Design of Power Electronic Converters
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Module: Analysis of Power Electronic Converters
Lecture 7
Unipolar PWM

Welcome to the course on Design of Power Electronic Converters. So, we were discussing the module on Analysis of Power Electronic Converters. And today's lecture, we will discuss Unipolar PWM. Previously, we had discussed Bipolar PWM for H bridge converters. So, there is another PWM method for it popular PWM method there are many other PWM methods as well, the other popular method, the another one is Unipolar PWM.

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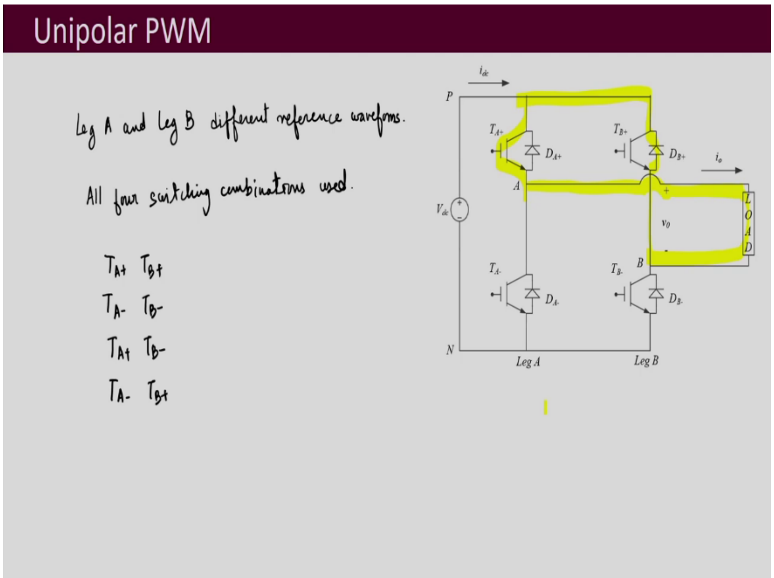

So, in this one what is done is that these legs this leg A and leg B they are treated individually. In Bipolar PWM what we had seen was these two diagonal switches T_A+ and T_B- and T_A- and T_B+ they were always switched on and off together. But, in case of Unipolar PWM we look into individual legs rather than looking into the whole converter together.

So, accordingly each leg A and B has got a reference waveform. So, different reference waveforms for modulation are given. And since, we are not using specifically your this combination of T_A+, T_B- and T_A-, T_B+ instead, we are looking into individual legs. So, therefore, all four switching combinations arise in Unipolar PWM, all four switching combinations they are used.

Now, for example, let us say this upper switch is ON for leg A. So, this one is On and for leg B also the way the reference waveform is for leg B the upper switch of leg B gets On. So, in that case T_A+ T_B+ is this switching combination which is going to be used. Then it may so happen that both the lower switches are getting on together depending on the leg A the reference waveform and its comparison with the carrier and leg B's reference waveform in comparison with the carrier.

So, all of these your T_A+ T_B+ being on together T_A- T_B- being on together and T_A+ T_B- and T_A- and T_B+ all these four switching combinations arise in the Unipolar PWM. And depending on that what is the direction of the current that we have seen before it depends on the direction of current. So, let us say your direction of current was positive and the upper switch of leg A and the upper switch of leg B was On.

So, now, what we can see here is that, that the current has to flow like this. Now this upper switch is On. So, it is going to then flow through the diode and come here and flow like this. This we have discussed before that depending on the direction of the current whether the IGBT is conducting or the diode is conducting it is dependent on that. And what is the current over here idc current over here that also depends on the switch combination and not on the direction of the load current.

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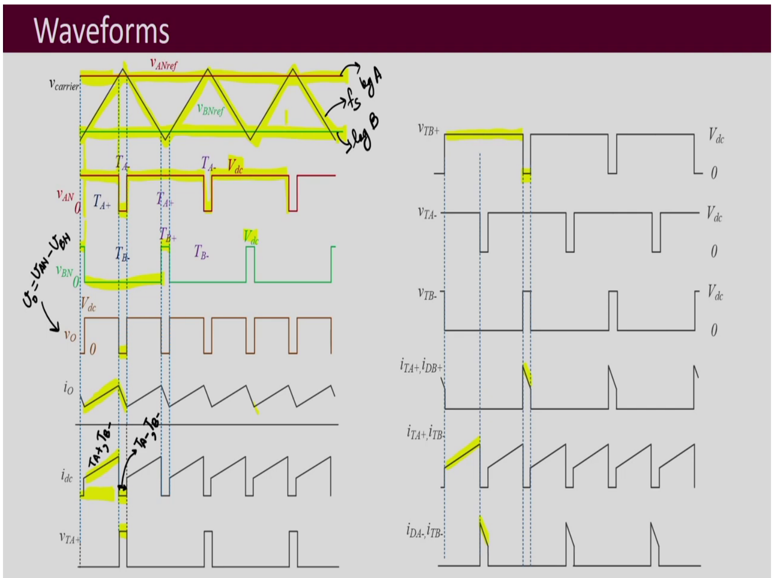

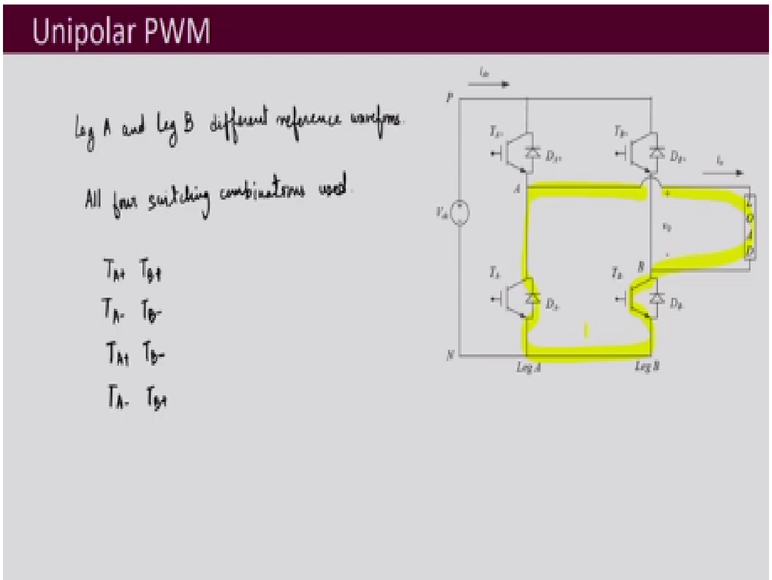

So, now, let us look into the waveforms. So, here you can see this is the carrier waveform, this is the triangular carrier waveform and this will have the switching frequency f_s, high switching frequency and then this is the reference waveform for leg A, this is for leg A and this one is for leg B. Now, when the comparison takes place, So, whenever you can see here in this part the reference we end ref the reference of leg A is greater than the carrier and so, the upper switch T_A+ is On.

And then for this much area your what you can see that it is T_A- the lower switch of leg A is On and so on this continues and what will be the leg voltage V_{AN}? Whenever the upper switch is On the voltage is going to be equal to Vdc otherwise it will be equal to 0. And for leg B. So, leg B this is the reference and then when you compare what will happen here you can see that this part your reference is greater than the carrier. So, upper switch T_B+ is On and here reference is lower than carrier. So, T_B- lower switch is On and so on it continues and whenever the upper switch is On, the voltage the leg voltage becomes equal to V_{dc}.

And then we know that your output voltage V_o can be written as the difference of the leg voltages V_{AN} - V_{BN} and that is what is shown here as the output voltage what you see here is that that over here this is V_{dc}, V_{AN} and this is 0. So, the difference is V_{dc} and here both of them are 0. So, the output voltage is 0, then further here again this is V_{DC} and this is 0. So, this is again V_{dc} and this continues like this.

Then we see the load current assuming it to be inductive load. So, what will happen whenever the voltage is output voltage is positive, the current will be increasing that is what we see here the current to be increasing and then here when the voltage is 0 output voltage there the current will decrease and so forth it will continue like this.

Then we see the i_{dc} current waveform there what will happen when in this part, in this part your what is on is your T_A+ and T_B-. Here your T_A+ and T_B- these two are On and you know that for this switching combination for positive direction of current if your i_{dc} equal to load current. So, what we see here this is equal to the load current.

Then in this part over here in this interval your what is on is your the lower two switches the bottom two switches T_A- and T_B- these two are On together and at that time what will happen your DC bus current will be 0 we have seen the equivalent circuits before, the four equivalent circuits and accordingly these waveforms are getting formed.

Then, we can look into the switch voltages. So, whenever the switch is on at that time the switch voltage is 0 otherwise whenever it is off it is blocking the dc bus voltage V_{dc} and that is what we see here for V_{TA}+ and similarly, for V_{TB}+ also the voltage across switch TB+ the upper switch of leg B we see that whenever it is off, then it is going to block V_{dc} and whenever it is On assuming it to be ideal the voltage is 0.

Similarly, for your V_{TA}+ and V_{TB}- the lower two switches voltages are also shown here you can obtain it like that. Now, coming to the switch currents, Now, depending on the switching combination and the direction of the current this gets decided that whether the switch is conducting that means the transistor is conducting or whether the diode is conducting.

So, what we can see here now, here we have assumed the direction of current to be positive. So, now, the two switching combinations that we saw is that T_A+ and T_B- are becoming On and the direction of the current is positive. So, it flows like this or these two lower switches are getting turned On.

So, when these lower two switches are getting turned on at that time, what will happen is that, that your current direction is still positive it flows through here and then it has to go through the diode. So, T_B- and T_A- are supposed to conduct. So, T_A+, T_B-, T_A-, T_B- these two combinations and here T_A+ T_B+ the upper two switching combinations that also we can look into.

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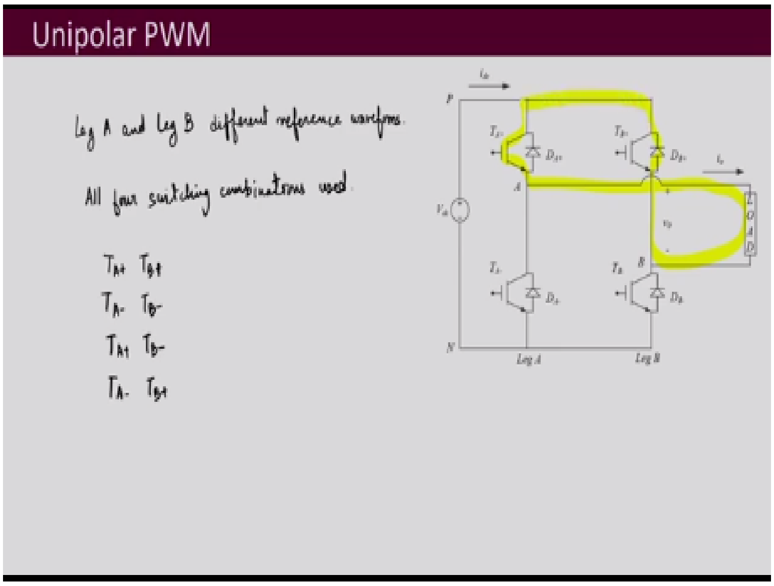

So, upper two switches it will be flowing like this here and then it flows through this diode. So, accordingly if we see this whenever the upper two switches are On that is the switching combination here your this current i_{TA}+ and i_{DB} + means through the diode of T_B+ and through the IGBT T_A+ this will be equal to the load current i_o otherwise it will be 0 and whenever the switching combination is T_A+ T_B- here in this part. So, then the current will be equal to load current through those devices i_{TA}+ i_{TB}-.

And then whenever the lower two switching combinations are arising, lower two switches being on at that time your diode D_A- and T_B- are carrying the current. So, at that time they will have the load current. So, this is what is the current waveform through these two i_{DA} minus and i_{TB}-. So, this is how you can obtain the current waveforms through the devices through the IGBTs and through the switches. So, it mainly depends on which of the devices are conducting depending on the switching combination which is arising and the second the direction of the load current.

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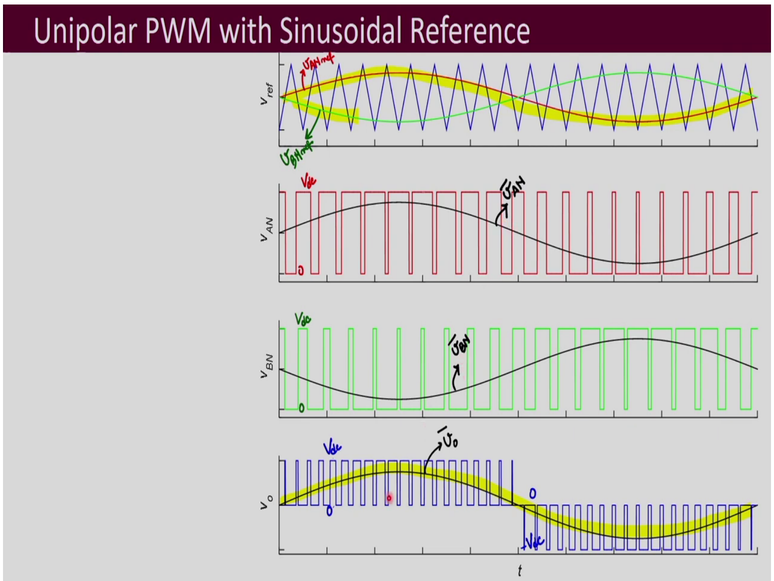

Now, in this case I have shown you where your references are not varying like the references appeared to be as DC references, but it may so, happen the references may be sinusoidal and this is what is shown here that this is your reference one of the references. So, this is for your reference for leg A, so, V_{ANref} and then this one is the reference for leg B, V_{BNref} and depending on these the comparisons takes place and whenever this is higher here your reference is greater than the carrier waveform, then at that time the upper switch gets On and the leg voltage becomes equal to V_{dc}.

So, this varies from this leg voltage varies from 0 to V_{dc}. Similarly, for leg B also you can do the comparison and this also varies from 0 to V_{dc} and the output voltage this output voltage gets formed by the subtraction of these two V_{AN} and V_{BN} and so you can subtract these two waveforms and you will see this is what you are going to get, this blue waveform and this varies from here you can see this varies from 0 to V_{dc} for this much period it varies from 0 to Vdc and then for another period you can see that that it varies from 0 to - V_{dc}.

Because that is how the difference over here is appearing here the V_{BN} voltages have got greater width than the V_{AN} with the V_{AN} switching the voltage that is appearing and so, accordingly it varies from 0 to - V_{dc}. And then if you take the average of this waveform, the switched voltage waveform so, this is that you are going to get and that is your Vo bar average means here average over one switching cycle.

And similarly, your average for these leg voltages are also shown this is your V_{BN} bar the average over one switching time period and continuously it is done like that. So, V_{AN} bar that is the average for V_{AN}, the switched voltage waveform that you are going into obtain. And you can see that this V_{AN} bar average it resembles the V_{ANref} and V_{BN} bar that resembles the V_{BN} ref and the subtraction of these two V_{AN} bar and V_{BN} bar is what you will be getting as the $\overline{V}_o$.

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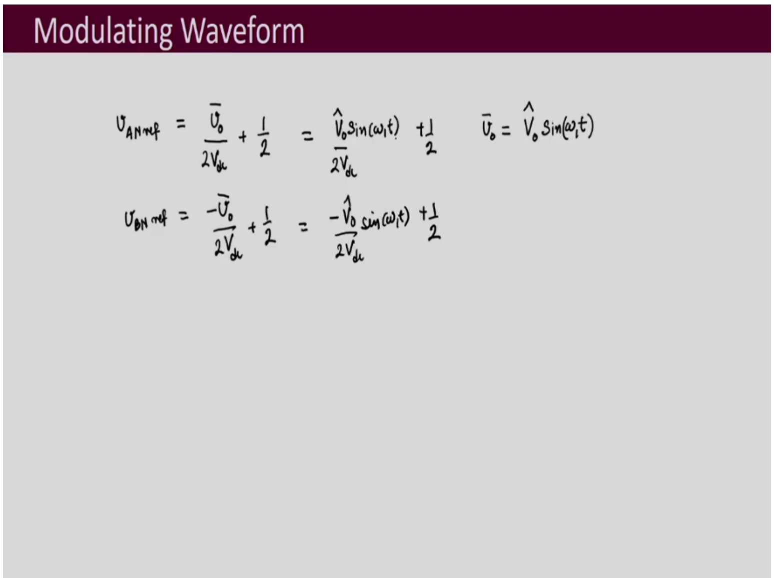

Now, let us discuss how do you obtain the modulating waveform for this Unipolar PWM. So, as we already saw that there are two reference waveforms one for leg A and leg B. So, this is given by your V_{ANref} which will be equal to your $\overline{V}_o$ means basically the average of the output voltage that you want to get

$$\frac{\overline{V}_o}{2V_{dc}} + \frac{1}{2}$$

Vo bar 2 Vdc plus half.

Again, to remind you that this average that we are telling is not over the fundamental frequency of $\overline{V}_o$ but over the switching time period.

$$\text{So,} \quad \frac{\overline{V}_o}{2V_{dc}} + \frac{1}{2}$$

is what is the reference that you can use for V_{ANref} and for V_{BNref} the reference waveform or the modulating waveform that you can use is

$$-\frac{\overline{V}_o}{2V_{dc}} + \frac{1}{2}$$

and this let us say your $\overline{V_o}$ the average that you need or the fundamental that you need of the switched output voltage waveform is equal to

$$\hat{V_o} Sin(\omega_1 t)$$

ω_1 is for to the denote that this is the fundamental.

So, then this will become equal to

$$\frac{\hat{V_o} Sin(t)}{2V_{dc}} + \frac{1}{2}$$

and this will become equal to

$$-\frac{\hat{V_o} Sin(t)}{2V_{dc}} + \frac{1}{2}$$

So, what you see is that these two reference waveforms are shifted by half means basically there is a DC shift and they are two sinusoids which are 180 degree out of phase.

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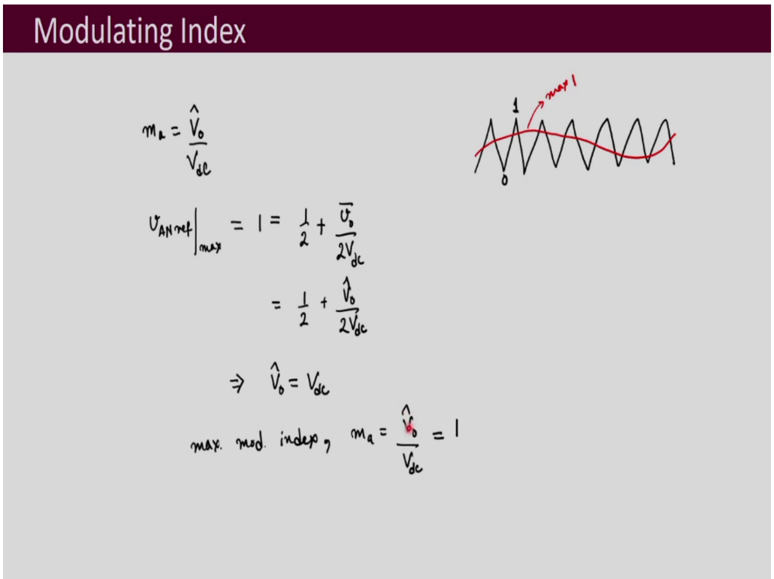

Next, let us look into the modulation index for Unipolar PWM. We had defined the modulation index m_a before in bipolar PWM also. So, it this we had defined as $\frac{\hat{V}_0}{V_{dc}}$ and what could be the maximum value for Unipolar PWM if we want to find out that so V_{ANref} what could be the max value of it. So, that is going to be equal to 1 because it is a sinusoid and its amplitude can be maximum equal to 1 as we are taking the carrier to be maximum equal to 1.

So, this carrier, this varies from 0 to 1. So, this modulating waveform can also be max equal to 1. So, then this will be equal to $\frac{1}{2} + \frac{\hat{V}_0}{2V_{dc}}$ based on what we just saw. So, $\frac{1}{2} + \frac{\hat{V}_0}{2V_{dc}}$ because $\sin\omega_1 t$ can have a maximum value equal to 1 and so, from here what you get this $\hat{V}_0$ can be equal to V_{dc} this is what is possible maximum.

So, that means the maximum modulation index that will be equal to your $\hat{V}_0/V_{dc}$ equal to 1 and if you cross that, then you will be doing over modulation that also is done sometimes, but if you want full control, then we should not exceed the maximum modulation index.

And so, from this what we understand is that to obtain $\hat{V}_0$ we have to at least have a dc bus voltage which is equal to V_{dc}. So, let us say if your $\hat{V}_0$ is equal to 500 volt, then you have to take the V_{dc} equal to 500 volt your dc bus had to be at least equal to 500 volts or it has to be greater than that. Now, let us discuss the Capacitor Current this is similar to what we had discussed for Bipolar PWM.

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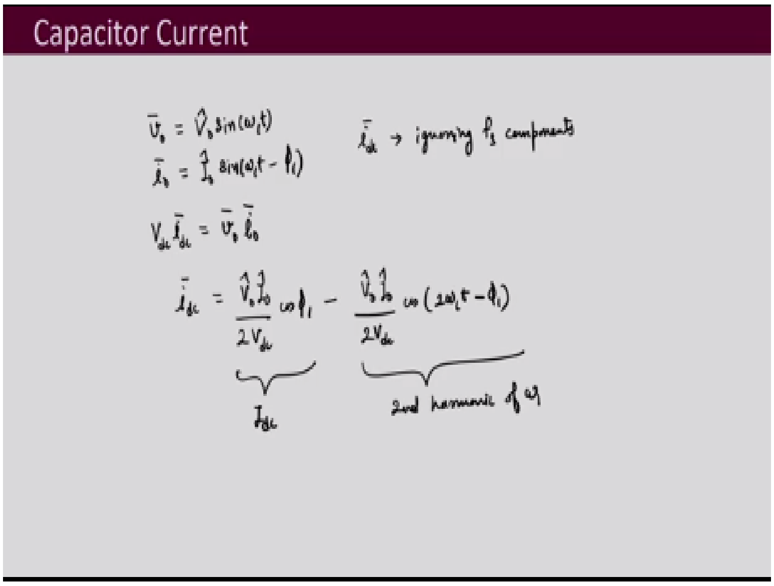

So, if we take the average over switching cycles, So, if this is

$$\overline{v_o} = \hat{V}_o Sin(\omega_1 t)$$

and $\overline{i_o}$ the average Current that you get over switching cycle

$$\overline{i_o} = \hat{I}_o Sin(\omega_1 t - \phi)$$

and this is all ignoring the switching frequency components. So, $\overline{V_{dc} I_{dc}}$ if we equate the DC power and AC power. So, $\overline{v_o i_o}$ and what is your $\overline{i_{dc}}$ that is your basically you have ignored switching frequency components.

So, when you substitute this and then you solve it what you will be getting is

$$\overline{i_{dc}} = \frac{\hat{V_o I_o}}{2V_{dc}} cos(\phi_1) - \frac{\hat{V_o I_o}}{2V_{dc}} cos(2\omega_1 t - \phi_1)$$

So, this is the i_{dc} the dc component and this one is the second harmonic of ω_1. So, what we see is that if we ignore the switching frequency components, then your, the DC component and the second harmonic component for Unipolar PWM also turns out to be the same.

So, that means irrespective of whether you are using bipolar, PWM Unipolar PWM, the capacitor that you choose for DC bus, it should be able to withstand the second harmonic component of your fundamental ω_1. And what it means that it should be able to withstand it basically means that your capacitor should be big enough that in spite of the second harmonic it is able to maintain the DC bus voltage and not higher ripples or voltage ripples are not increasing.

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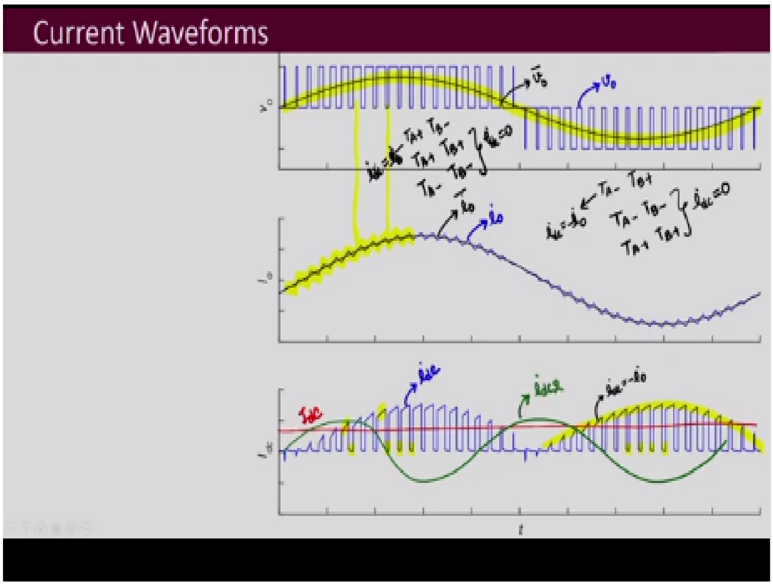

So, let us look into the waveforms. So, this is your output voltage waveform that we just saw. And this is the average τ of that which is your $\overline{v}_o$. And then, this one this current which is ripple that you see is your load current and whenever the voltage is positive let us say here this is positive this part you can see here that the current is actually rising it is increasing. And let us say over here, you can see that that the current is decreasing because the output voltage has become 0.

So that switching frequency ripple is there, but otherwise it is following a sinusoidal pattern. So, when you take the average of this rippled waveform, this black one, this is your $\overline{i}_o$ the averaged one and when you see the actual the blue one that is your i_o, which is what you will be seeing on the oscilloscope. And here also this one is the blue waveform is the actual waveform that you will be seeing on the oscilloscope and that is your v_o; instantaneous voltage waveform v_o.

Then your idc waveform the DC bus current waveform, you can form it using all the switching combinations in the direction of the current. So, what we see here is that here sometimes it is equal to i_o sometimes it is becoming 0 because we saw that when the voltage is positive this output voltage is positive at that time the switching combinations mostly that arise are the first two diagonal switches that means T_A+ T_B- are on.

So, in this region mostly your switching combinations that are arising are T_A+ T_B- and the upper two switches being on T_A + and T_B + and the lower two switches being on T_A- and T_B-. And for these two switching combination your i_{dc} equal to 0 whereas, for this switching combination when the Current is positive i_{dc} equal to i_o and so, that is what you will be observing here.

So, what you see here is that this is becoming in sometimes it is following your i_{dc} which is equal to i_o, same as i_o and otherwise it is becoming equal to 0. So, i_{dc} is switching between i_o and your 0 that is what we see. And over here when the voltage is becoming negative, the average voltage is becoming negative the switching combinations that mostly arise are T_A-and T_B+ and then next is your T_A- and T_B- or your T_A+ and T_B+ these are the three switching combination and corresponding to this switching combination your i_{dc} equal to minus of i_o and corresponding to these two switching combination your i_{dc} equal to 0.

So, accordingly you see here i_{dc} equal to minus of i_o that means what you just, if you flip this waveform if you invert it, so it will be following something like this and that is what we observe here i_{dc} equal to minus of i_o and otherwise it is becoming equal to 0. So, whenever these combinations are arising T_A- T_B- and T_A+ T_B+, then the Current is becoming equal to 0.

So, sometimes it follows plus i_o and 0 and other half it follows your minus i_o and 0. So that is your current waveform and it will have the components. So, one component is your this i_{dc}. i_{dc} you can say that the capital I_{DC} and this one is your instantaneous current waveform i_{dc} and but then you have another component which is the second harmonic component and that will be something like this that you are going to get and you can call it is i_{dc2}, the second harmonic component of the fundamental.

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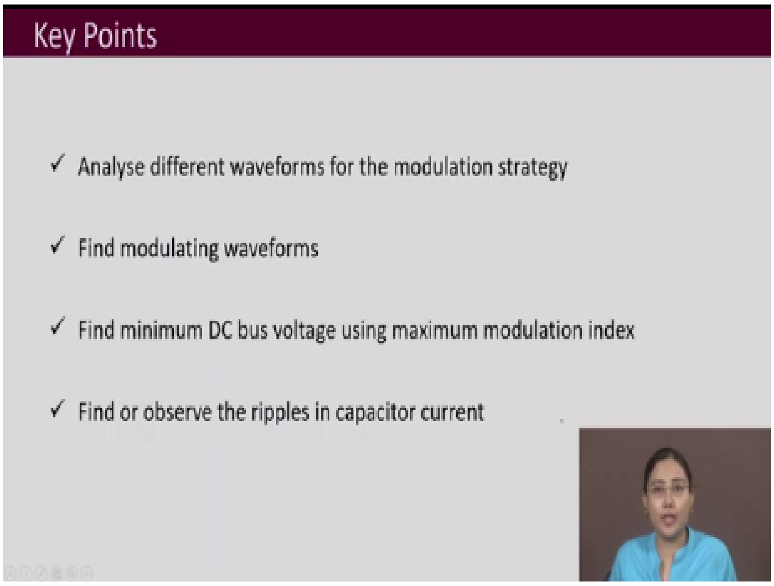

So, the key points of this lecture are the same as what we had the key points in Bipolar PWM. You have to analyse different waveforms for any modulation strategy, whichever modulation strategy you pick up, you find out the modulating waveforms because you have to get the reference to obtain your output and then you find out what is the minimum dc bus voltage that is required using the maximum modulation index. And then you also observe the ripples in the capacitor current that will help you in choosing the capacitor when you design the converter. Thank you.