**Design of Power Electronic Converters**
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**Module: Analysis of Power Electronic Converters**
**Lecture 6**
**Bipolar PWM**

Welcome to the course on Design of Power Electronic Converters. Today's lecture is going to be on Bipolar PWM. Last class we had discussed H bridge converters and we saw the different possible equivalent circuits and the switching combinations. And then I had mentioned you about pulse width modulations that there are different types of pulse width modulations for H bridge converters and depending on application you may choose the suitable one. The two most popular ones are bipolar PWM and unipolar PWM, the first one bipolar PWM is what we are going to see in this lecture.

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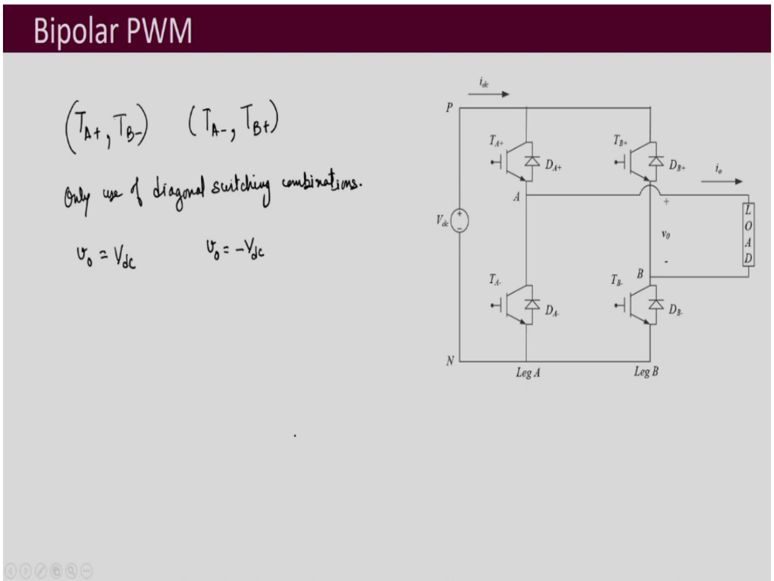


So, in Bipolar PWM what happens is that it uses only the two switching combinations that means, these two devices ($T_{A+}$, $T_{B-}$) the diagonal switch these two are operated together. They are always turned on and turned off together and the other two diagonal devices ($T_{A-}$, $T_{B+}$) these are also operated together and always turned on and off together.

So, you can consider it like a pair. So, ($T_{A+}$, $T_{B-}$) these always operated together and ($T_{A-}$, $T_{B+}$) these two devices are also always operated together. So, only use of diagonal switching combinations. Further, you may recall that what will be the output voltages. It has to be $V_o$ or $V_{dc}$ rather.

So, whenever we want $v_0 = V_{dc}$ and that time the switch $(T_{A+}, T_{B-})$ are on and whenever we want $v_0 = -V_{dc}$ at that time in $(T_{A-}, T_{B+})$ are turned on and we had also seen before that what will be the corresponding dc bus current $i_{dc}$ is going to be $(+i_o)$ whenever $(T_{A+}, T_{B-})$ are on and it is going to be $(-i_o)$ whenever $(T_{A-}, T_{B+})$ are on.

And depending on the direction of the current either the switch will be conducting so MOSFET will be conducting or the diode will be conducting. So, these things we have seen before.

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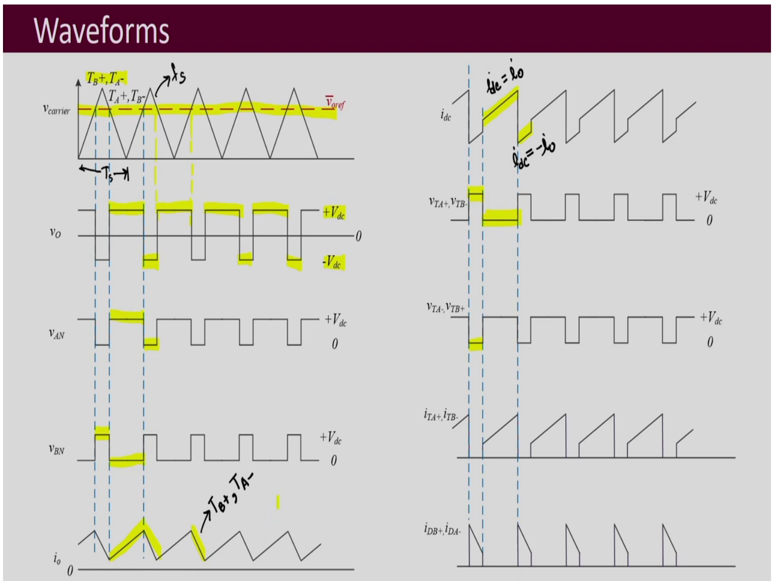


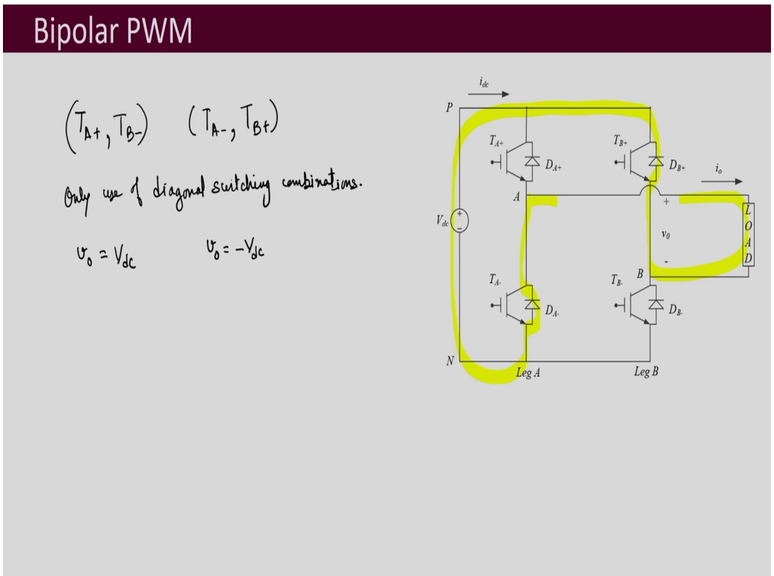


So, now, let us look into the waveforms. So, this is the carrier waveform which is shown here. Triangular carrier is chosen and this has the switching frequency $f_s$. So, one time period that you see here this is equal to $T_s$; the switching time period. Then this is the reference $v_{oref}$, the output voltage reference waveform with which we do the comparison.

And then on comparison, what we observe here is that the logic that is followed is whenever $v_{oref}$ is greater than $v_{carrier}$ at that time ($T_{A+}$, $T_{B-}$) are turned on. And whenever the opposite is happening that means $v_{carrier}$ is greater than $v_{oref}$, then the other two diagonal devices ($T_{A-}$, $T_{B+}$) are turned ON.

So, we can do these comparisons like this at every point and then accordingly here the output voltage wherever ($T_{A+}$, $T_{B-}$) are on at that place the output voltage $v_0 = V_{dc}$, otherwise, $v_0 = -V_{dc}$. So, the output voltage switches between $+V_{dc}$ and $-V_{dc}$ continuously. And what will be the leg voltages? So, leg voltage will be what whenever the upper switch is on at that time it is $V_{dc}$ otherwise, it is 0.

So, the leg A voltage $V_{AN}$ here $T_{A+}$ is on. So, it is equal to $+V_{dc}$ and otherwise $T_{A-}$ is on. So, it will be equal to 0 and so on. Similarly, for the leg voltage $V_{BN}$ also we see the same thing here. $T_{B+}$ on upper switch of leg B is on. So, this is $+V_{dc}$ and here $T_{B-}$ is on and so, the leg voltage is equal to 0 and this continues.

Then the load current, now load current for the waveforms that is shown here, here it is assumed that the load current is also positive. It is not going to negative, it depends on the load. Do not think that that is the case always. It may become positive, negative that depends on the load and also the on the output voltage. So, then what will happen whenever the voltage applied is $+V_{dc}$ at the output at that time the load current will increase because most of the time the load current, load is going to be inductive in nature so, when you apply a positive voltage across it the current will increase and then when we apply a 0 voltage or a negative voltage then the current will reduce and so, that is what is happening over here when output voltage is $-V_{dc}$ and this is continuing. Now, what about $i_{dc}$ the dc bus current? So, dc bus current here we see that in this part which are the devices conducting ($T_{A+}$, $T_{B-}$).

At that time current will be equal to $i_{dc}$, $i_{dc}$ will be equal to $i_o$ and whenever the other two diagonal switches are on $i_{dc}$ will be ($-i_o$) and that is what we observe here whenever ($T_{A-}$, $T_{B+}$) are on. So, this part is opposite of this part whenever ($T_{A-}$, $T_{B+}$) are on.

Then these device voltages, now blocking voltage will be $V_{dc}$ with $(T_{A+}, T_{B-})$ whenever they are not conducting else whenever they are conducting for ideal case it will be 0 and similarly, you can draw the other waveforms also for $(T_{A-}, T_{B+})$. Whenever they are conducting 0, not conducting blocking voltages $V_{dc}$. And the current that is carried by the devices. Now, here what we have assumed the current direction is always positive. So, when the current direction is also not positive what will happen whenever these two switches are turned on the first two diagonal switches$(T_{A+}, T_{B-})$ which are going to conduct. And whenever the opposite is happening, so, at that time the current direction is like this, it flows through the diodes comes through here and it flows through the diode here as well. So, $(D_{A-}, D_{B+})$ the two diodes are going to conduct. And that is what we see here $i_{TA+}$ and $i_{TB-}$ carries the current $i_o$ whenever they are on and else whenever these other two diagonal devices are on it is the two diodes which are carrying the current. Now, this is the waveform status that it shown here they are assuming the $v_{oref}$ is a dc reference.

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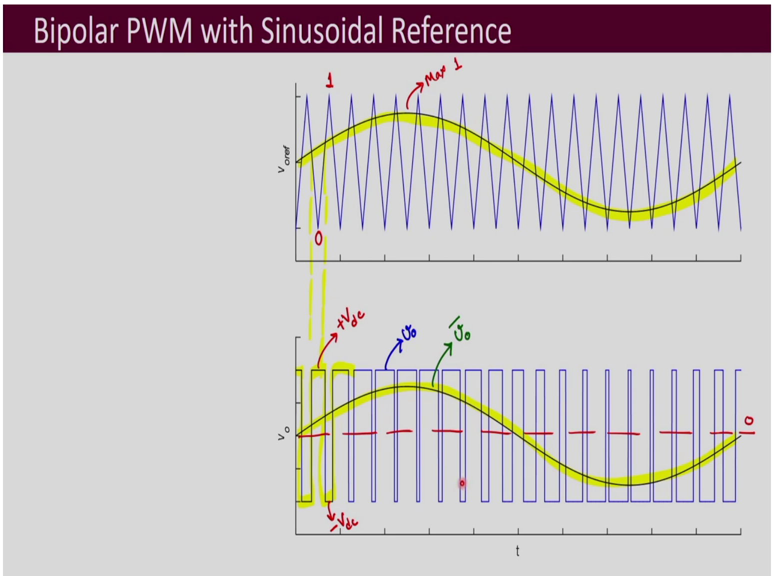


Now, this H bridge is also used for single phase DC to AC conversion. So, there the reference can be sinusoidal. So, how the waveforms are going to be then? So, this is $v_{oref}$ which is sinusoidal here you can see there and this reference, this is a triangular carrier which let us say goes from 0 to 1.

So, obviously this also can have maximum value as equal to 1 and not more than that. If it becomes more than that, then it will be greater than the carrier waveform and then the pulses will start getting missed out. And then this is the $v_{o(avg)}$. So, what this pulse says that we are seeing is what we get by doing the comparison. So, when we do these comparisons here, whenever this reference is greater than the carrier output is going to be $+V_{dc}$ else, this is going to be $-V_{dc}$.

So, this is what is 0 over here. So, this 0 goes from $+V_{dc}$ to $-V_{dc}$ and this waveform is actually the $v_o$ waveform the actual output voltage which you will see on the oscilloscope the instantaneous voltage waveform. And if we take the average of that waveform if we do the average of it, so, that is this $\overline{v_o}$ for every $t_s$ time period every switching time period if you take the average of $v_o$, then what you will be getting is this $\overline{v_o}$ which is this sinusoid which you are getting and which has to resemble the reference waveform to begin with. This average is also you can say is the fundamental component of this switch to voltage waveform.

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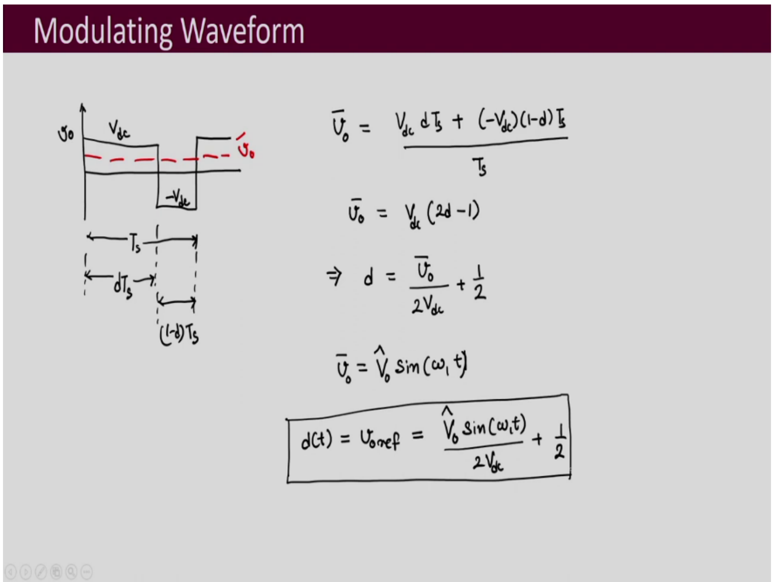


Now, next let us see how to obtain the reference waveform. How do you obtain the equation for it? So, for that let us consider only one switching time period $T_s$. So, let us say this is $v_o$ waveform for one switching time period $T_s$ and this part is when the first two diagonal switches are on. So, we call it as $dT_s$ and this other is $(1 - dT_s)$ and this waveform will have an average and that is that $\overline{v_o}$ that we are talking about and this varies from $+V_{dc}$ to $-V_{dc}$.

So, we can write

$$\bar{v}_0 = \frac{V_{dc}\, d\, T_S + (-V_{dc})(1-d)\, T_S}{T_S}$$

So, then further what you get from this is

$$\bar{v}_0 = V_{dc}(2d - 1)$$

From which you can write,

$$d = \frac{\bar{v}_0}{2V_{dc}} + \frac{1}{2}$$

So, using this equation you can obtain the duty ratio. Now our target voltage, target output voltage is a sinusoidal voltage. Let us say

$$\bar{v}_0 = \hat{V}_0 \sin sin\, (\omega_1 t)$$

Now, I am using this $\omega_1$ to denote that this is the fundamental. So, in that case,

$$d(t) = v_{0\,ref} = \frac{\hat{V}_0 \sin sin\, (\omega_1 t)}{2V_{dc}} + \frac{1}{2}$$

So, this is the equation for the modulating waveform which you can use to compare with the triangular carrier and generate the get pulses for the bipolar PWM. There is another term corresponding to pulse width modulation which is used in Power Electronic Converters which is called as the modulation index.

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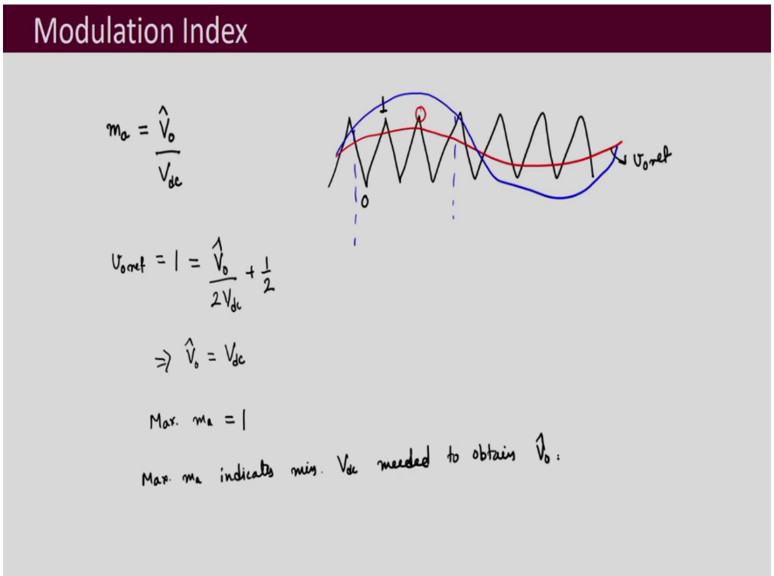


Now, this modulation index it is denoted as

$$m_a = \frac{\hat{V}_0}{V_{dc}}$$

Now, I am defining it as $\hat{V}_0$ the peak of the output voltage by $V_{dc}$. Peak of the output voltage means the peak of average waveform $\overline{v}_0$. Sometimes in books people also write the RMS value of it. So, know that value of modulation index will change accordingly.

So, you can use either definition but you just have to be aware which definition you are using because modulation index value will change accordingly. So, now, what happens is that if this is triangular carrier waveform and then you have this reference, the carrier varies from 0 to 1. Let us say, the $v_{oref}$ that we are using it can have a maximum value as equal to 1 otherwise, it will start crossing these carrier peaks and so, then what will happen is that the comparison will not happen, some pulses will start to miss out like for example, if the reference waveform becomes like this. So, here till here you will actually get no pulse.

So, then that means we are losing over the control the desired average waveform that we were supposed to get which we are targeting that is not going to come by the PWM method and it will have more harmonics into it, or lower order harmonics may start coming as well. So, this is mostly avoided, but although there may be situations where this rule may be violated that we would like to keep this reference waveform below 1.

So, then what that is called as over modulation. So, that is also done from but for our purpose, we would not like to violate it let us say we want to keep it below this the reference should be below the carrier waveforms maximum. So, accordingly, there is a maximum value for this modulation index which this modulation index can take for a particular method of PWM. So, then if we want to write that, if we want to find out that for bipolar PWM what that maximum modulation index is going to be.

So,

$$v_{0\,ref} = 1 = \frac{\hat{V}_0}{2V_{dc}} + \frac{1}{2}$$

So, if you solve it what you get

$$\hat{V}_0 = V_{dc}$$

So, that means maximum modulation index can be equal to 1 in case of bipolar PWM.

So, what is the use of these maximum modulation index? This gives us an indication of what is the minimum $V_{dc}$ that you require. Usually when you are designing a converter then you know what is output, what is the targeted output. Then if you have the targeted output then you have to find out how much is the DC bus voltage that needs to be created.

So, using the maximum modulation index for the particular PWM we are using you will be knowing that this is the minimum DC bus voltage that is required. So, maximum modulation index indicates minimum $V_{dc}$ needed to obtain $\hat{V}_0$.

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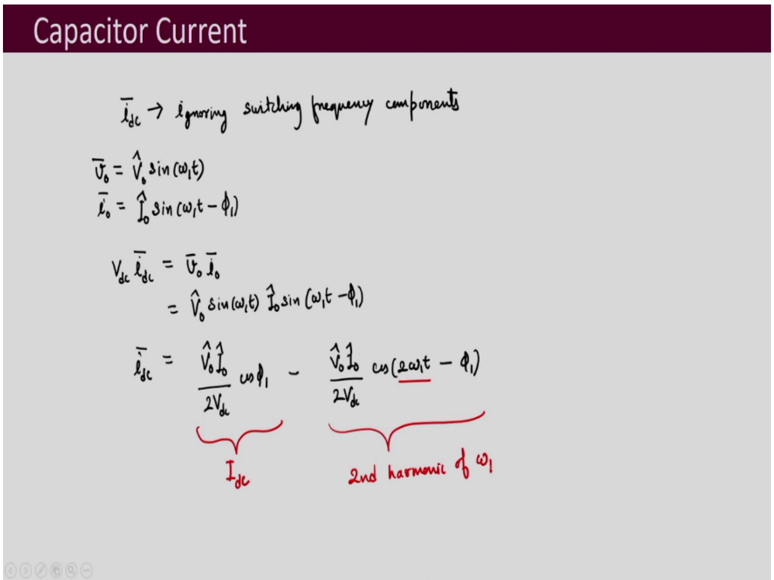


Now, let us find out an expression for Capacitor Current. This Capacitor Current also plays a very important role in the choice of capacitor. And here to do this we will ignore the switching frequency component we will use this $\bar{i}_{dc}$ because DC bus Current is $i_{dc}$, which is the actual current and we will be ignoring the switching frequency components for now, and that we will be denoting as $\bar{i}_{dc}$.

So, everything taking as the average expression so,

$$\bar{v}_0 = \hat{V}_0 \sin sin\,(\omega_1 t)$$

$$\bar{i}_0 = \hat{I}_0 \sin sin\,(\omega_1 t - \emptyset_1)$$

$\bar{i}_0$ this is also the average of the output current, the load current over one switching time period. So, let us say $\emptyset_1$ there is a lag in it and which is $\emptyset_1$.

So, if we assume everything to be ideal and lossless, we can write

$$V_{dc}\bar{i}_{dc} = \bar{v}_0\bar{i}_0$$

It is the DC power is equal to AC output power. So, then you substitute.

$$= \hat{V}_0 \sin sin\,(\omega_1 t)\ \hat{I}_0 \sin sin\,(\omega_1 t\ -\ \emptyset_1)$$

If you solve it, you have to do little trigonometry here if you solve that what you will be getting

$$\bar{i}_{dc} = \frac{\hat{V}_0\hat{I}_0}{2V_{dc}}\cos cos\,\emptyset_1\ -\ \frac{\hat{V}_0\hat{I}_0}{2V_{dc}}2\omega_1 t\ -\ \emptyset_1)$$

Now, what you observe here is that this component is not varying it is a DC value. So, this is dc component $i_{dc}$ of the capacitor current. Usually what we will expect is that it is a dc bus current means that should be a flat dc, but we have seen flat dc is not what flows through the dc bus it is a ripple. It has got a switching frequency ripple which we have ignored.

So, then definitely it should be only the dc component which should be there. So, that of course we are seeing but what we see is that there is something else to it and this is varying with frequency twice the fundamental. So, this is the second harmonic of $\omega_1$. So, second harmonic component is also present in case of H bridge converter when we use this bipolar PWM and that is a disadvantage because then second harmonic is a much lower frequency harmonic. Let us say if you have a 50 Hz output and 100 Hz component in the capacitor current. So, you have to choose a capacitor large enough which can withstand that 100 hertz component of current in the dc bus and still maintain the dc bus voltage.

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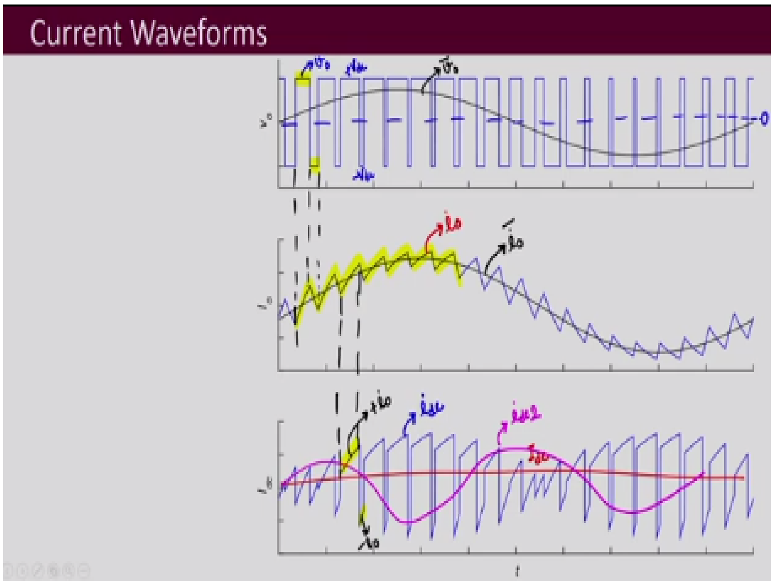


So, let us look into the current waveforms. So, this is the output voltage waveform instantaneous output voltage waveform this is $v_o$ which varies from $+V_{dc}$ to $-V_{dc}$ and this is the 0 of it, instantaneous output voltage waveform and this is the $\bar{v}_0$ the average of it what we saw over switching time periods if we average the instantaneous output voltage waveform we will be getting that $\bar{v}_0$.

Then what happens further is that that if we draw the load current waveform then if it is a sinusoidal waveform the load current will be how it is going to appear since it is assuming an inductive load. So, whenever the voltage is positive so, here the voltage is positive its $+V_{dc}$ what will happen the current will increase and then whenever the voltage is $-V_{dc}$ the current will decrease and this nature of the current increasing decreasing continues and it follows a kind of a sinusoidal nature.

So, then this current, this is actual $i_o$ current, which you will be seeing on the oscilloscope and if you again take the average of it, so, that is the average current this is the average current the black one is the average current or $\bar{i}_0$ which we just used for calculation. So, this is the $i_{dc}$ waveform you can see here that whenever this part, let us say whenever the first two diagonal switches are on at that time this is equal to $i_o$.

So, here this is equal to $i_o$. So, this part it is equal to $(+i_o)$ and this part you can see that it is equal to $(-i_o)$ here and so forth it continues like this. So, using this waveform, you can find out this $i_{dc}$ waveform also. And what we see is that it's a very switched current waveform.

So, it has got several components in it, one component is this DC that will be there which is $i_{dc}$ and then it will have also the second harmonic component so that will be $i_{dc2}$ let us call it and of course the switching frequency component will be there and finally this is actual $i_{dc}$ waveform that we see that you are going to see on the oscilloscope.

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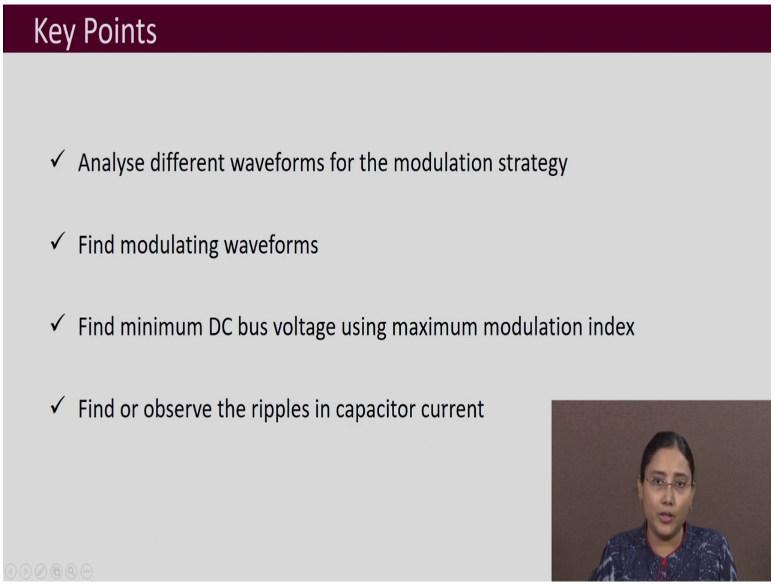


So, the key points of this lecture are that when you choose a modulation strategy, you have to analyse that modulation strategy. Different modulation strategies are there and you can pick one for your converter, you can analyse different waveforms for that modulation strategy. And you have to find out the modulating waveform because when you are going to design it you have a particular output and you need that output.

So, you have to get the modulating waveform which can generate that particular output. So, those equations are required. And then you also find out the maximum modulation index that will give you an indication of the minimum dc bus voltage that is required. And you should also observe the capacitor current ripples or you can find it out if equations are available for that or you can simulate and you can observe the capacitor current waveforms then that will give you an idea that how big capacitance you need to maintain the dc bus voltage. Thank you.