Design of Power Electronic Converters
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Lecture 39
Power Loss - II

Welcome to the course on Design of Power Electronic Converters. We had started the module of Thermal Design. And the last lecture, I told you about power losses, the different power loss that take place in power electronic converters. And we were mainly discussing the semiconductor device losses. So, let us look more into it about the loss calculation of semiconductor devices.

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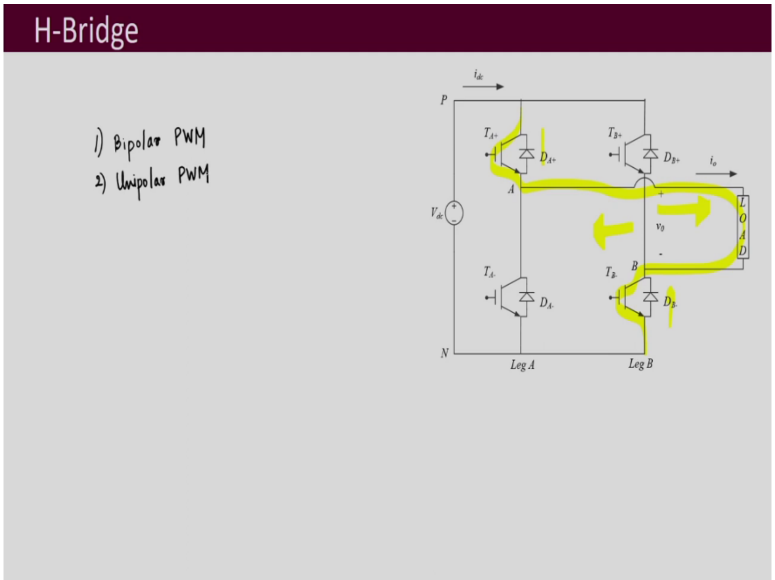

H-Bridge

1) Bipolar PWM
2) Unipolar PWM

Last lecture, I took example of a very simple converter, the buck converter, where loss calculations are going to be much simpler because the waveforms, your the waveforms across the devices, the device currents and the device voltage waveforms are very simple in nature, but for every converter that is not going to be so, the device voltage waveforms and current waveforms may be much more complex.

So, to see what is the challenge there, let us take the example of H-bridge converter. So, this is the familiar H-bridge converter, which we have discussed before. So, just to refresh your memory, so, here if this TA plus and your TB minus are conducting that means, these two diagonal switches are conducting. So, at that time the voltage that appears over here is plus Vdc.

And if the opposite two diagonal devices are conducting, that is your TB plus and TA minus then the voltage that appears here is equal to minus Vdc. And if the current direction is positive that is it is in this direction, then your these two devices TA plus and TB minus the transistors are going to carry the current, but if the current direction is opposite it is in this direction then it is the diodes DA plus and DB minus which are going to carry the current.

So, depending on the direction of your output current io it gets decided whether the transistor will conduct or whether the diode will be conducting. And apart from the diagonal switching combinations there are other switching combinations possible that means, the upper two devices may be on or the lower two devices may be on. And further we had seen two modulation strategies also before one is your bipolar PWM and the second is Unipolar PWM. So, let us look into those waveforms.

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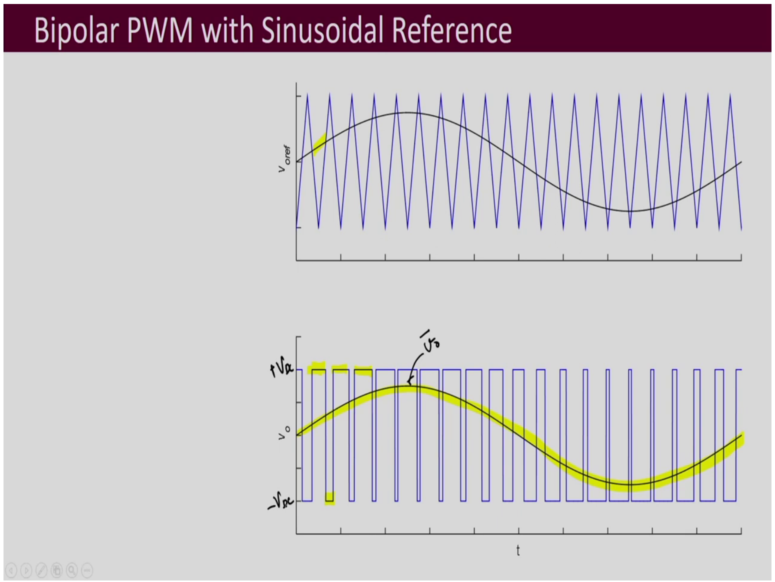

Bipolar PWM with Sinusoidal Reference

So, this is the bipolar PWM which sinusoidal reference where whenever this career is smaller than the reference waveform that is here you can see that then what happens is that at that time the output is equal to plus Vdc, this is what we see here this is equal to plus Vdc. And whenever your the opposite happens, the output voltage becomes equal to minus Vdc.

And this continues in then if we take the average of it, so then this is that waveform the average on the switching time interval, this is the Vo average that you will be obtaining. So, this is your Vo bar, the Vo average and this is your plus Vdc and this is minus Vdc.

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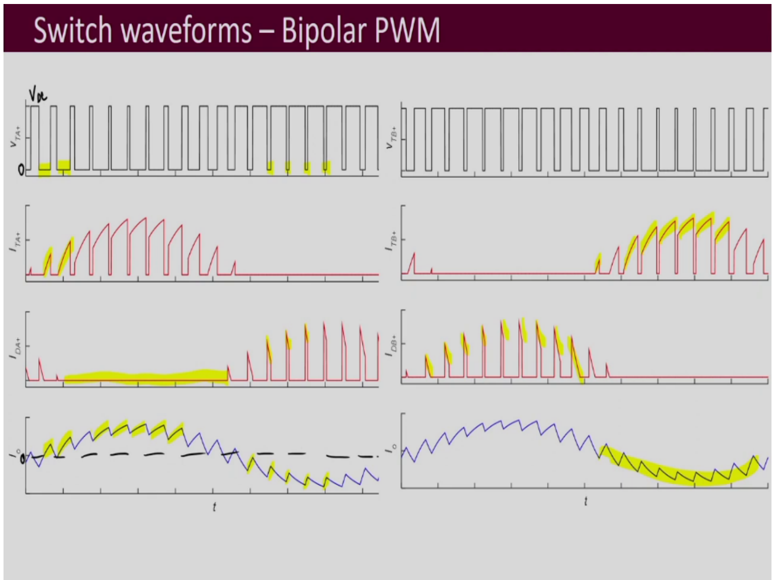

Switch waveforms – Bipolar PWM

Now, if we plot the voltage waveform and current waveform across the devices. Now, we have got four devices actually eight of them, four IGBTs and four diodes, four anti parallel diodes. So, we should draw the voltage waveforms and current waveforms across all of them. To find out how much is the conduction loss and switching loss that will be taking place.

Now, here I have shown only four of them, that is your voltage and current through the diode of TA plus and of the transistor TA plus and also your voltage across the upper switch TB plus and the diode DB plus. So, this TA plus voltage and current through it and this diode DA plus voltage across it and current through it. Now, voltage across both of these TA plus and DA plus will be same.

And also have shown for the TB plus and DB plus again the voltage will be the same across both the devices it is the current which may be different. So, this is the voltage waveform across TA plus and this is the current waveform for TA plus and this is the current waveform for DA plus and this is the load current Io. Now, here what we see is that this is when the switch voltage is 0 or low that means, this switch is on at that time.

So, here this is your 0, you can say that and this is equal to Vdc. So, here your switch voltage is low, so the device is on. So, at that time, we know that if the current direction is positive, so then your transistor will be conducting. So, here for this time interval what we see that the current is positive. So, here this is the same current that appears over here.

So, this is the 0 of the current. Further again what we see when again TA plus is on at that time if the current is positive. So, Io becomes equal to your ITA plus. And in those intervals while the current is clearly positive over here and the switches on at that time, what we see is that this diode current is equal to 0 that means, your diode DA plus is not conducting. When the current becomes negative and then this switch is turned on, for example, these intervals.

Here, the current has become negative and during these intervals what we observe is that it is the diode which is going to carry the current and that is what we see here. Now, this is of course, is going to be opposite because the direction of the current which is assumed positive for the diode. So, that will be opposite to what is the direction of the current which was assume positive for the output current.

So, that is why it is appearing as positive. But, what we observed from here is that sometimes the transistor conducts sometimes the diode conducts and how the voltage waveforms and current waveforms are getting formed from the output current. Similarly, this is for your TB plus the voltage across the device and this is the current through TB plus.

Now, TB plus conducts when the current is negative and that is what we see here that during these interval the current is negative and that is when we see TB plus whenever it is on to be carrying the current. And when the current is positive, the output current is positive and the switch is turned on we see that the diode DB plus is carrying the current and so this is the finally the shape of the current waveforms through the devices. And similarly, you can also see the voltage and current waveforms across the rest of the devices.

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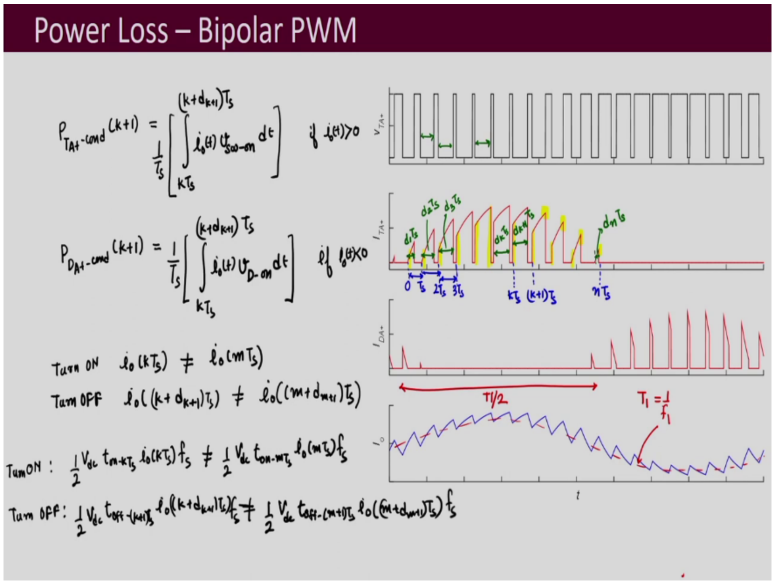

Power Loss – Bipolar PWM

$$P_{TA+\text{-cond}}(k+1) = \frac{1}{T_s}\left[\int_{kT_s}^{(k+d_{k+1})T_s} i_o(t)\, v_{sw\text{-}on}\, dt\right] \quad \text{if } i_o(t) > 0$$

$$P_{DA+\text{-cond}}(k+1) = \frac{1}{T_s}\left[\int_{kT_s}^{(k+d_{k+1})T_s} i_o(t)\, v_{D\text{-}on}\, dt\right] \quad \text{if } i_o(t) < 0$$

Turn ON $i_o(kT_s) \neq i_o(mT_s)$

Turn OFF $i_o((k+d_{k+1})T_s) \neq i_o((m+d_{m+1})T_s)$

Turn ON : $\frac{1}{2} V_{dc}\, t_{on\text{-}kT_s}\, i_o(kT_s)\, f_s \neq \frac{1}{2} V_{dc}\, t_{on\text{-}mT_s}\, i_o(mT_s)\, f_s$

Turn OFF : $\frac{1}{2} V_{dc}\, t_{off\text{-}(k+1)T_s}\, i_o((k+d_{k+1})T_s)\, f_s \neq \frac{1}{2} V_{dc}\, t_{off\text{-}(m+1)T_s}\, i_o((m+d_{m+1})T_s)\, f_s$

Now, let us have some more insight into what is happening here. So, half of this interval, let us call it as T1 by 2. Now, what is T1? T1 is equal to 1 by f1 which is your fundamental frequency. The first harmonic you can say that the fundamental, so this current whatever is the average that you take place, its frequency will be equal to f1. Here, this frequency is f1.

Now, over here let us divide these in different, different small Ts intervals, let us call this as the 0 interval, 0 and this is Ts and this is equal to 2Ts. Similarly, this is 3Ts. So, this is one switching time period, this is another second switching time period, this third switching time period. Similarly, we can continue doing it and let us say this is equal to k Ts. So, this one here will be equal to k plus 1 Ts. Now, here this is let us say is equal to n Ts.

So, what we are saying is that, that your T1 by 2 interval is divided into n Ts switching time intervals that means, your n switching intervals are present in half of the fundamental, let us take it like that. Now, this one your duty ratio, let us say here the duty ratio is d1. So, this interval is d1Ts, then further this interval, let us say this is equal to d2Ts, because what we observe here is that that these duty ratios are different.

You can see here the duty ratio over here and the duty ratio here, and here these are all different, at each point the duty ratio is different in whenever you have a sinusoidal reference, because you have a career and you have a sinusoidal reference and you are comparing, so different, different points and duty ratios are different.

So, let us say this is equal to d3Ts and here because this is the k Ts interval, let us say this is equal to d k Ts and for the K plus 1 interval this is equal to d K plus 1 times Ts. And this one here, this is equal to dnTs. Now, if we have to write the conduction loss for TA plus for let us say the K plus 1 interval, so, for K plus 1-th interval, it will be given as

$$P_{TA+\_cond}(k+1)=\frac{1}{T_s}\left[\int_{kT_s}^{(k+d_{k+1})T_s} i_o(t)v_{sw\_on}dt\right] \qquad \text{if } i_o(t)>0$$

And this we are assuming that during this time the output current is positive because that is only when the transistor TA plus will be conducting. So, what we have done here is that that this for this k plus 1 net interval your this Io current is what will be getting, is what the transistor will be carrying. So, that is why for this interval from K ts to dk plus 1 Ts is we multiply the on-state voltage drop with the current to obtain the conduction loss.

And then we integrate and divided it with the switching time interval. Similarly, we can write for the diode as well,

$$P_{DA+\_cond}(k+1)=\frac{1}{T_s}\left[\int_{kT_s}^{(k+d_{k+1})T_s} i_o(t)v_{D\_on}dt\right] \qquad \text{if } i_o(t)<0$$

And this we are assuming that during this time the output current is negative, because when the current is negative that is when the diode conducts.

Now, what we observed from this is that for each interval each switching time interval this integration is going to be different, because first of all your duty ratios are different and secondly, the load current the output current is also different in different switching time interval. So, conduction loss is different in each switching time interval.

So, now, if you want to do it by hand it will not be as simple as far as buck converter where we got a very simple expression dIL square into Rds-on and that gives you the conduction loss, that is not how simple it is for when you are using H-bridge and want to obtain sinusoidal output from it. So, then we have to use some simulation tools to estimate the conduction losses.

Now, let us also see for the switching loss. So, what we see here is that at these points over here. So, these are the points where the device is turning on and these are the points where devices turning off. And what we see here is that for each turn on, so these are your turn on instances. So, what we see is that that each turn on the current with to which it has to reach that is different.

And similarly during every turn off also we will be observing the same thing that every turn off switching time, every switching time period you turn off current means how much it has to turn off by here the current is has to turn off from here then in this interval it has it is a different level here it is a different level here the current level is very small to turn off. So, different switching time periods your turn off current is also different.

Your Vdc that may be an unchanged, but the current the turn on current and turn off currents are different. So, if we have to write it, so for your turn on your output current

Turn on

$$i_o(kT_s) \neq i_o(mT_s)$$

And similarly, for your turn off .

Turn off

$$i_o((k+d_{k+1})T_s) \neq i_o((m+d_{m+1})T_s)$$

So, your switching loss also, so if you have the turn on loss

$$\frac{1}{2}V_{dc}t_{on-kT_s}i_o(kT_s)f_s \neq \frac{1}{2}V_{dc}t_{on\_mT_s}i_o(mT_s)f_s$$

And similarly, we can write for turn off as well.

$$\frac{1}{2}V_{dc}t_{off-(k+1)T_s}i_o((k+d_{k+1})T_s)f_s \neq \frac{1}{2}V_{dc}t_{off\_(m+1)T_s}i_o((m+d_{m+1})T_s)f_s$$

So, what is the takeaway from here is that your turn on losses and turn off losses, each interval is different each switching time period is different.

And not only that, the turn on time and the turn off times are also going to be different. Let us say if using a simulation tool you can find out the turn on currents and turn off currents, but it will be difficult for you to estimate the turn on time and turn off time in different, different switching time intervals. Because the turn on and turn off time they are dependent on different things, they are also a function of the current they has to turn on or turn off.

Apart from that we have seen before that turn on and turn off times depends on various other things like temperature and what is the DC bus voltage several factors are there which make them variable. Similarly, your on state voltage drop that also is not fixed. So, what we get from here is that these conduction loss and switching loss you can have an estimate of it, but it is difficult to exactly calculate what the conduction loss and switching losses are going to be.

So, simulation tools you can take help of them and you can try to estimate how much is the loss the semiconductor device loss that is taking place in your power electronic converter and from there you can have an estimate of the efficiency. But the actual efficiency you get to know only when you do the experiment there you measure the input voltages and input currents and you measure the voltages and output currents and from there you get what is the efficiency of your converter.

And then now, you may be wondering because there are so many other losses that are also taking place there are magnetics losses, then I square losses from different, different miscellaneous elements that are present in the converter. So, what is exactly the semiconductor device loss, that will be difficult to separate it out, but overall for your thermal design for your heatsink selection, you can use simulation tools to estimate them and based on it then you can select a heatsink and your cooling method and you can perform the experiment find out the efficiency and then you if required you might have to change the thermal design.

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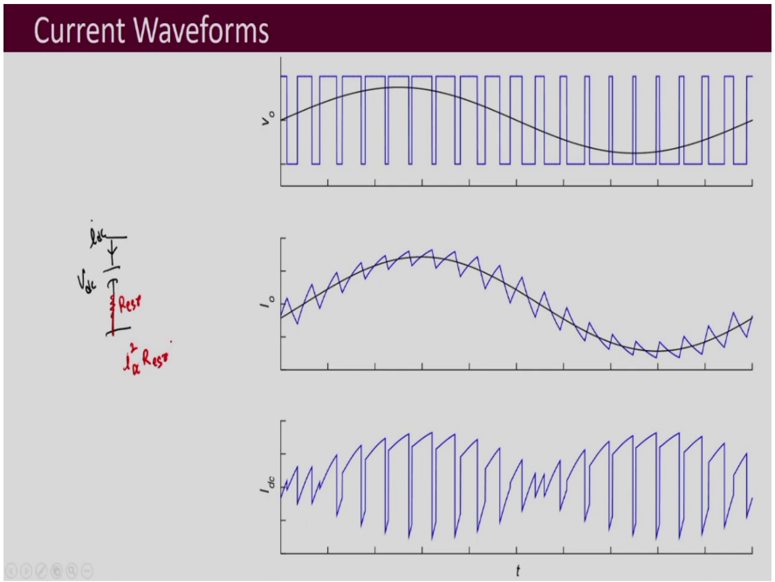
Current Waveforms

So, your current waveforms this also we had seen before. So, this is your output voltage waveform, the switch voltage waveform, this is the output current waveform and the sinusoidal ones are the average of them and from there we previously we had seen this is the DC bus current that you obtain. Now, this DC bus current you can see here this is a switched current waveform. And then this DC bus current multiplied by the ESR of the DC bus capacitor that will be leading to the losses that takes place in the capacitor.

So, what I am telling is that that you have a DC bus. So, here you will be having your voltage Vdc and your idc, this DC bus current to can flow through it, and then that it will have its own ESR. So, that is the Resr if you want to call it as. So, idc square Resr will be the loss that will be taking place in the capacitor.

So this is just to give you an idea of the I square R losses that takes place in different element, so like that you have so many elements where I square R losses will be taking place and you have to take into account the different ESRs of different passive elements.

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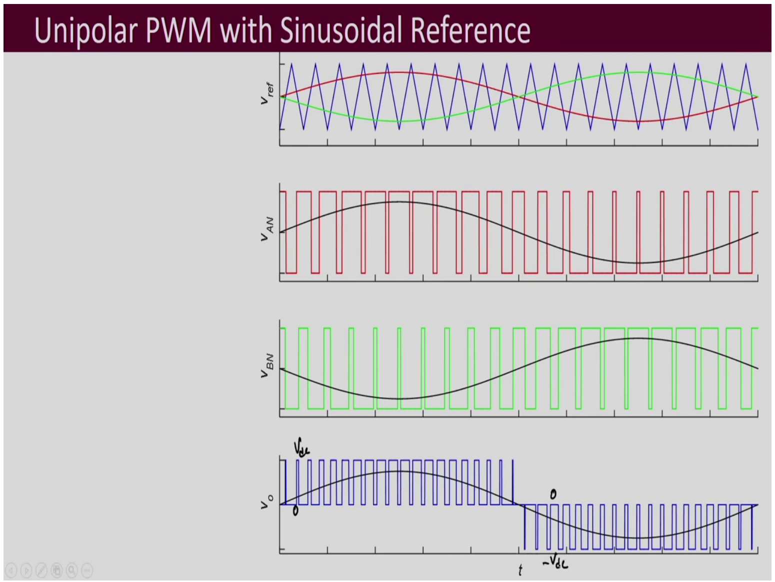

Unipolar PWM with Sinusoidal Reference

Now, let us look into the waveforms of unipolar PWM. This is the waveform that we have discussed before. Unipolar PWM you have got two references and these are the two leg voltages Van and Vbn and then accordingly from there the subtraction of these two gives you the output voltage waveform and it varies from 0 to Vdc and from 0 to minus Vdc.

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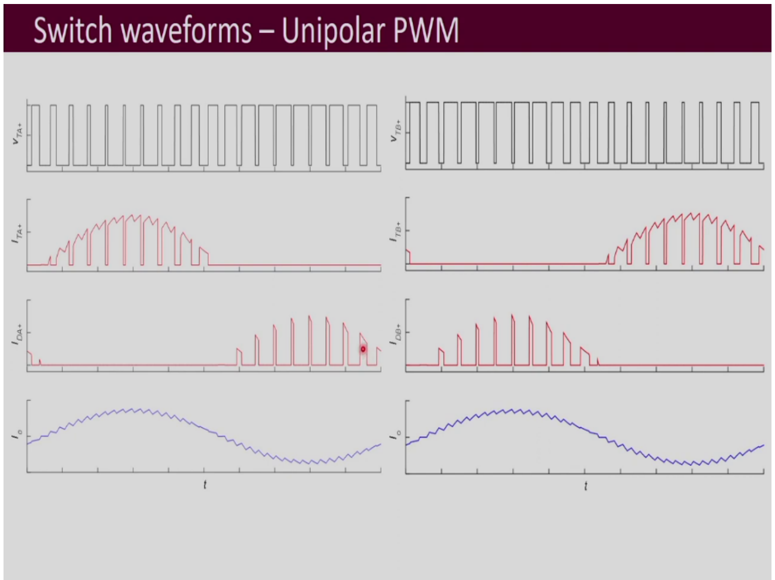

Switch waveforms – Unipolar PWM

So, let us look into the switch waveforms. So, for the same devices TA plus DA plus TB plus and DB plus I have shown the voltage waveforms and current waveforms. You can see here these different voltage waveforms and these current waveforms ITA plus and IDA plus and this is the output current Io. Now, what you can see here is that that here the shape of the current waveforms the switch current waveforms is different because your Io current nature itself is different.

And also your VTA plus that shape has also changed. So, now, if we calculate the conduction loss and switching loss for this Unipolar PWM the losses that you will be getting will be different than what you will be getting for bipolar PWM. So, what we understand from this is that your switching loss and conduction loss, not in each switching time interval that different and depends on other things that we just discussed a while ago.

It also depends on the modulation strategy, which modulation strategy you are using for your power electronic converters that play an important role in the total loss that takes place and also therefore in the efficiency of the converter.

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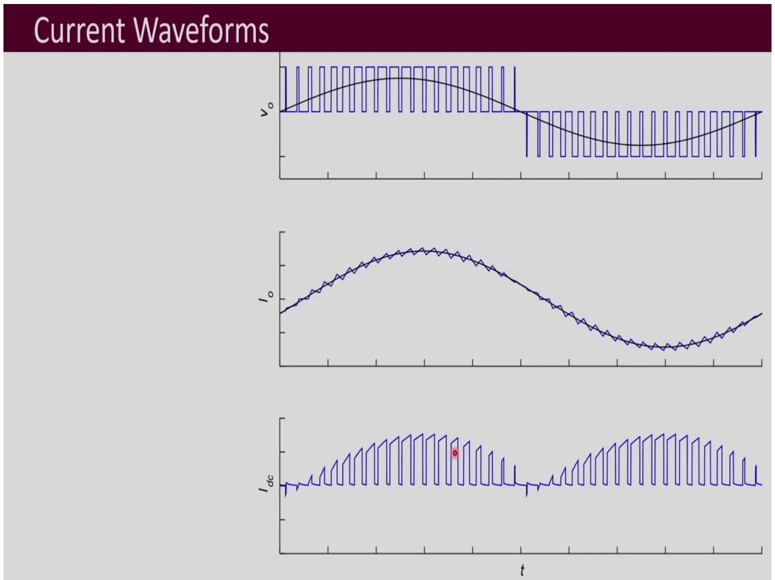

Current Waveforms

And further these current waveforms which I just showed you for bipolar PWM. The same waveforms are now here shown for Unipolar PWM, you can see here the nature of the DC bus current is very different. And so obviously your I square R losses that will be taking place in the capacitor will also become different. So, overall losses will change if you are using Unipolar PWM as compared to linear bipolar PWM or if you use any other PWM method.

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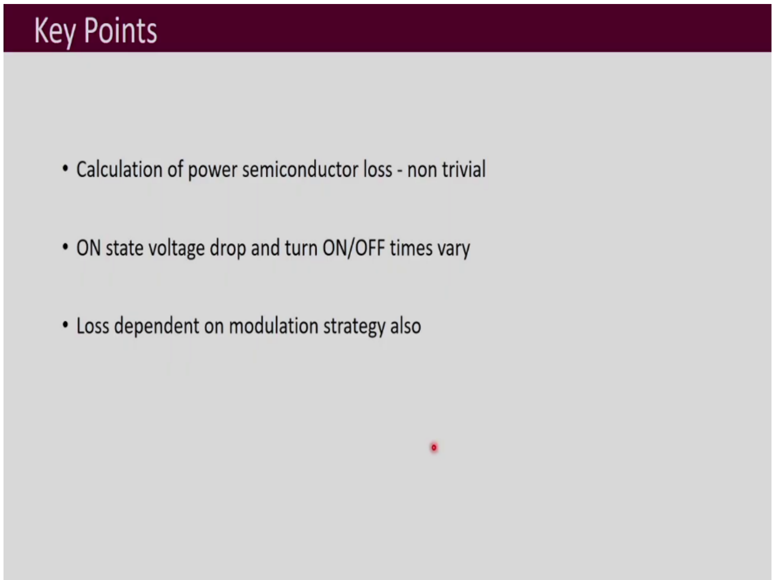

Key Points

- Calculation of power semiconductor loss - non trivial
- ON state voltage drop and turn ON/OFF times vary
- Loss dependent on modulation strategy also

So what are the key points of this lecture? So, what we see that the calculation of your power semiconductor device losses, they are non-trivial. You cannot just simply use some very simple equation and you can obtain the device losses. You may use simulation tools to have an estimate of the device losses. And the on-state voltage drop and turn on and turn off times they vary on depending on several factors.

So, that is why we can only estimate them using simulation tools. To know it, how much is the total loss that is taking place you have to perform experiments. And also know that the power losses are also dependent on the modulation strategy that you are going to use in your converter. Thank you.