. We wrote this as when there is no overlap, it was V_{AB}. When there is overlap, we said it is $\left(\frac{V_{AB} + V_{CB}}{2}\right)$, this is what is the difference. So, we wrote the difference between these two as the overall difference that comes up in the DC link voltage for the interval between α and $\alpha + \mu$ and this came out to be

$$= V_{AB} - \left(\frac{V_{AB} + V_{CB}}{2} \right) = \frac{V_{AB}}{2} - \frac{V_{CB}}{2} = \frac{V_{AC}}{2} .$$

So, we said that $\frac{V_{AC}}{2}$ is the difference that exists between whatever is the DC link voltage that would have existed without overlap and that is existing with overlap. So, there is a good amount of drop in the DC link voltage that is what we concluded ultimately. So, let us try to draw the waveforms now corresponding to this and let us see what happens in each of the cases. So, if I am looking at this as ωt let me probably draw 2-3 waveforms together at the same time interval so that I have an idea as to how each of them is changing. If I try to look at the DC link voltage, let me draw it probably for $\alpha = 60$ because that is one of the waveforms which we are very familiar with.

I am going to draw it for $\alpha=60$. For $\alpha= 60$, I am going to have a waveform somewhat like this, I am going to have one then second one, third strip this is without overlap of course, fourth strip and so on and so forth. This is how the waveforms are going to be. If I assume that I am starting off with 5 and 6 conducting together, this is probably 5 and 6 then this is 6 and 1, then this is 1 and 2, this is 2 and 3, this is 3 and 4 and so on, right. So obviously 5 and 6 together I will have the voltage waveform to be V_{CB} this will be V_{AB}, this will be V_{AC}, this will be V_{BC} and this will be V_{BA} and so on.

These are all the waveforms that I would have gotten as the DC link voltage, so I should show this as V_{PQ}, am I right? And I am talking this with respect to $\alpha= 60$, I am firing one at this point, that is what it means, so that means I am going to have this as α because every 60 degree I am going to have a strip of voltage. That strip of voltage is 60 degree so and I have taken α to be 60, so hopefully this should have been my α. So, V_{AC} zero crossing would have been somewhere here, this point is V_{AC} zero crossing, am I right? Because with respect to V_{AC} zero crossing I am calculating α and have drawn the waveform for α equal to 60. So clearly that is the V_{AC} zero crossing point.

If there had not been any overlap, I should have gotten actually my current somewhat like this, the current should have increased abruptly and it should have gone until here as far as device number 1 is concerned, this is how the current should have been. I am assuming ripple free current. I am not taking into consideration any ripple, so if I am talking about ripple free current, it should have been my A phase current. So, I should say this is i_A or i_1. Similarly, I should have had my i_A coming up in the negative direction somewhat like this when I am having 4 conducting.

On the other hand if I try to draw for example i_5 that is C phase current, I should have had the C phase current going somewhat like this and it should have abruptly come down to zero, it should have coincided with the rate of course but am showing it so that you are able to see exactly i_5 should have come down like this. This is all without overlap. So, this should have been my i_c, right and i_c should have started again at this point. It should have gone like this, so this should have been i_c, negative side without overlap. And now I am going to have the overlap. Because of overlap there are going to be changes in the current waveform.

So, I will have actually the current not abruptly ending up in zero rather it is going to come down like this, that is the difference that is going to happen as far as the current wave shape is concerned due to overlap. The same way instead of i_A rising like this, it would have risen like this. And it should have reached the maximum value of I_d if I may call this value as I_{de} within the period of μ, so I am calling this period as μ, overlap interval where I am going to have 5 and 1 simultaneously conducting.

And we are going to have the current somewhat rounded, it is not abrupt rise and abrupt fall, it is somewhat rounded. If I have more and more inductance value, this conduction interval must have been more because the inductance stored energy would have been more. So the current would have been more rounded. So, I am not going to have the abrupt rise and fall, from abrupt rise and fall it is going to become more and more smooth, the current is become smoother because of the presence of the source inductance.

Now if I try to look at what happens to the voltage until this $\alpha+\mu$. I have to look at the voltage. The voltage is going to be the average of V_{CB} and V_{AB} for this interval alone from α to $\alpha+\mu$. This is V_{CB} so I should take V_{CB} further as though it is coming down, that is V_{CB}. Whatever I have shown in the dotted line because I have just drawn V_{CB} before when 5 and 6 were conducting, it is continuing to conduct, and it is going to come up until here. But V_{AB} is here, so I have to take the average between these two. So somewhere in the middle I should take, and this is the average.

Whatever I am drawing let me probably draw this in green or something, a little different colour, so this happens to be the average between V_{AB} and V_{CB}. So this particular green waveform whatever I have got happens to be the DC link voltage, so this is going to be the

DC link voltage which corresponds to this VAB plus V CB by 2, so I am going to have until 5, 6 and 1 conduct instead of getting V_{AB} I am going to get the average of V_{AB} and V_{CB}. The moment 5 gives up then the energy in L_S is gone, it will go back to V_{AB}.

So, my voltage waveform is rather than going to have a single strip it is going to have some wave shape like this. Similarly, I am going to have a wave shape like this and again I am going to have a wave shape like this and so on. So, I am going to have a reduction in the DC link voltage and how much is the reduction is given by this particular area. Whatever is the area difference between the original value of V_{AB} which I should have gotten without overlap and what I am getting now because of overlap $\left(\frac{V_{AB}+V_{CB}}{2}\right)$, that difference amounts to, we calculated that as $\frac{V_{AC}}{2}$. So that is going to be really the difference between what DC link voltage I would have gotten without overlap and what I am getting with overlap.

So there is the gross reduction at least some amount of reduction in the DC link voltage. So if I want to really get what is the reduction in the DC link voltage, quantified it then I have to integrate $\frac{V_{AC}}{2}$ from α to α + μ. This is the area what I have marked as the shaded area, the shaded area is $\frac{V_{AC}}{2}$ but that is going to be integrated from α to α + μ, that is the amount of voltage that is getting stripped off from the DC link voltage i.e. $\int_{\alpha}^{\alpha+\mu}\frac{V_{AC}}{2}d\omega t$, but this happens every one-sixth of the cycle.

This does not happen once, every time when I am going to have the conduction transferred from 5 to 1 and then maybe 6 to 2 and again 2 to 4, 1 to 3 so every 60 degrees this happens. One positive device takes over and the other positive device goes away or one negative device takes over and the other negative device goes away. Every time a new combination comes up, this particular voltage drop is going to take place. So this is the area under the curve, alright but if I want to average it out I had to say it has to be averaged over $\frac{1}{\pi/3}$.

i.e. $=\frac{1}{\pi/3}\int_{\alpha}^{\alpha+\mu}\frac{V_{AC}}{2}d\omega t$

So, I should say this is the average reduction in DC link voltage or DC output voltage due to overlap. So, I am integrating this from α to α + μ but I am averaging it over the entire 60 degrees because this kind of drop or stripping out of the voltage takes place every 60 degrees, so I am averaging it over 60 degrees. If you may recall the last time, we wrote $V_{AC} = 2L_s \frac{di}{dt}$.

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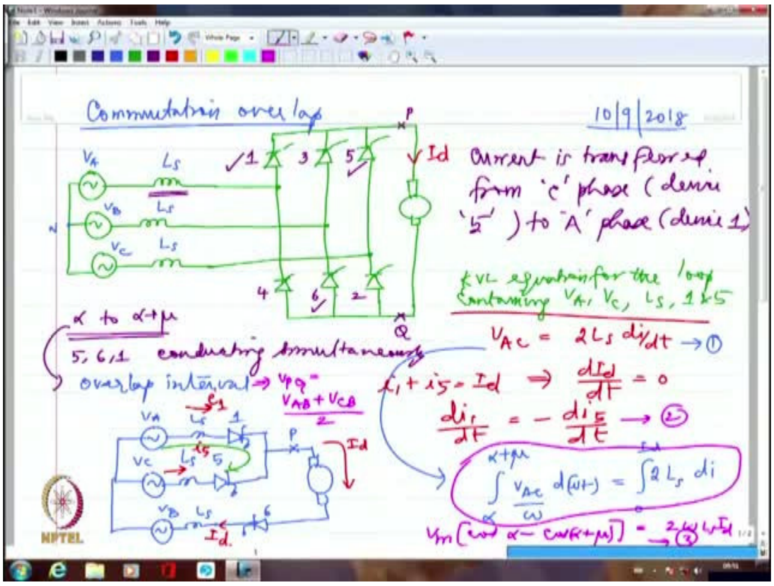

Commutation overlap

10/9/2018

Current is transferred from 'c' phase (device '5') to 'A' phase (device 1)

KVL equation for the loop containing V_A, V_C, L_s, 1 & 5

$V_{AC} = 2L_s \, di/dt \rightarrow ①$

α to α+μ

5, 6, 1 conducting simultaneously

overlap interval → "V_{PQ}" = $\frac{V_{AB}+V_{CB}}{2}$

$i_1 + i_5 = I_d \Rightarrow \frac{dI_d}{dt} = 0$

$\frac{di_1}{dt} = -\frac{di_5}{dt} \rightarrow ②$

$$\int_{\alpha}^{\alpha+\mu} \frac{V_{AC}}{\omega} \, d(\omega t) = \int_{0}^{I_d} 2L_s \, di$$

$V_m[\cos\alpha - \cos(\alpha+\mu)] = 2\omega L_s I_d \rightarrow ③$

We also wrote this particular thing that is α to α + μ when I actually integrated, it happens to be equal to $2\omega L_s I_d$ but when I integrated V_{AC}. So, if it is $\frac{V_{AC}}{2}$ it should be $\omega L_s I_d$. So, if I may call this as equation number 3, I can say from equation number 3 in the previous page, right.

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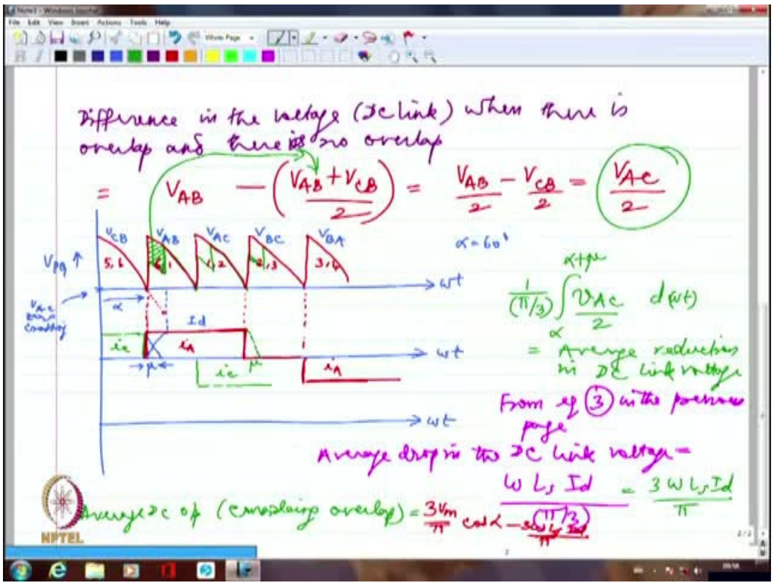

Difference in the voltage (DC link) when there is overlap and there is no overlap

$$= V_{AB} - \left(\frac{V_{AB}+V_{CB}}{2}\right) = \frac{V_{AB}}{2} - \frac{V_{CB}}{2} = \boxed{\frac{V_{AC}}{2}}$$

$\alpha = 60°$

$$\frac{1}{(\pi/3)}\int_{\alpha}^{\alpha+\mu} \frac{v_{AC}}{2}\, d(\omega t)$$

= Average reduction in DC link voltage

From eq ③ on the previous page

Average drop in the DC link voltage = $\frac{\omega L_s I_d}{(\pi/3)} = \frac{3\omega L_s I_d}{\pi}$

Average DC of (considering overlap) = $\frac{3V_m}{\pi}\cos\alpha - \frac{3\omega L_s I_d}{\pi}$

I can write this as average drop in the DC link voltage, equal to $\omega L_s I_d$ averaged over $\pi/3$ because I have written the integrated value directly $\omega L_s I_d$.

$$\text{Average drop in the DC link voltage} = \frac{\omega L_s I_d}{\pi/3} = \frac{3\omega L_s I_d}{\pi}$$

$\frac{V_{AC}}{2}$ integrated from α to α + μ happened to be $\omega L_s I_d$. So, I am writing directly $\omega L_s I_d$ divided by $\pi/3$, so this I can write this as equal to $\frac{3\omega L_s I_d}{\pi}$. So, this value of voltage has to be subtracted from the original value of average voltage we had calculated without overlap. The original value of average voltage we had calculated was $\frac{3V_m}{\pi}\cos\alpha$. So, from $\frac{3V_m}{\pi}\cos\alpha$ if you subtract this much, this will tell you that that is the value of average DC link voltage that is available across the output side when I am considering overlap.

When I consider overlap this is going to be the reduction in the voltage, so I should say average DC output considering overlap will be

$$\text{Average DC output(considering overlap)} = \frac{3V_m}{\pi}\cos\alpha - \frac{3\omega L_s I_d}{\pi}$$

$\frac{3V_m}{\pi}\cos\alpha$ was the original expression we derived where V_m is the line to line peak, and what is given generally in your problems is line to line RMS, so you to multiply that by $\sqrt{2}$ to get V_m.

And this one is what we calculated as the voltage drop for every 60-degree interval. So that has to be subtracted. So, if I try to look at the overlap, two effects now we have arrived at. One is I am going to have the current rise delayed because of which the current is rounded. Abrupt rise and fall you do not see in the current. You see the current been rounded. The second effect is reduction in the DC output voltage. So, because the current is rounded if I try to actually calculate the harmonic analysis or harmonic components in each of the current, that current is not going to be as abrupt rising or as abrupt falling as it was.

So it is not as far away from the sinusoid as it was earlier. Previously it was very far away from sinusoid, please understand sinusoids never have any abrupt rise and abrupt fall. And you are reducing that abrupt rise and abrupt fall by having an inductance, you did not put the inductance, it is there in the system, so that is essentially causing the current to rise and fall in a slower fashion. So, the current becomes a little bit more rounded. Because the current becomes smoother and rounded, you would see that the harmonic content in the current comes down, so it is closer to the fundamental or sinusoid.

So, this is another effect which the corollary of is saying that the current has become smoother. One more thing I have to say one more effect is there because of overlap. Previously when I had the current, I had the current somewhat like this, it was abruptly rising and I had 60 degree interval dead to the world basically, another 60 degree of negative. You remember I had always 60 degree positive current, 120 degree positive current, 60 degree in between zero current interval, another 120-degree negative current and then another 60 degree dead basically.

But now because of the overlap I am going to have this current extending. So, there is the current interval which is actually extending beyond that $\alpha+\frac{2\pi}{3}$, it started from α, it used to go only until $\alpha+\frac{2\pi}{3}$ but now it is going until $\alpha+\frac{2\pi}{3}+\mu$, there is one more μ. So, if I look at the dead current interval zero current interval, it used to be 60 degrees, now it is 60 minus mu. Please understand that the current zero current interval period has decreased from 60 degrees to 60 degrees minus mu, that means if I originally had drawn the fundamental current, I should have drawn the fundamental current somewhat like this, it was actually 120 degree interval like this.

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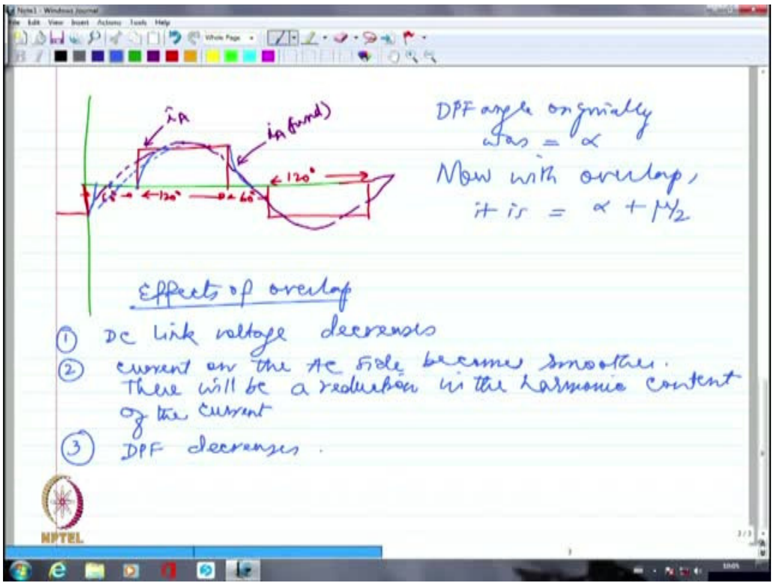

DPF angle originally was = α

Now with overlap, it is = $\alpha + \mu/2$

Effects of overlap

① DC link voltage decreases

② current on the AC side becomes smoother. There will be a reduction in the harmonic content of the current

③ DPF decreases.

Then 60-degree interval and another 120 degree interval like this, so this is 120 degree, this is 60 degrees and this is another 120 degrees and this is 60 degrees, this is how it was, right. The current was somewhat like this and if I am drawing the fundamental, I should have drawn the fundamental exactly through the midpoint and it would probably become a sinusoid like this not exactly to scale and then it should have become something like this, this is how it will be.

It will always flow through the midpoint of that 60-degree interval where the current is zero. If I try to draw the fundamental, the fundamental can never dwell on zero for longer because it is a sinusoid. It can go through the zero only for a very very short span of time, that is it, one instant. So, this is how the fundamental current is going to be, right whereas this is what is actual i_A value. But now if I try to look at the current, the new current is actually not going down here, it should have gone down to zero something like this abruptly. It should have started like this, this is how it should have been earlier.

The current should have been somewhat like this, the negative current then the zero current interval then the positive current, then again zero current interval again the negative current, that is how it should have been. But now because of my overlap this is going to go down to zero slowly, it will definitely not go abruptly to zero. Similarly, this current also should have risen slowly and this current should have fallen slowly and so on and so forth. So, the zero current interval now has become $60-\mu$, so obviously instead of the fundamental passing exactly through the zero at 30 degree point in the middle, it will pass at $60-\mu/2$.

$60-\mu$ is the zero current interval period, so it would pass through the zero slightly away.

So, it will look as though it is delayed by a $\mu/2$, so I am going to probably have the current go somewhat like this, that is the new kind of fundamental current wave I am going to have because the zero current interval has shrunk. Originally, it was 60 degrees now it has become $60-\mu$, so I am going to have the fundamental delayed by an angle of $\mu/2$. Voltage has not changed, voltage is still the same, but the current has changed because of the delay in the rise and fall. The rise and fall in the current have been delayed because of source inductance. That is going to delay the fundamental by some angle, that angle we can calculate it to be $\mu/2$.

So, the power factor what I would have calculated originally as the displacement power factor between the fundamental of voltage and fundamental of current, it was probably whatever was my $\cos\alpha$. We calculated this way back when we were analysing the rectifiers. Now it will become $\cos\alpha$ again delayed by another $\mu/2$, so I should say DPF angle originally was α. Now with overlap it is $\alpha+\mu/2$. So, I am going to have 2α, I have to add $\mu/2$, so there is a small delay in the fundamental currents zero crossing as compared to what it was originally. It is delayed by $\mu/2$. And this is definitely going to cause the power factor to come down somewhat.

So, if we calculate reactive power as Sin of this DPF angle multiplied by V_{RMS} I_{RMS} whatever then it is going to correspondingly increase the reactive power demand of the converter. So overall the power factor comes down for the circuit because of the presence of the source inductance. So, 3 effects let me recount again, the first effect being DC link voltage or average DC voltage decreases because of overlap. The second one, we said current on the AC side become smoother not really as abrupt as it was, so there will be a reduction in the harmonic content, content of the current. Third effect, we said DPF decreases, displacement power factor decreases, that is the third effect.

The last effect which I have still not discussed, let us try to take a look at that. With that we are concluding on overlap.

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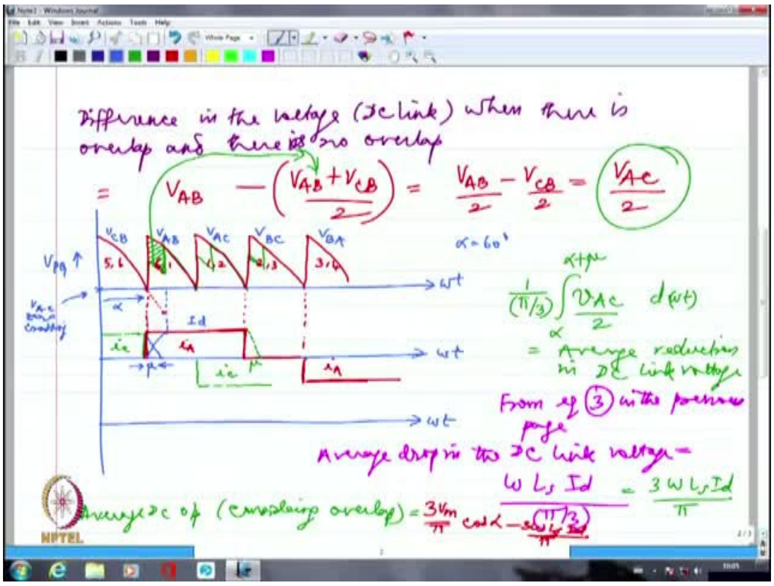

Difference in the voltage (DC link) when there is overlap and there is no overlap

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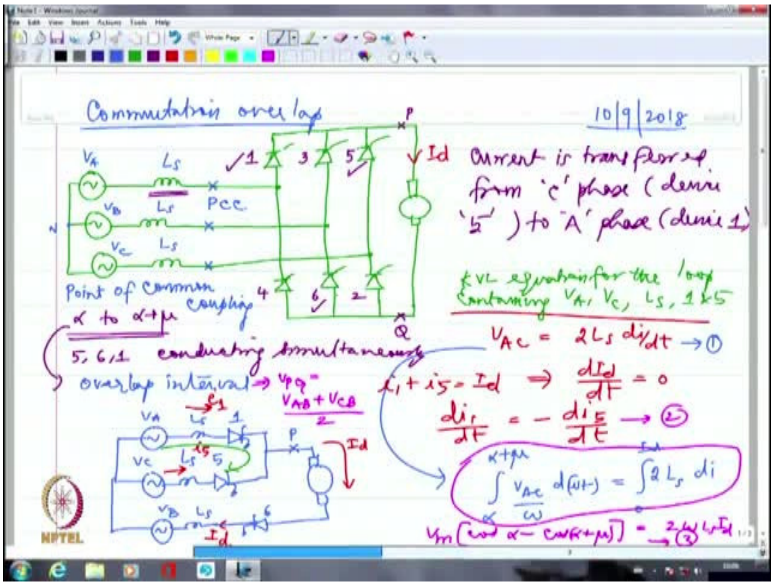
$\alpha = 60°$

$\frac{1}{(\pi/3)}\int_{\alpha}^{\alpha+\mu} \frac{v_{AC}}{2}\, d(\omega t)$ = Average reduction in DC link voltage

From eq ③ in the previous page

Average drop in the DC link voltage = $\frac{\omega L_s I_d}{(\pi/3)} = \frac{3\omega L_s I_d}{\pi}$

Average DC o/p (considering overlap) = $\frac{3V_m}{\pi}\cos\alpha - \frac{3\omega L_s I_d}{\pi}$



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10/9/2018

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KVL equation for the loop containing V_A, V_C, L_s, 1 & 5

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$i_1 + i_5 = I_d \Rightarrow \frac{dI_d}{dt} = 0$

$\frac{di_1}{dt} = -\frac{di_5}{dt} \rightarrow ②$

$\int_{\alpha}^{\alpha+\mu} \frac{v_{AC}}{\omega}\, d(\omega t) = \int_0^{I_d} 2L_s\, di$

$V_m[\cos\alpha - \cos(\alpha+\mu)] = 2\omega L_s I_d \rightarrow ③$

Point of common coupling

α to α+μ

5, 6, 1 conducting simultaneously

overlap interval → $v_{pq} = \frac{V_{AB}+V_{CB}}{2}$

We said that this is our circuit. This point we call as point of common coupling, PCC which you will see repeatedly if you do a course in power quality, power systems. In those places we will call this as PCC, PCC is point of common coupling. First of all, we should know what is PCC. Let us say I have a factory and I have an incoming transformer, from 11 KV I am bringing it down to 415 V. So, the incoming point I will have 3 phases, A, B, C. I may not even have neutral in all probability. Many factories will not have neutral, they will have only A, B, C because the secondary of the transformer what you use in your factory may be delta, it may not be star.

If you do not have star, you will not have the neutral, so you may have only A, B, C points, that is it. So, I have brought out A, B, C points. So, if I try to look at my factory, I will simply have A B and C, that is it.

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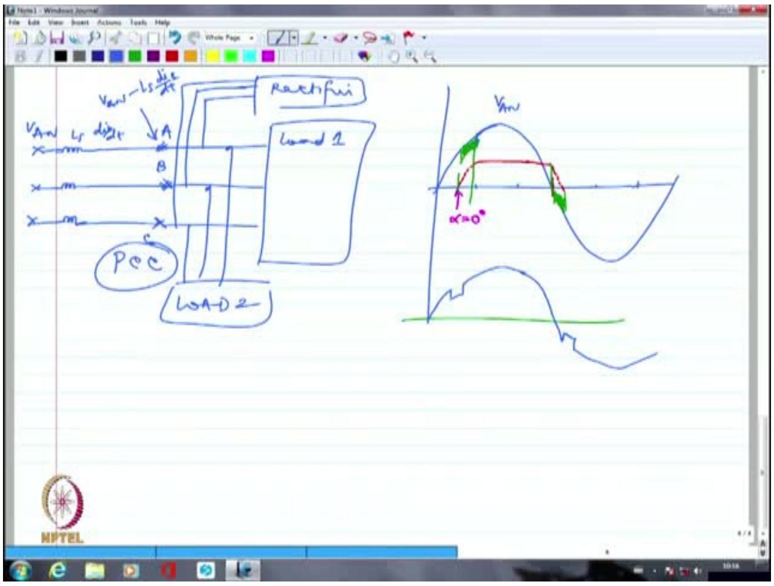

And to these 3 points I will be connecting all the motors, drives whatever I want, heaters and so on and so forth. Please remember before that I have had the transformer which I have not shown here. So, this is A, B, C point, that means the transformer's leakage reactance I had to show it as though it is sitting here behind, it is sitting there which is creating havoc. So, this is actually the point to which I am going to connect many loads. So, at this point I may connect load 1 which is connected to these 3 points. I may connect again. From the same point I may connect load 2. I may connect from the same 3 points again, I may connect load 3 which may be a rectifier for what you know.

So, this point happens to be the common point for all my loads. I have connected many loads in parallel from this particular point, so I call this point as PCC because this is the point of common coupling for all the loads that are there in my factory. So, if I connect an induction motor as load 1, the induction motor is going to see the voltages at this point not at this point. This is the point before the transformer, it is not going to look at that voltage, it is going to look at the voltage what is available after the leakage reactance.

So, if there is a problem in the voltages at this point which is at PCC, it is going to affect all my loads one way or the other, I just cannot help it. And once I put the rectifier especially a controlled rectifier with a large inductive load, I am bound to have problems because the currents are far from being sinusoidal. So, if I have a big rectifier 500-kilowatt rectifier may be sitting there for whatever reason, maybe charging the battery, maybe doing some electrolysis, maybe it is an alkaline industry, so I need some electrolysis to be done. Maybe there is a DC motor drive whose speed has to be controlled. So, I may have a big rectifier sitting there which is connected to the point of common coupling.

If I have a rectifier connected, I had it, I will definitely have problems with respect to my currents because of which I am going to have, if I try to look at the voltage at this point it will be whatever was my original V_{AN} which was sinusoidal because it is coming from the grid minus $L_s \frac{di}{dt}$. That is the way the voltage will come, I cannot do anything because that is Kirchhoff's Voltage Law. So, if I try to look at the voltages at this point for example at PCC, it will be V_{AN} which is originally sinusoidal minus $L_s \frac{di}{dt}$. If I may call this as i_1, this may be $\frac{di_1}{dt}$.

So if I have $\frac{di_1}{dt}$ to be zero, fantastic but when $\frac{di_1}{dt}$ is non-zero like what happened in commutation overlap, I am definitely going to have some kind of abrasion from the sinusoid for that small duration of α to $\alpha + \mu$. Whenever there is a rise in the current or fall in the current, correspondingly I will have $L_s \frac{di}{dt}$ being added or subtracted depending upon whether it is a rise in the current or fall in the current. I am going to have V_A getting kind of deformed, it will get deformed because of $L_s \frac{di}{dt}$. So, if I actually say originally my sinusoid was like this, this is what was V_{AN} without any abrasion.

And let us say I am talking about alpha equal to zero for example, so this is 60, so I am just dividing this into 60-degree strips. Alpha equal to zero belongs to this point. Because V_{AN} and V_{AC} are displaced from each other by 30 degrees and V_{AC} is lagging behind. So, this point is $\alpha=0$, so this is where if I am operating at $\alpha=0$, this is where I am going to see sudden rise in the device number 1 current. Device number 1 will start getting its current at $\alpha=0$ if I am firing the converter at $\alpha=0$, maybe it is a diode converter, whatever does not matter.

So, the current is going to rise at this point. So, I am going to see as though the current is probably going to rise like this and then it will become steady. This is how the current is going to be. When this is happening, I definitely do not have di by dt to be zero. If I try to look at this interval from here until here, I am not having $\frac{di}{dt}$ to be zero. If $\frac{di}{dt}$ is not zero, I have to subtract that $L\frac{di}{dt}$ from V_{AN} and that is what will be the voltage at the point of common coupling. We already said this $L\frac{di}{dt} = V_{AC}/2$. So whatever is my V_{AC}, maybe it is still rising at that point, so I am going to have from here maybe something like this as the strip off the voltage which has to be subtracted, that is part of V_{AC} which is being subtracted from the original V_{AN} value.

So I am going to have some kind of valley, suddenly there is a dip in the voltage. Once that overlap is done then it will go back to my regular blue coloured waveform, no problem. And again when this current is going to probably come down, at that point again I have to look at $L\frac{di}{dt}$ being again subtracted from V_{AN} but here $\frac{di}{dt}$ happens to be negative, so because of which it will as though I am adding a voltage. So, during this interval I would see, during this particular interval I would see to the negative voltage I have to add some value of voltage.

It becomes less negative, so if I actually draw the waveforms it will look kind of awfully bad, it is going to look like this, there is going to be a strip like this and again it is going to go round like this and then here there is going to be again a strip like this and then it is going to go like this. It is not sinusoidal anymore. It is sinusoid in other places except for these two. This will happen again when device number 4 current is again increasing and decreasing. Every time device 1 current is increasing and decreasing, similarly every time device 4 current is increasing and decreasing.

So, 4 portions I will see. In 4 points I will see $L\frac{di}{dt}$ effect coming at the voltage at the point of common coupling, PCC voltage will get far from being sinusoidal. So, this is going to cause if I connect an induction motor to this kind of a sinusoid and I imagine maybe $\frac{di}{dt}$ is large or L_S is large, this voltage is going to almost touch down to zero, then obviously the induction motor will groan. It will say you are not giving me sufficient voltage.

Maybe you are not doing it for too long but from α to $\alpha + \mu$ every now and then you are applying a voltage which is not sinusoidal anymore. So, in one sense this commutation overlap affects all the loads that are connected at the point of common coupling. So, to add to the effect of commutation overlap what we wrote earlier, the fourth affect will be voltage at the PCC.

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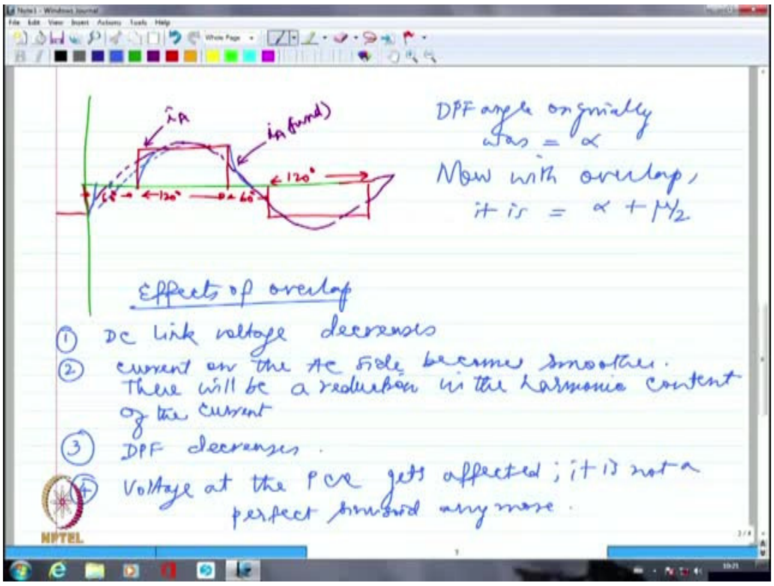

DPF angle originally was = α

Now with overlap, it is = $\alpha + \mu/2$

Effects of overlap

① DC link voltage decreases

② current on the AC side becomes smoother. There will be a reduction in the harmonic content of the current

③ DPF decreases.

④ Voltage at the PCC gets affected; it is not a perfect sinusoid any more.

The point of common coupling gets affected; it is not a perfect sinusoid anymore. It is definitely not a perfect sinusoid anymore, so whichever equipment requires pure sinusoid all of them are going to have some trouble, maybe they will make more noise, maybe they can get spoiled, their longevity life expectancy can decrease. All those things can happen, right. So, these are really problems faced especially in high voltage DC transmission system (HVDC), there we are going to use a rectifier on one side and an inverter on the other side.

Both are generally thyristor based because HVDC systems generally work at plus 500 KV and minus 500 KV kilo volts, and they normally transmit the power which is of the order of 2000 megawatts, so very very large power they transmit over very long distances. So that is one reason why HVDC transmission systems normally use only thyristor and that too light activated SCRs. Mostly we use only LASCRs, so if they have to withstand a voltage of about 500 KV then 85 to 100 devices we connect them in series, all of them are connected in series with parallel connected big resistors, snubbers, inductors, you name it. Every auxiliary component is connected along with that to protect them against any of the failures.

You might have heard about the blackout we had in 2011 in Delhi, big blackout we had complete North India because of HVDC line which failed which is actually working between Rihand and Dadri. Dadri is a big power station which is actually generating a huge amount of power but Delhi’s peak load was 4 GW couple of years ago, it must have increased further. 4 GW is actually the peak load of Delhi, so Dadri what it generates, what Badarpur generates, what all the other surrounding power station generate is not sufficient. So because of which we also try to take it from Rihand, which is close to Varanasi. So, there is a NTPC power station, from there we generally take the power which is coming through the HVDC transmission system. And it generates a very huge amount but about 1800 MW is transmitted to Delhi and that is still not sufficient quite often.

So that is the reason why once that line was snapped because of problems in the thyristor complete unit, it had to be completely put away. So that is when we actually the entire thing plunged into darkness because there was huge amount of oscillations in the frequency, power, reactive power. All of them oscillated in a big way that all the protection systems opened up simply.

So that is one typical case where the commutation overlap could be as high as 13 degrees. Commutation overlap angle μ happens to be as high as 13 degrees in many of the HVDC transmission systems. Because we have so many synchronous machines all the synchronous machines have a very large amount of synchronous reactance excess which is equivalent to our L_S. Then you have the transformer, then you have all of them connected to our converters which are making the current far from being sinusoidal.

So, these problems are real, we are not talking anything imaginary, so I just wanted to emphasise that that is the only reason why I wanted to dwell on commutation overlap at least for a little while so that you guys know really what are all the problems associated with phase controlled rectifiers or SCR based rectifiers. Right, so much so far commutation overlap.

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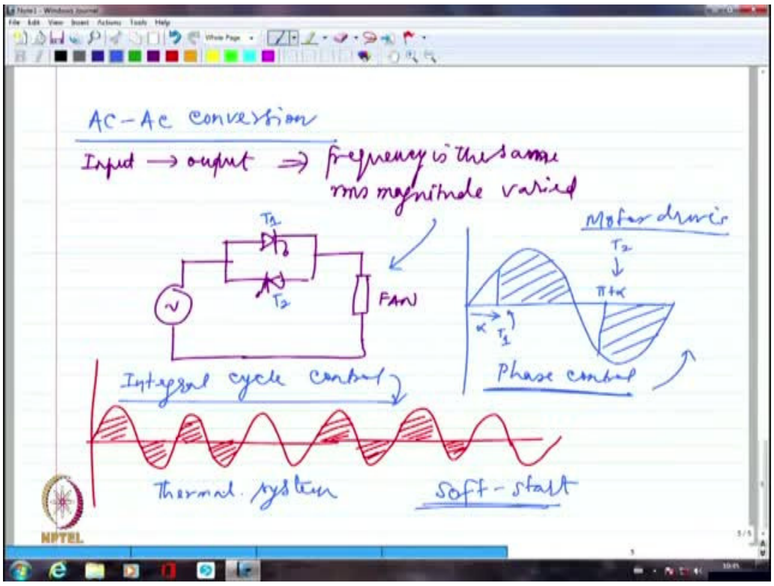

Now we are migrating to the next topic, we will at least start the topic today then we will move to whatever we have to do further. Because this second topic what I am taking up is a shorter topic. It is not as vast as the rectifier, I am going mainly concentrate on AC to AC conversion. Same as transformer in one sense. Same as transformer but the only thing is I am not going to have any electromagnetic device, I am going to have only semiconductor devices.

So, 2 types of AC to AC conversion are possible, one is input to output, frequency is the same. I am not going to change the frequency, frequency is the same. But RMS magnitude varied, this is one type of conversion we do whenever we want to change only the magnitude of the voltage that we are applying to any of our equipment. Typical example is your fan regulator, electronic regulators what you see these days not the old regulator where we used to have a resistance, big resistance, that is it.

Nowadays what we have is an electronic regulator where you will have 2 thyristors back-to-back connected. So, I will have one thyristor connected in this direction like this, another thyristor which is connected in the opposite direction like this. So, I will just connect a single phase voltage here and here is my fan. So, depending upon if I fire this at zero this at 180 then I will get full voltage. If I fire this later than zero degrees, similarly if I fire this later than 180 degrees, I will apply only part of the sinusoid not full sinusoid. So, I will accordingly reduce the amount of voltage that is being applied to my fan. So, if I reduce the voltage, correspondingly the speed will come down.

You may not see a huge variation in the speed normally in many of the fans because induction motor speed is not going to be dependent heavily on the voltage rather it is dependent upon the frequency. I am not changing the frequency, so the speed is somewhat changed but it may not be a very nice linear smooth variation, that is what you would see most of the times. So, this is typically the electronic regulator what we have in our actual systems most of the times for the single-phase induction motor. So, in this case you are changing only the magnitude, but the frequency is not changed at all.

This can be done simply by varying the firing angle. So, I can just change the firing angle I may call this as α, this will be $\pi-\alpha$. If I may call this as T_1, this as T_2, so T_1 is fired here and T_2 will be fired here. Please note I have shown a single-phase voltage, so α is calculated with respect to its own zero crossing unlike what we did in the three-phase case, its own zero crossing. We are calculating it with respect to its own zero crossing. So, this is how it is going to be controlled.

So, this kind of control is called phase control. So far whatever we have done is also phase control because with respect to the zero crossing of one of the voltages I am changing the phase at which a particular device is being fired. So that is known as phase control. If I do not want to do phase control because understand this not sinusoid anymore, I am applying only part of sinusoid. So, there are huge amount of harmonics. I have large amount of harmonics being pumped in because the voltage is not sinusoidal, the current will also not be sinusoidal, so there will be huge amount of harmonics in the entire motor if I try to look at it and it is not good for the motor.

Normally motors would like to receive only sinusoidal as much as possible. Instead of that I can have let us say this is my multiple sinusoidal cycle that is available. I apply power for 2 cycles, I do not apply power for one cycle, again I apply power for 2 cycles. I do not apply power for the next cycle. What happens if I try to look at the whole 10 or 15 cycles together, I would see that I am applying power only for two-thirds of the entire cycle. So obviously the net amount of power I am applying to my appliance gets decreased if I try to do this. So, what I am doing is applying power for integral number of cycles and not applying power again for integral number of cycles. So, this is generally known as integral cycle control.

We call this as phase control whereas this as integral cycle control. So, I apply power for N number of cycles, I do not apply power for M number of cycles for a total number of M+N cycles. So, obviously I am going to definitely have no power transfer during this portion.

Hence, I am going to have the net power that I am transferring is decreased as compared to what I had done originally, had I connected it directly to my circuit rather than having this kind of a circuit in between. In this case I would have fired it at zero degree and 180 degree, so I would have fired for two cycles. Third cycle, I would have not given any firing signal.

Then again for fourth and fifth cycle I would have given firing signal, 6th cycle I would have not given firing signal. So this would also work, no doubt this also decreases the amount of power that I am applying to my appliance, only thing is if the motor drive's inertia is very small what you have generally as fan motors are hardly 40 Watts consuming motor, input is 40 Watts and efficiency is pathetic normally 30 percent or 40 percent. So, what you get as the output is only 16 or 17 W. It will not run.

And again, you apply power, it will start all over again. Again, when you do not give power it might just stop. So, it depends upon what is the time constant of your system. If the time constant of your system is larger then it may be able to pull along with the inertia. If the time constant of the system is smaller, integral cycle control is not good because once again you must start afresh which is not good for the system.

So typically, integral cycle control is used in thermal systems. Let us say I have an immersion heater, maybe I have some kind of heat convector. Please understand thermal time constants are generally of the order of minutes or hours, it will take a long time to get heated up, it will take a long time to come down to cooling. So, you switch it off for 2 cycles it will not even feel it. So, in thermal systems integral cycle control can be implemented whereas in motor drive systems generally we do not use integral cycle control rather we use phase control.

So, phase control is very commonly used in induction motor drive systems, be it single phase, be it three-phase. Even in three-phase sometimes starting the induction motor, you guys have done with auto transformer starting in electromechanics lab, so instead of auto transformer I can use this kind of a phase-controlled SCR pair, back-to-back connected SCR pair. This is back-to-back connected, antiparallel, right. So, this kind of system can be used for slowly decreasing the firing angle, rather you will have 120 degrees or 110 degrees as the firing angle, slowly bring it down towards zero degree so that you are applying slowly increasing voltages to your induction motor and it can pick up speed at a slow pace.

That kind of starting mechanism is known as soft start. You are starting it slowly softly, so you call that as soft start. So soft start is the mechanism which we use for three-phase induction motor with back-to-back connected thyristor in all the 3 phases, of course we will need in all the 3 phases So this kind of a mechanism we may use for starting the induction motor in a slow fashion which we call as soft start. So, if I am talking about soft start, I have to show one phase then second phase and the third phase.

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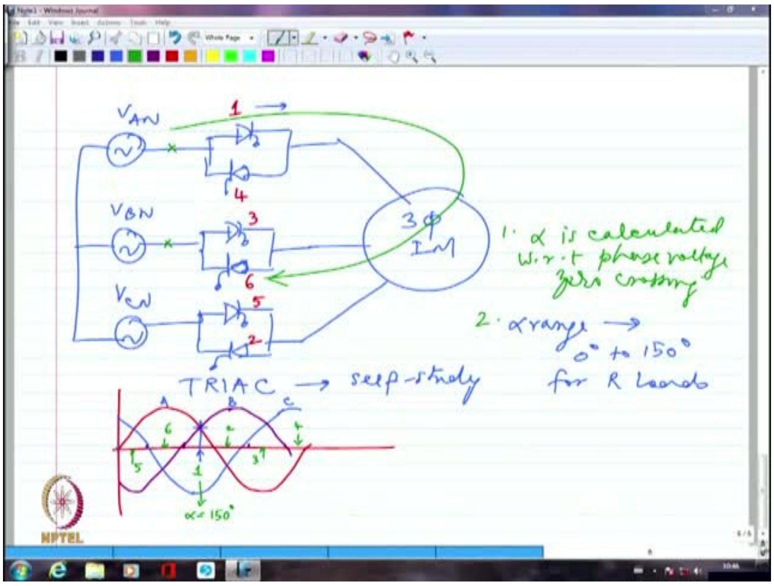

1. α is calculated w.r.t phase voltage zero crossing

2. α range → 0° to 150° for R Loads

TRIAC → self-study

All the 3 phases will be connected together like this and then I may have one phase, second phase and third phase power supply, let me call this as V_{AN}, V_{BN} and V_{CN} and then this is the three-phase induction motor. In fact, the back-to-back connected thyristor pair together is available in the form of a single device which is known as Triac. One terminal will be called as M_1 the other terminal will be called as M_2, main terminal 1, main terminal 2 and the gate terminal.

So, the gate terminal will be given pulses at α degree and 180+α. In both the times the pulses have to be given so that the forward conducting device conducts during α degree time and 180+α then reverse conducting device will conduct. So, we have a single phase AC voltage controller, we have three-phase AC voltage controller, we can have in either of them phase control or integral cycle control. So, these are the different types that are available in the AC voltage controller.

If I take for example an AC voltage controller like this, please understand that if again I can number it the same way as what we did 1,4 3, 6, 5, 2 please note I am numbering it the same way like what we did in the case of a rectifier. A phase positive device I am calling as 1, B phase positive device 3, C phase positive device 5 and the negative devices are correspondingly numbered 4, 6, and 2. Now if I am assuming that I am having the three-phase voltages somewhat like, this is A phase, this is B phase and this is C phase. if I am having one of the phases conducting, the return has to be through the other one of the phases.

Like if A is conducting in the forward direction, the return path has to be provided by either B or C. So, one has to join hands either with 6 or with 2; otherwise I am not going to be able to have a continuous current. If I fire only 1 and nothing else is conducting, there is no way the current can flow. The current has to flow through the other phase. So, if I look at normally a resistive kind of load, let us say forget about induction motor, if I have a resistive load. if I fire 1 here for example. if 6 has to conduct along with that, the B phase voltage has to be negative. If it is not negative, I am not going to be able to have a current in the opposite sense because it is resistive. I am talking about a resistive load. So I will have B phase actually, this is A, this is B and this is C. I will be able to see a current flowing in the opposite direction through the B phase only if at least V_{AB} happens to be positive because please understand the current is flowing from device number 1 and it has to return through B phase.

So V_{AB} has to be positive only then I can have a current in that particular direction. So, which means I can have the firing possible only until this point. I can delay the firing of A phase only until that particular point theoretically, this is the major difference between a rectifier and an AC voltage controller. In a rectifier we said α is first of all calculated with respect to V_{AC} zero crossing whereas here it is calculated with respect to its own phase voltage. The second point is in rectifier we could go until α equal to 180 theoretically whereas here we will be able to go only until 150 (α is 150).

We cannot go beyond α equal to 150 for resistive loads. For inductive load it is different because inductance will have stored energy, it can continue the current for longer and so on and so forth. But for resistive loads I can have α ranges only from zero degree to 150 degree for R loads.

See if I am saying that the current has to go from 1 and it has to return through 6, we are again following the same firing sequence 1, 2, 3, 4, 5, 6, again I will fire 1, 2, 3, 4, 5, 6 and so on. So, I assume that 6 is already fired, it is up and running. If 6 is up and running and 1 has to aid the conduction, then V_{AB} has to be positive only then the current can flow from here and it has to return through this. So, I am talking about V_A coming here and V_B coming here. Unless V_{AB} is positive I will not be able to have a current flow directly in the direction that have shown provided it is a resistive load.

If V_{AB} has to be positive, V_{AB} could be positive only until here. Beyond this I am going to have basically V is increasing and A is decreasing. So V_{AB} will become negative. If V_{AB} has to be positive it can happen only until 150 degrees of the V_A waveform point. If I try to look at V_A waveform it starts from zero here and it is exactly 150 degrees here. So, I can have a range of only the delay could be only as high as 150 degrees. If I try to fire it beyond 150 degrees device number 1, it will not have any chance to conduct because 6 and 1 combination cannot work beyond α=150.

The combination cannot work beyond α equal to 150. So, 2 major differences between a three-phase rectifier and a three-phase AC voltage controller are one is α is calculated always with respect to phase voltage zero crossing not line voltage zero crossing. The second one is the maximum α that is permissible for resisting load conduction if the conduction has to be feasible in the rectifier case theoretically, it could be 180 degrees whereas in the case of AC voltage controller it has to be only 150 degrees. These are the major two differences between AC voltage controller and the rectifier that we discussed so far.

Right and firing of course is done symmetrically. If I say that 1 is fired at this point obviously 2 will be fired at this point and 3 will be fired here and 4 will be fired here and 5 and 6 will be fired respectively at this point. Symmetrical firing is generally done in this particular manner again. I chosen α equal to 150 this is Alpha equal to 150. So, α is calculated with respect to phase voltage zero crossing.

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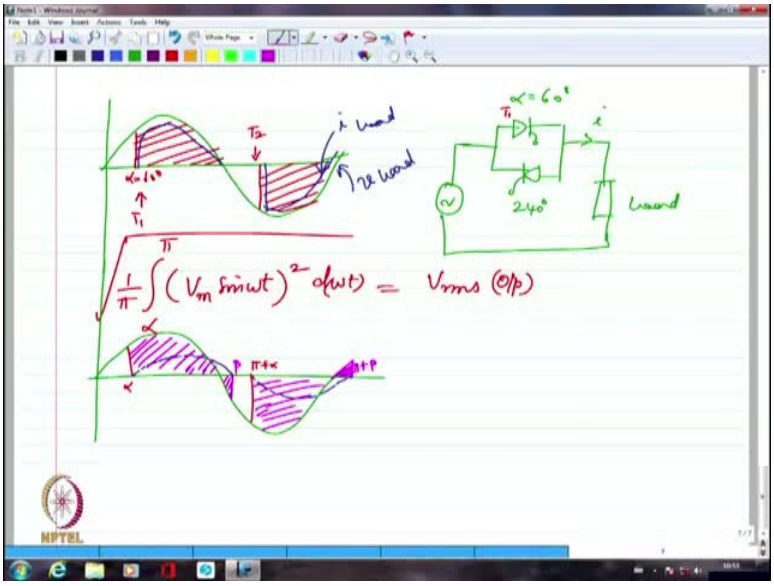

$$\sqrt{\frac{1}{\pi}\int^{\pi}(V_m \sin\omega t)^2 d(\omega t)} = V_{rms}\,(O/p)$$

One last point before we move on further is that, if I am taking a single-phase AC voltage controller, for example this is my voltage waveform, single phase AC voltage controller's input waveform. If I am going to look at this device being fired at α equal to 60, so obviously this device will be fired at 60 plus 180, so this will be fired at 240 degrees. They are always shifted from each other by 180 degrees. So, this is my input and this is my load. Let me look at the current waveform along with voltage waveform. If I am looking at α equal to 60 that means I am firing somewhere here, this is where T_1 is fired and this is where T_2 will be fired.

And if I am talking about RMS value for this with resistive load, it is pretty simple because I will have basically device number 1 conducting for this entire duration for R load and device number 2 conducting for this entire duration for R load again. So, I should be able to write this as

$$\sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi}(V_m \sin\omega t)^2\, d\omega t} = V_{rms}(\text{o/p})$$

This is what is V_{rms} that I will be getting at the output. This will be the RMS value at the output.

So obviously I will have some cosα and so on and so forth or $1-2\sin\omega t/2$, whatever. So, this is going to be the output voltage as far as the resistive load is concerned, so it is not a simple expression like what we got in the case of rectifier and this is in resistive load. If I look at inductive load, for the same thing if I try to draw for inductive load, so let me again draw the sinusoid and I am firing it at α and again I am firing it at $\pi+\alpha$.

I will have the current rising from 0. In the other case I would have had the current somewhat like this, the current would also have been something like this. For the resistive load the current would have been something like this exactly the same wave shape as that of the voltage. Whereas if I so this is the current waveform, this is I and this is V, whereas here the current would have started like this, I have to write the equation again $V_m \sin\omega t = Ri + L\dfrac{di}{dt}$

if am taking a RL load.

And then I have to again apply the same equation like what I did where $V_m \sin\omega t$ becomes equal to Ri, I will have the peak of the current and so on and so forth. All those things will be valid here as well. So, I am going to have the current probably rise like this and then it will fall beyond π, please note this. The current is falling beyond π, it will come down to zero. And again, the current would have increased here and then it would have fallen beyond π, this is how it is going to be. Now if I draw the voltage the voltage is going to be somewhat like this, I am going to have the voltage this entire thing coming up as the voltage until here.

So it is coming from α and it will go until β and solving for β is not going to be easy again. Similarly, it will start from α+π and it will go until π+β. So, some portion of the positive voltage will also show up here and I will have this entire portion coming up. If I have higher and higher inductance, this beta will delay, get delayed further and further. If I have higher and higher inductance, I will have this β delayed further and further, so at some point where I have a very large inductance, I may have β almost reaching until π+α.

Then I will have the full voltage applied, there is no way I am going to have any control. So, for highly inductive loads I may not have any control almost until α reaches even 60, 70, 80 degrees, I may not have any control over the voltage at all. So highly inductive loads for lower values of α I may not have any control over the voltage output and hence the current output as well. So, we will continue with this in the next class to look at the limits of the control in an AC voltage control.