CHARGING INFRASTRUCTURE

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Week-05

Lecture-25

Lec 25: Three Phase AC-DC Converter-III

Hello everyone welcome to the lecture number 25 of this NPTEL lecture series on charging infrastructure in this particular lecture we will continue our discussion on three-phase DC DC converter and if we recap it what we have done in previous lectures so we have understood the operation of three-phase issue DC converter By changing this delta value, sine of delta value, we can allow the power to flow from AC to DC or DC to AC. And by changing the magnitude of delta, we can able to control the IS current which is being drawn from the grid. Here again, we have to ensure that we are maintaining a constant output voltage or regulate the output voltage at V_o and while drawing the current from the source that too at immunity power factor.

So, that is why we have kept this $I_{sphasor}$ and $V_{sphasor}$ in the same phase. There is no phase angle between them. and we have then derived the expression for the inductance L value which we got

$$L = \sqrt{\left(\frac{mV_o}{2}\right)^2 - \frac{v_{s,pk}^2}{\omega(i_{s,pk})^2}}$$

And from here we can calculate the inductance value because these are the some of the given in the specification some of the things are the designer's choice and once we calculate the inductance value we have to ensure that the voltage drop across the inductor for the fundamental component should not be greater than 10 percent of the $V_{s,pk}$ because otherwise the most of the voltage will drop across the inductor itself for the against the inductor impedance corresponding to the line frequency of 50 Hz. Then we moved ahead and did the sizing of the switches we saw what are the rms current ratings what are the voltage blocking voltage rating of those switches and after that we have we moved to sizing the capacitance here again we first follow the same procedure what we did in the case of single phase ac to dc converter where we have did the power balance between the input between the input average power and the output power and then

After that we come to conclusion that there was at the output of the converter there is the second line harmonic frequency component is there and that second line harmonic frequency currents will be going through the output capacitor and which corresponds to the capacitor ripple and then the capacitor size can be selected in such a manner that the second line harmonic voltage ripple is minimal or within the prescribed or within the permissible limit for I mean given the specification however when we did that what we did a simple thing the we calculated the input power we calculated the output power obviously only considering the that we have the fundamental current which is flowing through the converter and then finally what we come to conclusion that we are only having at the I converter there is no second line harmonic component it only has the DC component and that DC component so capacitor blocks the DC current so it will directly go into the load however this is not the case Because if we see the circuit for the fundamental frequency, how our single phase equivalent circuit looks like, where we have the voltage source, we have the AC voltage source coming at the output of the v_{conv} or at the output of the half bridge configuration and that lead to some current, the fundamental component of current which will be flowing between the two voltage sources. And however, we know that this v_{conv} what we have written over here will also have along with the fundamental component, we also have the harmonic component and that harmonic component will be at the side bands of mf.

More precisely, it will be $imf \pm$j. Those are the harmonic numbers. So, here when we write n, n is nothing but $imf \pm$i.

$$n = imf \pm j$$

And J is again the odd or even number. This J corresponds to under root minus one, so this is the component of the voltages which will be applied at the output of the half bridge. Then we have the inductor; however, in the AC voltage source, we have the pure AC. That's why for the harmonic frequency component circuit or single-phase equivalent circuit for the harmonic frequency, component, what we see is that there is no component of voltage from the grid because the grid is pure AC. That's why we have shorted it, and that's when we saw that the current there will be harmonic current corresponding to that harmonic voltage. This will be only limited by the impedance corresponding to the inductor for that harmonic frequency. However, this n is very much higher compared to the fundamental because fundamental n is equal to 1. However, in most cases for the harmonic component, this N is somewhere greater than 20. The harmonic number is greater than 20 or 25, so that's why automatically these harmonic components of currents are smaller. However, this harmonic component of current is the one responsible for the frequency component in this i_{conv} current, and that

harmonic component of current in the I converter will be flowing through the capacitor, which will actually lead to the current of this capacitor. Thus, we have to calculate what is the RMS current which will be flowing through the capacitor because that will determine what will be the capacitor size—I mean, what will be the series-parallel combination of the capacitor bank. So, in order to derive that particular RMS current which is flowing through the capacitor bank, let us see how we can calculate the current flowing through the capacitor bank. For that, we have to calculate what is the i_{conv}, which comprises some average value which is actually going through these load RL and some AC component which will be going through the capacitor. So, we have to calculate that RMS current. So, let us try to first find out how we can calculate the current flowing through the capacitance because that will determine our size of the capacitor.

So, if you look very carefully, we have here V_a, which is nothing but $V_{spk} sin\omega t$, Vbn, which is nothing but $V_{spk} sin(\omega t - 120°)$; and V_{cn}, which is nothing but $V_{spk} sin(\omega t - 240°)$;. Now, if we see this, we can say this is V_{an}, this is V_{bn}, and this is V_{cn}. So now, if we look very carefully at this particular thing, we can divide this entire, entire one. So, if we see from here to here, from here to here, it is one-line cycle given as T, which is nothing but $1/f_s$, f_s is the line frequency we are talking about here? And if we look very carefully, we have in total, if we see, we can divide this thing into similar-looking modes. We can say this is the first thing. So this is first. Now, if you look very carefully, between this point and this point, we can say this is the first mode. Let me write this as operating portion one.

This side to this side, we can say two. This side to this side, we can say three or mode three. This side to this side, mode four. This side to this side, mode five. And this to this, mode six. If we try to write, this is zero. If we write with respect to ωt or with respect to theta, it is zero angle. Similarly, we can define other angles like $\pi/6$, $\pi/2$, $5\pi/6$, $7\pi/6$, $9\pi/6$, $\frac{11\pi}{6}$ and 2π as shown over here.

Now, if you look very carefully, if we can calculate the current flowing through the capacitor in the first mode, the same thing will be there in the second mode, third operating mode, fourth mode, fifth mode, and sixth mode. Let us define that as a sector. So, if we have six sectors in one-line cycle, then we see that in the first sector, one of the phases or one of the voltages are maximum voltage, mid voltage, and the minimum voltage, and that changes every $60°$ cycle or after every $60°$. So, if we can calculate for one of the sectors, let's say sector 1, we could be in a position to say that the same thing will repeat after sector 2, sector 3, sector 4, sector 5, and sector 6. So, what we can do is let us try to understand how we can calculate for the first sector the current which is going through the i_{conv}.

I mean, let us try to find out the i_{conv}. Then, once we know the i_{conv}., we can calculate its average value and its RMS value. From there, we can calculate the I capacitor current. Now, let us assume that since we know that we have three phases, a, b, and c, and we know that these three phases are $120°$displaced from each other. Thus, we must ensure that this one half-bridge is actually modulated with the sine waves which are $120°$away from each other. So, let us define these as the modulating wave for phase a, V_{ma}. We can say this is V_{mb}, this is V_{mc}, modulating wave for phase a, for phase b, for phase c. And we know that the modulating wave of phase a is nothing but V_{ma} is nothing but $V_m \sin sin\, \omega t$, V_{mb} is nothing but $V_m sin(\omega t - 120°)$ and V_{mc} equals $V_m sin(\omega t - 240°)$. And if we see this one, this is again with respect to omega t, we can say. And this particular thing will be compared with the very high-frequency carrier signal, and that carrier signal we can draw like this as shown over here which goes from $- v_c$to $+ v_c$, while the modulating wave V_{ma}, V_{mb},V_{mc}will get compared to generate gate pulses for S1 to S6 switches. So this carrier I have drawn for I mean very last time period carriers for understanding I have just exaggerated that time period now if you look very carefully this carrier goes between vc and minus vc and this will get compared at every carrier cycle with the modulating wave so what happens at every carrier cycle all the three modulating waves are sampled and then they were compared and if we can say that if the modulating wave is greater than the carrier wave then the top switch is on in that particular phase and if my modulating wave is smaller than the carrier then my bottom switch is on in that particular phase So, now if you look very carefully, it is going between $- v_c$ to $+ v_c$. So, what one can do is, this is going between plus, let us say plus peak value of the modulating wave to the negative peak value of modulating wave.

So, we can give a constant shift of v_c. That is when we can ensure that our carrier goes between 0 and $2v_c$ and everything is being pushed to 0. and I mean we can just add everything together and that's when everything gets pushed to v_c constant v_c voltage and that's when everything will come in the positive direction. That's when we can take one of the instances and in one of the instances of this mode 1 we will have this V_m, V_{ma}, V_{mb} and V_{mc} voltage coming over here.

So, if you see this one I have given this T_c whatever I have done drawn this T_c or T_s whatever I have drawn is very much bigger in time period. However, it is very small. I mean generally it is so small that this sampled modulating wave looks like a pure DC. So when we take in one of the switching cycle or one of the carrier cycle in sector 1 what we will get is this is you know operating mode 1 for operating mode 1. Operating mode 1 or you can say sector 1 is nothing but T_c carrier cycle or switching cycle both are same.

Where my T_c is nothing but 1 by carrier frequency and you can say that it is nothing but equal to T_s, which is nothing but a switching frequency. You can say $1/fs$ω. Now, if we see, if we take operating mode one, it is the top one is the V_a phase, middle one is the V_b phase and last one is the v_c phase. And we have added a constant voltage of v_c such that everything becomes positive value. So, this one will become, so our red one, red sample, sampled value of red one will be $V_{ma} + v_c$.

Yellow one will be V_{ma}, c because we have this c phase coming v_c and this is $V_{mb} + v_c$, this is what we will get and if we look very carefully we will we have already assumed that modulating wave greater than carrier then top switch is on else bottom switch is on and in that case my top switch is off and top switch is off and here bottom switch is off So, if we take this condition, so in this particular carrier, we see this is the first sample, second sample, third sample in which we have added the constant value of the carrier voltage v_c. So, what we will get is we will get at this point my S1 switch this top switch in because this is for a phase. So, for a phase it is S1 switch my S1 switch here it is carrier is greater than the modulating that's when my bottom switch is on and top switch is off that's when my top switch S1 is 0 at this point my top switch S1 is 1 which is on from here to hear the in-c phase

In c phase which is S5, my S5 will be 0 and at that point my S5 will be 1. And in case of c phase, from here to here my S3 will be 0 and from here to here my S3 will be 1. And whenever my S1 switch is on, so if you see the i_{conv} current which is going out of this bridge, it is nothing but the current whenever my top switch of any of the half bridges is on, that's when there will be current which is contributing to the I converter current. So, from T0 to T1 period, there is no current through the i_{conv}. from T1 to T2 there is only S1 switch is on so i_{conv} is nothing but the current which is going through here which is i_{sa} from T2 to T3 since your S5 and S1 is on so i_{sa} and i_{sc} will be flowing through the i_{conv} however since this is i_{sa} and i_{sa} current is going this i_{conv} will be nothing but i_{sa} and i_{sc} because my both S1 and S5 is on

Then at that point of time, at this point of time, what happens is that S1, S3 and S5 is on. And during that time, at this place, what is happening is we have $i_{sa} + i_{sb} + i_{sc}$. And since we are assuming that we are having the balanced operation of the circuit, so we can say that this is nothing but equal to 0. Assumption. We assume that balanced three phase operation is happening.

If balanced three phase operation is happening, that's when we can say that $i_{sa} + i_{sc}$ or $i_{sb} + i_{sc}$ is equal to zero. Since we have assumed that we have a balanced three-phase operation, so thus at this point when all the three, S1, S3 and S5, all the three are on, my i_{conv} is nothing but equal to $i_{sa} + i_{sb} + i_{sc}$ and that is actually equal to zero. That's why the zero is being drawn. Similarly, between this point and this point also, we have the zero current flowing. From T4 to T5, what happens is that my S1 and S5 is on.

That's when my i_{conv} is nothing but $i_{sa} + i_{sc}$. and then between T5 and T6 it is my only S1 is on so it is nothing but i_{sc}. is there and then finally between T6 and T7 since all the switches are off and bottom are on so my current there is no current which is going to the i_{conv} and that's when i_{conv} is nothing but equal to 0 so now we know that in one in one carrier cycle or in one switching cycle the Ts duration for some of the period the i_{conv} carries the current i_{sa}. For some of the period, my i_{conv} carries the current $i_{sa} + i_{sc}$. and in some other duration, the i_{conv} has current nothing but equal to 0.

Now, this is the case only in the operating mode 1 or you can say that sector 1. In sector 2, there could be some other value. In sector 2, we have a and then we have we have a we have this b and b will go up as compared to vmc so that's when we will see that here instead of i here we have i_{sa} and here we have $i_{sa} + i_{sb}$ and here we have i_{sa} and i_{sb} and here we have i_{sa} only then in more operating mode 3 or sector 3 it will be different so in all the sector the magnitude I mean the steps will remain be the same that means for some portion one of the phase current will be there in some another portion both the phase current will be there and some portion all the three phase current will be contributing to i_{conv} which is actually nothing but equal to zero I mean when all the phases are there so that's when we know that for calculating the rms current through the capacitor we must calculate the $i_{conv,rms}$ first for one carrier cycle or one switching cycle.

And then whatever RMS current we get in one switching cycle, then we have to take the RMS current or the average current over one line cycle. So that's why let us first try to calculate RMS or average current in one switching cycle. So this is my T0 value, this is T1 value, this is T2 value, this is T3, this is T3, this is T2, this is T2, T1, this is T0. Now, let us try to find out what will be this values T0, T1, T2 in terms of my modulating signal, how it looks like. If we see this is nothing but between t0 to this point is nothing but my, you know half the cycle.

Once we have half the cycle and then the other half cycle, we will have the another half cycle. This is another half cycle ts by 2. So, if we look very carefully, I converter current is symmetrical around this $T_s/2$ period. So, if we could able to calculate $T_s/2$ period, we can just do the multiplied by 2. We can do to calculate the RMS or average value for I converter in 1 Ts period.

Now, let us first calculate what is the value of T0, T1, T2. Now if we look very carefully T0 is nothing but the portion of the $T_s/2$ whenever the carrier is greater than $V_{ma} + v_c$, . And if we see T1, T1 is the portion of the $T_s/2$ whenever the carrier is between $V_{ma} + v_c$. That means between this point and this point. That is nothing but the T1.

So, we can say T1 is nothing but out of $T_s/2$ period, it is the period whenever

$$\frac{V_{ma}+v_c-V_{mc}+v_c}{2v_c}$$

Because if we go from 0 to $T_s/2$, if we go from this point to $2v_c$ point. So we have taken out of this $2v_c$. Whenever we are in between these two, we are having the duration T1.

So, this will correspond to $T_s/4$. We can write

$$T_1 = \frac{V_{ma}-V_{mc}}{V_c} \qquad (1)$$

This is my T1 value. Similarly, for T2 value, we can say that, so we can say Vmc plus Vc minus Vmb plus Vc. And this will give, let us define this as 1 square by 4 , Vmc minus V_{mb} by $2v_c$ and this is let us define this as equation number 2

$$T_2 = \frac{V_{mc}-V_{mb}+v_c}{2v_c}$$

$$T_2 = \frac{V_{mc}-V_{mb}}{2v_c} \qquad (2)$$

and then T3 is nothing but the portion of the $T_s/2$ whenever my value goes from $V_{mb} + v_c - 0$, so we can say that it is nothing but

$$T_3 = \frac{\frac{T_s}{4}+v_c}{2v_c}$$

this is 2 and that we can write T3 is nothing but TS by 4 1 plus VMB by VC

$$T_3 = 1 + \frac{V_{mb}}{v_c}\frac{T_s}{4}$$

this is nothing but my duration T3 now this will give me my T1 T2 T3 and that's when i can also calculate my T0, T0 is nothing but out of this th by 2 period I have $T_1 + T_2 + T_3$ and when we put down this expressions what we have is we have $\frac{T_s}{4}$ coming out from 1 to 3 and we have $V_{ma} - V_{mc} + V_{mc} - V_{mb}$ and this we can just write plus $v_c +$,we can write down this is V_{mb} and this everything we can write down as vc and if we look because this is v_c which is coming over here and this we see if we see vmc vmc will get cancelled this will get cancelled and then we can again take out ts by 2 outside that will become 1 minus $2v_c V_{ma} + v_c$ this when we write down T0, 1 divided by 2 comes out is 2 vc minus 3ma minus vc by 2 vc

$$T_0 = \frac{2v_c - V_{ma} - v_c}{2v_c}$$

it is nothing but you know one we have $T_s/2$ and this when we do that we will get $T_s/4$ this becomes

$$T_0 = \frac{v_c(1 - V_{ma})}{v_c}$$

(3)

Now this is nothing but my T_0 and we know that our V_{ma} is nothing but $V_m sin\omega t$. V_{mb} is nothing but $V_m sin(\omega t - 120°)$. V_{mc} is nothing but $V_m sin(\omega t - 240°)$, and we also know that V_m/V_c we can write something equal to V_m we can also write that which is nothing but the modulation index so we can write down my T1 value

$$T_1 = \frac{\frac{T_s}{4} V_m sin(\omega t - 240°)}{v_c}$$

$$T_1 = \frac{\frac{T_s}{4} V_m sin\left(\omega t - \frac{2\pi}{3}\right)}{v_c}$$

$$T_1 = \frac{T_s}{4} \left[V_m sin\omega t - V_m sin\left(\omega t + \frac{2\pi}{3}\right)\right] \quad (4)$$

$$T_1 = \frac{T_s}{4} V_m \left[sin\omega t - sin\left(\omega t + \frac{2\pi}{3}\right)\right] \quad (5)$$

Similarly, we can write down T2 as Ts by 4 and it is Vmc. So, it is Vm sine omega plus 2 pi by 3 minus Vm sine omega T minus 2 pi by 3 and this is nothing but Vc. So, we can write T2 as Ts by 4. It is m sin omega t plus 2 pi by 3 minus m sin omega t minus 2 pi by 3.

$$T_2 = \frac{T_s}{4} V_{mc}$$

$$V_{mc} = V_m sin\left(\omega t + \frac{2\pi}{3}\right) - V_m sin\left(\omega t - \frac{2\pi}{3}\right)$$

$$T_2 = \frac{T_s}{4}\left[V_m sin\left(\omega t + \frac{2\pi}{3}\right) - V_m sin\left(\omega t - \frac{2\pi}{3}\right)\right]$$

$$T_2 = \frac{V_m T_s}{4}\left[sin\left(\omega t + \frac{2\pi}{3}\right) - sin\left(\omega t - \frac{2\pi}{3}\right)\right]$$

(6)

this we can define this as 6 ,

$$T_1 = \frac{T_s}{4} V_m \left[sin\omega t - sin\left(\omega t + \frac{2\pi}{3}\right)\right]$$

$$T_1 = \frac{\sqrt{3}}{4} T_s V_m sin\left(\omega t - \frac{\pi}{6}\right)$$

(7)

$$T_2 = \frac{\sqrt{3}}{4} T_s V_m \cos cos\, \omega t$$

(8)

Now if we look very carefully, my i_{conv}, my i_{conv} is only non-zero during the T1 period and during T2 period. So even if I could calculate T0 and T3 it is of no meaning for me to actually evaluate the average value of this i_{conv}, in one switching cycle or carrier cycle. So let us try to use this particular thing to calculate our I converter average.

So now what we have to do is we have to now calculate the I converter current and we have to find the RMS and the average current. So, let us try to find the i_{conv}, average value over the one switching cycle or carrier cycle. You can say over the Ts. So, we can say average over Ts period.

So, it is nothing but 1/Ts over the existing 0 to Ts, i_{conv}, over Ts. So, in one this carrier cycle since in this carrier cycle this i_{sa} is constant i_{sa} and i_{sc} is constant and that is their non-zero value between T1 and T2 and between T2 and T3. So, this particular thing and it is also symmetrical around this T /Ts /2. So we can write it is we can just write T1 to T2 this i_{sa} value which is constant value multiplied by this dt plus T2 to T3 it is which will be there and here it is isa plus isc dt and remaining period it will be 0 so this will be nothing but and remaining period will be 0 and since it is a symmetrical around this so we can just multiply this by this multiplied by 2 so instead of 2 multiplied by this we can write this the factor 2 comes from symmetricity around is by 2 and we know that $i_{sa} + i_{sb} + i_{sc}$ because of the balanced three-phase operation is nothing but equal to zero that's when we can say

$$i_{sa} + i_{sc} = 1 - i_{sb}$$

And in these things, since this i_{sa}, i_{sc} and i_{sb}, the sample current value in that switching cycle and we know that our switching cycle $T_s \gg T$. So, we can say that this i_{sa}, so that's when we can say i_{sa}, i_{sc} and i_{sb} is constant in T_s duration.

So, in that way we can just take out $\frac{2}{T_s}$, isa comes out and then we (T2-T1), further the term involving i_{sb}(or i_{sc}) can be written as $-i_{sb}(T3 - T2)$. Now this I can write $(T3 - T2) = (T2 - T1)$ this term reduces to T1. Hence, the expression becomes

$$i_{conv,avg} = i_{sa}T1 - i_{sb}\mathrm{T1} \qquad (9)$$

this is my i_{conv} current average over Ts duration. Now, let us define this as equation number 9.

Similarly, we can also find out I rms So, $i_{conv,rms}$ TS duration for this TS duration only. Let us define this as square if we do that. So, just we have to find the mean of squares. So,

$$i_{conv,rms} = \frac{1}{T_s}\int_0^{T_s} i^2_{conv}(t)dt$$

Now, in T_s duration we will just write $\frac{1}{T_s}$.

$$i_{conv,rms} = \frac{2}{T_s}\left[\int_{T_1}^{T_2} i^2_{sa}dt + \int_{T_2}^{T_3}\left(i_{sa} + i_{sc}\right)^2 dt\right]$$

$$i_{conv,rms} = \frac{2}{T_s}\left[i^2_{sa}T_1 + \left(i_{sa} + i_{sc}\right)^2 T_2\right]$$

$$I^2_{conv,rms} = \frac{2}{T_s}\left[i^2_{sa}T_1 + i^2_{sb}T_2\right] \qquad (10)$$

This is nothing but $I^2_{conv,rms}$ over Ts duration and this wil define this as let's say equation number 10. So, we understood the average value of i_{conv} over this Ts duration and RMS current over the Ts duration or Tc duration. So let us now calculate the RMS and I average over one line cycle. So now if we look very carefully in this particular thing, this we have drawn it for sector 1. This we have drawn it for sector 1 or you can say operating mode 1. And if we see our operating mode 1, our operating mode 1 is actually between π /6 to π /2 and it will repeat and the same thing will repeat over the line cycle.

So, we just if we can able to calculate the average and RMS in this for this operating mode 1, it will be the same for the for the entire line cycle. So, in that case, we can now calculate I converter average is

$$d(\omega t) = \omega dt$$

Hence, the averaging over one fundamental cycle segment becomes, from equation (9), the converter current is given by

$$i_{conv,rms} = \frac{2}{T_s}\left[i_{sa}^2 T_1 + \left(i_{sa} + i_{sc}\right)^2 T_2\right]$$

Substituting this into the above expression, we obtain

$$\frac{d(\omega t)}{dt} = \frac{3}{\pi}\int_{\pi/6}^{\pi/2} d(\omega t) = \frac{3}{\pi}\left[\int_{\pi/6}^{\pi/2} \frac{2}{T_s}\left[i_{sa}T_1 + i_{sb}T_2\right]\right]$$

Now, substituting the expressions of T1 and T2 from equations (7) and (8), respectively,

$$T_1 = \frac{\sqrt{3}}{4} T_s V_m sin\left(\omega t - \frac{\pi}{6}\right)$$

$$T_2 = \frac{\sqrt{3}}{4} T_s V_m \cos cos\, \omega t$$

And if we put this one, so $i_{conv,avg}$ will be $\frac{3}{\pi}$. This 2/Ts as we can take it out, $\pi/6,\ 2\pi/2$. And again, in this one, since we are doing it for the line cycle. So, our i_{sa} will now become equal to $I_{spk} sin\omega t$. i_{sb} will be $I_{spk} sin\left(\omega t - \frac{2\pi}{3}\right)$And i_{sc} is nothing but $I_{spk} sin\left(\omega t - \frac{4\pi}{3}\right)$. And this when we wrote down here IS peak sin omega t and here again assuming UPF operation.

So that's when there is no phase angle term coming over here. T1 we know our T1 value is nothing but equal to if we can draw from here this

$$T1 = \frac{\sqrt{3}}{4} T_s V_m sin\left(\omega t - \frac{\pi}{6}\right)$$

and this is minus $\pi/6$ to $\pi/2$ again here it is i_{sb} which is

$i_{sb} = I_{spk} sin\left(\omega t - \frac{2\pi}{3}\right)$,

$$T2 = \frac{\sqrt{3}}{4} T_s V_m \cos cos\, \omega t$$

Substituting T1, T2, andi_{sb} into the expression of the converter current from (9)

$$i_{conv} = \frac{2}{T_s}\left[i_{sa}T_1 - i_{sb}T_2\right]$$

and using the change of variable $d(\omega t) = \omega dt$, the integration can be carried out over the interval $\pi/6$ to $\pi/2$, Upon solving this expression, the average converter current is obtained as

$$I_{conv,avg} = \frac{3}{4} I_{s,pk} V_m \quad (11)$$

Now, let us say defined as 11 and similarly we can calculate from 10 from 10 our $i_{conv,rms}$ means rms over the line cycle we can just calculate by again writing the same thing $3/\pi$ going from $\pi/6$ to $\pi/2$ just like here $\pi/6$ to $\pi/2$, i_{conv} this is converter rms over Ts square into $\frac{d(\omega t)}{dt}$, and since it is the root over that it will be root of this particular term and that is when you put this values over here this is $\pi/6$ to $\pi/2$, i_{conv} is

$$i_{conv} = \frac{2}{T_s}\left[i_{sa}^2 T_1 + i_{sb}^2 T_2\right]$$

and this is $\frac{d(\omega t)}{dt}$ and this T1 and T2 we know T1 and T2 from 7 and 8 this when you equate this thing and put it find out the integration higher computation softwares you can use this you will get isp under root root 3 by pi m 5 by 4 this is the value you will get the i_{conv} as

$$I_{conv,rms} = I_{s,pk}\sqrt{\frac{3}{\pi} V_m \frac{5}{4}} \quad (12)$$

value and this let us define this as 12 and once we know so if we look very carefully in our circuit in our circuit we know our this rms value which is flowing through this we know through the RL value it is the average value which will be flowing through the i_{conv}. So, we can calculate the I_{rms} flowing through this by the subtract by this subtraction of the squares of them so we can Write down my, $I_{c,rms} = \sqrt{i_{conv}}$ is. Again, this $I_{conv,rms}$ is over the line cycle square minus my $I_{conv,avg}$ over the line cycle. Because this is nothing but over the line cycle. The line cycle and this average value is again over the line cycle and then we have we can calculate the $I_{c,rms}$ by subtraction of that of the rms value which is rms value of converter I_{conv} which is coming out of the half bridges and average and $- I_{avg}^2$ because that's the current which is going into the load so we can say I_{conv} average is going through the load which is in this case RL And the remaining will be going through the capacitor. So, we can get this value from this $I_{c,rms}$ from this expression. And this you can put it from equation number 11 and 12.

$$I_{conv,avg} = \frac{3}{4} I_{s,pk} V_m$$

$$I_{conv,rms} = I_{s,pk} \sqrt{\frac{3}{\pi} V_m \frac{5}{4}}$$

Accordingly, the capacitor RMS current can be written as

$$I^2_{C,rms} = I^2_{s,pk} \left(\frac{\sqrt{3}}{\pi} Vm \frac{5}{4} - \left(I_{conv,avg} \right)^2 \right)$$

From the previous result, the average converter current is

$$I^2_{conv,avg} = \left(\frac{3}{4} Vm I_{s,pk} \right)^2 = \frac{9}{16} M^2 I^2_{s,pk}$$

Substituting this into the above expression, we obtain

$$I_{C_{rms}} = I_{s,pk} \sqrt{\frac{\sqrt{3}}{\pi} Vm \frac{5}{4} - \frac{9}{16} Vm^2}$$

Here, Vm is the modulation index. The peak phase current $I_{s,pk}$ can be obtained from the system specifications. For a lossless converter, the peak current can be calculated from the load power as

$$I_{s,pk} = \frac{R_{asd}}{3V_{phase,rsus}} \sqrt{2}$$

If converter losses are considered, the input power can be divided by the efficiency to estimate the peak current more accurately.

Now, if you look very carefully, this capacitor RMS current depends on the modulation index m. So, we have to say depending upon the modulation index selected, this capacitor current will be changing. So, with this, we have understood how we can calculate the RMS current through the capacitor. That is when we can calculate the capacitor bank because we can assume the series parallel combination of capacitors.

However, we still don't know what the capacitance value we can take will be, so we can calculate the capacitance value. Let us quickly take the calculation of the capacitance value. This capacitance value can be defined using our normal principle of how much energy you want to take from the capacitance, so we can define the minimum. The minimum DC link capacitor we can use, so we can say

$$C_{min} > \frac{\Delta P_{max} T_2}{2V_0 \Delta V_0}$$

where ΔP_{max} is the maximum. Power variation you want in the converter. That means, whenever we are doing closed-loop operation, what is the maximum power variation you can expect in the converter? That means a sudden change in the loads—how much variation in the maximum power variation of the converter. Td is the response time of your converter. Response time of your closed loop, meaning how much time it will take to respond to that sudden change. That's when we can calculate the energy, and we can say ΔV_0 is nothing but the permissible voltage ripple—the output voltage ripple. On the capacitor, and $V_0$is the output voltage. You might wonder how we can calculate this. This particular capacitance can be obtained by just doing the energy equivalence of the capacitance, where the capacitance values go from V1 voltage to V2 voltage.

And this energy, which is there, has to be greater than if we want to keep it within the ΔV variation. It is nothing but we can say $\Delta P_{max} \frac{T_d}{2}$, and when we equate this, we will get the energy variation of the capacitor is given by

$$\frac{1}{2} C_{min} \left(V_1^2 - V_2^2\right) \gg \Delta P_{max} T_d$$

This energy must be greater than the energy associated with the maximum pawer variation aver the response time, which can be written as

$$\frac{\Delta P_{max} T_d}{2}$$

So, when I am talking about Δ. P_max variation, it means I am talking about the variation of values. So, my power ΔP_max means if this is my PL, this one, so the variation goes from, let's say, here to here and here to here. So, it goes from P1 to P2, and this going from P1 to P2 is nothing but equal to ΔPmax. And while when it goes to P1, which is away from the PL value or the power, when it goes to a higher value than the nominal power. So, it comes back.

So, here we get this one value from P1 to PL is nothing but ΔPmax / Δ. 2,

$$PL = \frac{\Delta P_{max}}{\Delta 2}$$

This will become nothing but

$$\left(V_1 + V_2\right)\left(V_1 - V_2\right) = \Delta P_{max} T_d$$

and here, whenever this is happening, our capacitor will have a voltage ripple. The capacitor voltage, if we see. It goes from here to here and here to here, and the maximum value is V1, and the minimum value is V2.

So, this is nothing but ΔVo. We can say

$$\Delta V_0 = \frac{\left(V_1 + V_2\right)}{2}$$

Is the average value of $\left(V_1 + V_2\right)$, which is nothing but V_0. And my $\left(V_1 - V_2\right)$is nothing but ΔV_0.

So, that's when I can write C_min is nothing but 2 * V_0 * ΔV_0 must be greater than. ΔP_max * T_d,

$$2V_0 \Delta V_0 C_{min} > \Delta P_{max} T_d$$

$$C_{min} > \frac{\Delta P_{max} T_d}{2V_0 \Delta V_0}$$

This is what we have written here. So, ΔV_0 is generally given in the specification, V_0 is also given in the specification. This is the designer's choice, and this again depends on the circuit operation. This is the ΔP_{max} you will get, so this is again.

Designer's choice or designer's choice—this is the specification given in the specification. It is given; this is again given in the specification, and ΔP_{max} is also given in the specification. Sometimes given in the specification or otherwise, one can take the required judgment to calculate this value of capacitance. So, we have understood how we can calculate the capacitance value, and then once we calculate the capacitance value, how we can design the capacitor bank depending upon the RMS current of the capacitance, which actually determines how many numbers of parallel branches we need. We also know that the voltage rating—the voltage rating of the capacitor will be— Capacitor has to be greater than my $v_0 + \frac{\Delta v_0}{2}$.

So, this way, we can actually design our capacitor bank. Now, in the next lecture, we will see the closed-loop operation of this converter.

Thank you.