High Power Multilevel Converters - Analysis, Design and Operational Issues

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Lecture - 02
Basic Understanding of Converter - (Half bridge and full bridge circuit operation)

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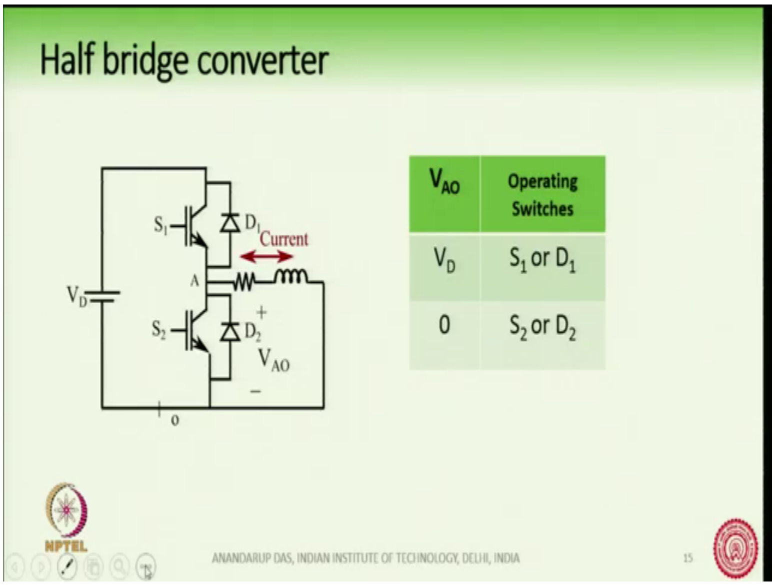

So, in this Half bridge converter we see that the switch S 1 or D 1 or the switch S 2 and D 2 may be conducting. So, how do they conduct, it is shown in this slide.

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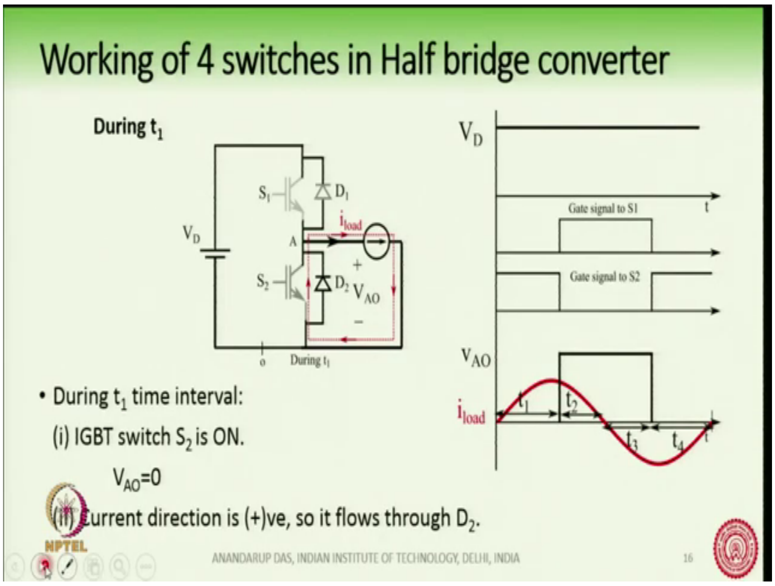

Here we have given the gate signal to S 1 and the gate signal to S 2 here. So, if S 1 gate signal has been given then the upper switch turns on the voltage between point A and O will be like this here, suppose the current waveform is alternating in nature. So, sometimes the current is positive and sometimes the current is negative.

Let us take the interval t 1 where the current is positive while the voltage between points A and O is 0, which means the lower switch is on. During this time we have now two possibilities either S 2 will be on or D 2 will be on and we see that because the current is positive direction; that means, the current is flowing from left to right only D 2 is conducting, because D 2 has this path and the path of the current is like this. So, the path of the current is shown here this is the path of the current and D 2 is conducting so, the circuit is getting completed like this D 2 i load and like this here.

So, we see that in spite of giving pulse to S 2 during this time, the IGBT is not conducting it is the diode D 2 which is conducting and the voltage between point A and O is 0, because if it is an ideal diode, the voltage drop across the diode is 0. So, basically point A and O are at the same potential.

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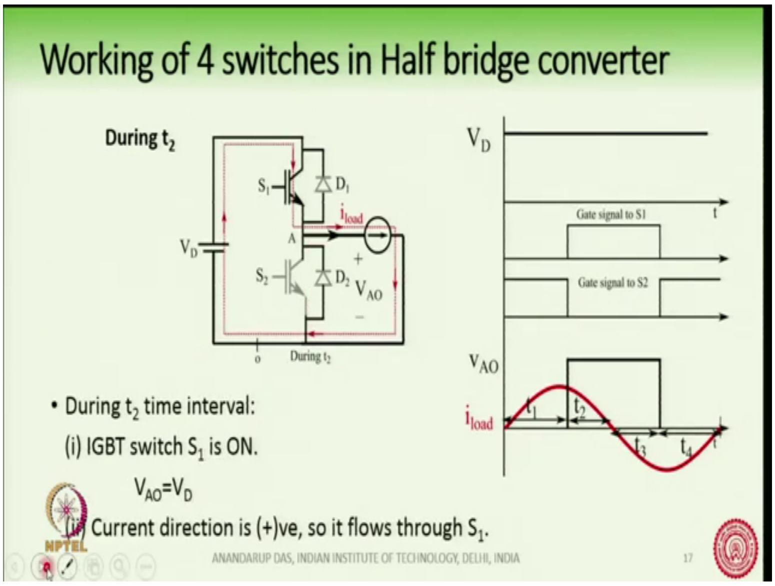

Now, let us take the second interval t 2 here, during the time interval t 2 we see that we have given gate pulse to S 1 while the current is still positive, if this is the case then we see that we have given the gate signal to S 1. So, which means either S 1 or D 1 will be on and since the current direction is positive.

Therefore, the IGBT here must conduct because this is the path of the current. So, it is flowing through the IGBT, through this here through current source and then through the voltage source and there is the path complete. So, during this time interval t 2 we see that the voltage between point A and O because switch S 1 is conducting the voltage between point A and O will be equal to V D.

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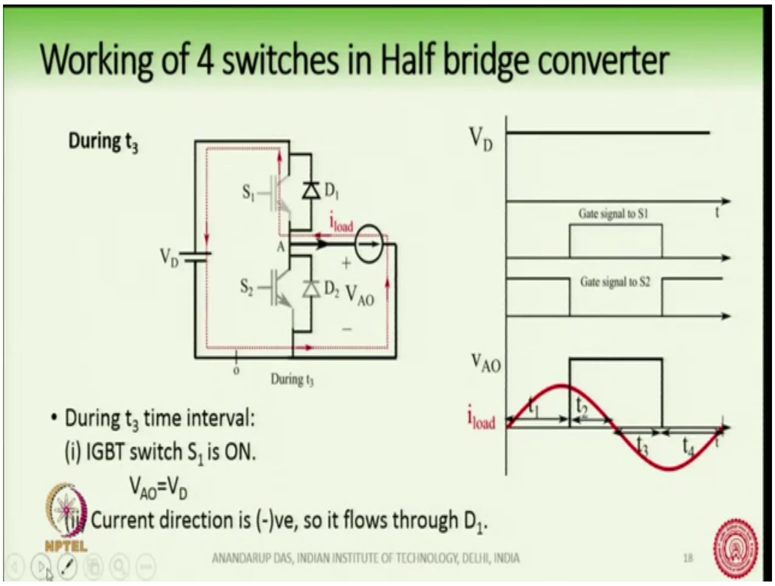

Next let us see the case during time interval t 3. So, we are looking now into this time interval t 3, during this time we see that the gate signal has been given to switch S 1 while the current is negative. So, since gate signal has been given to S 1 so, the either S 1 or D 1 will be conducting here.

In this case since the current direction is negative; that means, the current is now flowing from right to left here. The current must now flow through diode D 1 here and when diode D 1 is conducting assuming an ideal diode the potential at this point and at this point becomes same and hence the voltage at point A with respect to point O will be equal to V D. So, we get a positive voltage. So, V AO here is a positive voltage the diode D 1 is conducting and the current is negative here.

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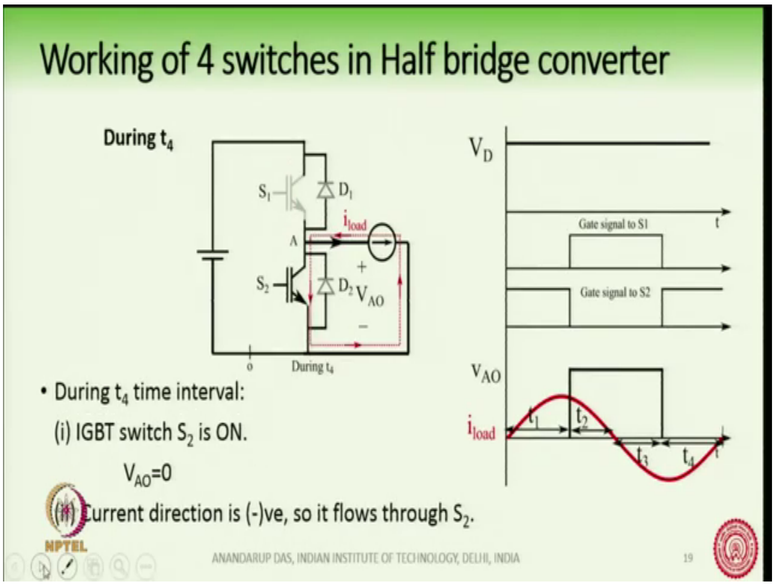

Let us take the last case where the gate signal has been given to the switch S 2 while the current is flowing negative. In this case we find that switch S 2 is conducting here. So, there are so, we have analyzed the 4 switches of the half bridge converter and when they will be conducting at different time instants. If in summary we can say that the voltage that is V AO produced by the half bridge converter can be is unidirectional in nature while the current can be bi directional in nature, before I go to full bridge converter I must stop here for a minute and explain something which needs some attention.

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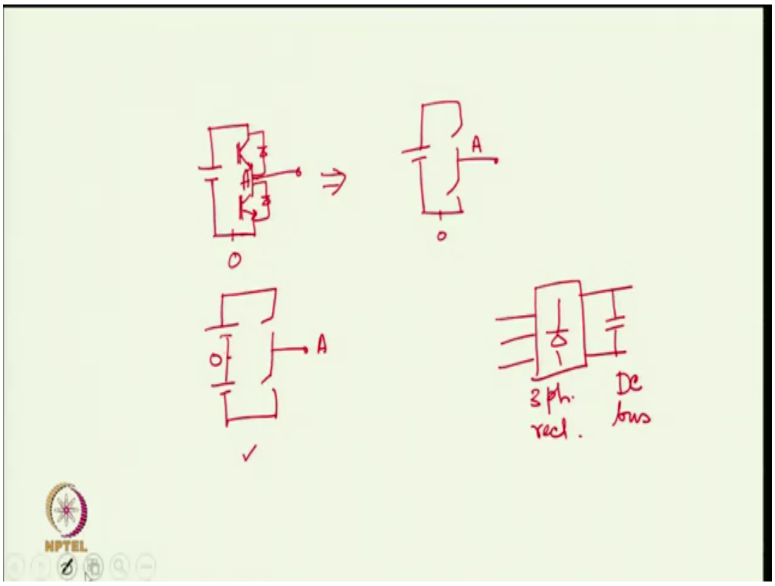

So, if you see here, we have so far talked about a circuit like this where we have said that this is point O and this is point A and this is point O, this is the circuit which we have talked about. Often we represent this circuit as something like this, 2 switches ideal switches bi directional switches.

Now, in many literatures and also in books you will find an alternate representation. What is the alternate representation? The alternate representation, in the alternate representation we have a circuit something like this V AO like this, what is the difference? First of all understand that this circuit here, in this circuit the point O is actually an imaginary point it is a fictitious point. In a real circuit if you analyze say for example, you analyze a half bridge how will you get the DC bus of the half bridge you will do it from a rectifier.

For example the rectifier circuit, say if you take a 3 phase rectifier here comes the DC bus, the DC bus is so this is a 3 phase rectifier and here is the DC bus. The DC bus is or is made up of capacitors and there is no midpoint of these capacitors unless someone makes a special connection to get a midpoint of the capacitors. Normally, it is just a capacitor there is no midpoint; however, in many books and literatures also you will find that the O point has been taken here. Now, this means there is a reason for it, remember this O point is an imaginary point it does not exist in a real physical system.

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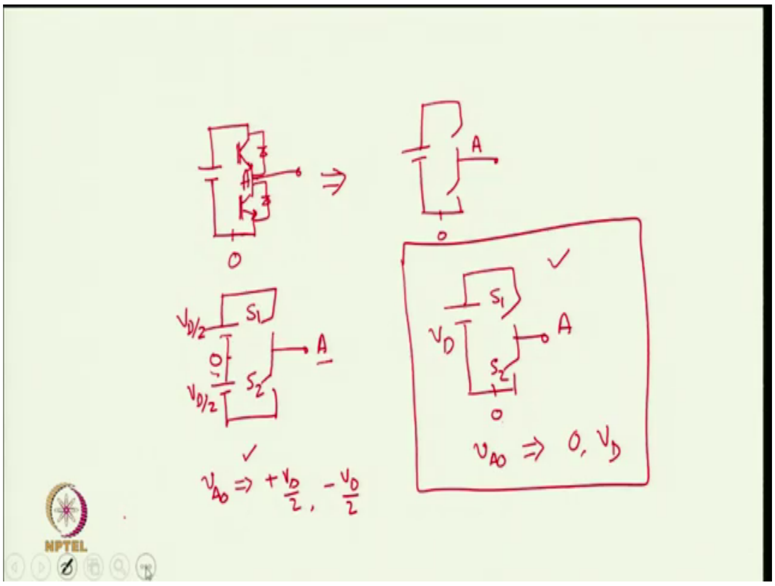

Now, if you analyze the 2 circuits for example. Suppose, we analyze these 2 circuits then we see that here the V AO voltage; the V AO voltage; the V AO voltage is always fluctuating between 0 and V D, where V D is this voltage here. the V AO voltage always oscillates or fluctuates between 0 and V D. On the other hand, the V AO voltage here always fluctuates between V D by 2 or minus V D by 2.

So, we see that in this case the when they say for example, in you have S 1 and S 2 here and S 1 and S 2 here. If S 1 is on in this circuit here if S 1 is on then V AO is V D by 2, if S 2 is on V AO is minus V D by 2, on the other hand here if in V AO it is 0 or V D. So, we see that if we use this circuit then there is always a DC in V AO voltage produced, because it is always oscillating between 0 and V D whereas, in this circuit we always oscillate between plus V D by 2 and minus V D by 2. These two circuits are equivalent only the difference is that in this circuit there is always a DC offset in V AO waveform.

So, the presence of this DC offset or the DC offset if we can remove it by using this circuit the analysis becomes much more simpler and so, many people prefer to use this circuit here with O point at the middle. Many people prefer this circuit to be analyzed because the DC offset in V AO voltage does not exist in this circuit, but this circuit analysis is more close to the real system.

So, therefore, we will use we can use either of them, but in the present analysis we will use this circuit here all the time, because this is more real this is closer to the real system. So, this V AO is between 0 and V D this is what we will assume; however, remember that this analysis with plus V D by 2 and minus V D by 2 is also equally valid.

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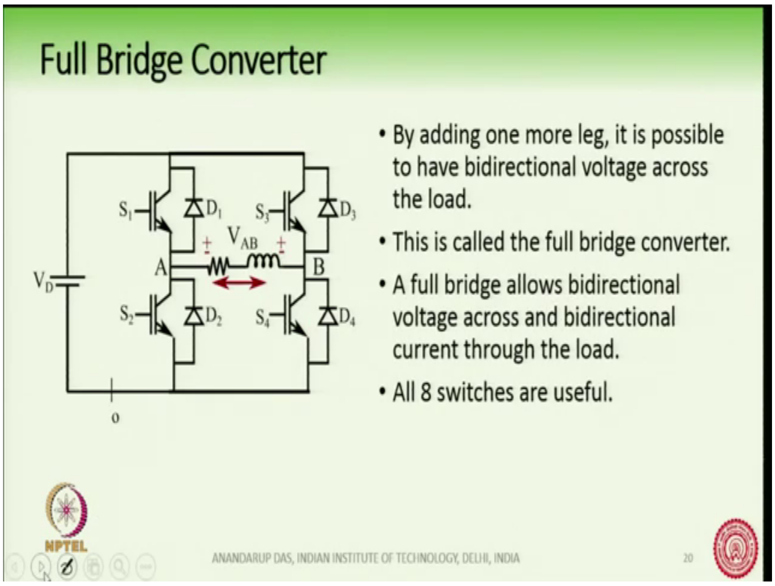

Now, so far we have analyzed the half bridge circuit; now, let us add one more leg to this converter which is called in fact, the full bridge converter. So, here you see that we; so, this is one half bridge and we have added one more half bridge to the circuit. Note that these 2 half bridges are completely independent of each other in fact, they do not know their existence they are just operating independently. So, the left hand half bridge does not know about the right hand half bridge.

So, here why are we then adding this second half bridge? The second half bridge is added mainly because we want to get bi directional voltage across the load, remember in the half bridge with a single half bridge we got unidirectional voltage and bi directional current.

Now, with the full bridge it is possible we will see this later, it is possible to have bi directional voltage across the load, but more importantly there is another advantage. The advantage is that we get double the voltage from the same DC link using the full bridge as compared to the half bridge. So, how first let us understand how the full bridge is operating.

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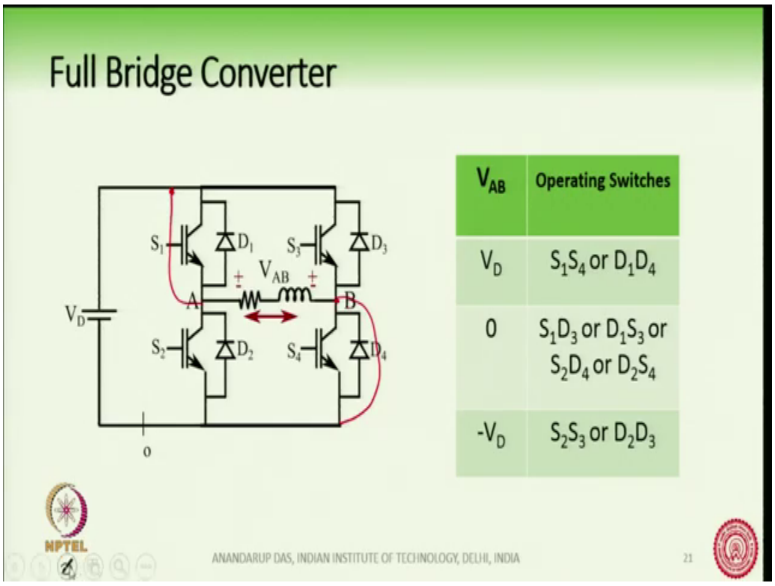

V_{AB}	Operating Switches
V_D	S_1S_4 or D_1D_4
0	S_1D_3 or D_1S_3 or S_2D_4 or D_2S_4
$-V_D$	S_2S_3 or D_2D_3

So, in the full bridge of course, as I told you there are 2 half bridges which are operating independently of each other. So, if you want to get so, there is now this leg, there is point A here and there is point B here. So, if we want to get the V D voltage here then you can turn on S 1 and S 4; if you turn on S 1 and S 4 then if you turn on S 1 then A point is shorted to the positive terminal, if you turn on S 4 B point is shorted to the negative terminal and so, the voltage V AB is equal to the DC bus voltage.

As you can see here, if this is turned on so which means that this point is shorted to this point and this point is shorted to this point. If I turn on S 1 and S 4 the diagonal switches if they are turned on so, I can see that the voltage V AB is nothing, but V D. Similarly, if I turn on the other 2 diagonal switches and these other 2 diagonal switches are say S 3 and S 2 here, then I can get minus V D across the load.

On the other hand if I turn on both the upper switches or both the lower switches together then I get a 0 voltage across AB, because if I stop suppose I turn on the lower 2 switches then A point is shorted here, B point is shorted here and I get a 0 voltage here, basically the load is freewheeling during that time, it also happens when you turn on both the upper switches is like this here.

Now, similar to half bridge where we analyzed the operation of all the 4 I mean 2 diodes and 2 transistors here also we can analyze the operation of all the 8 switches here.

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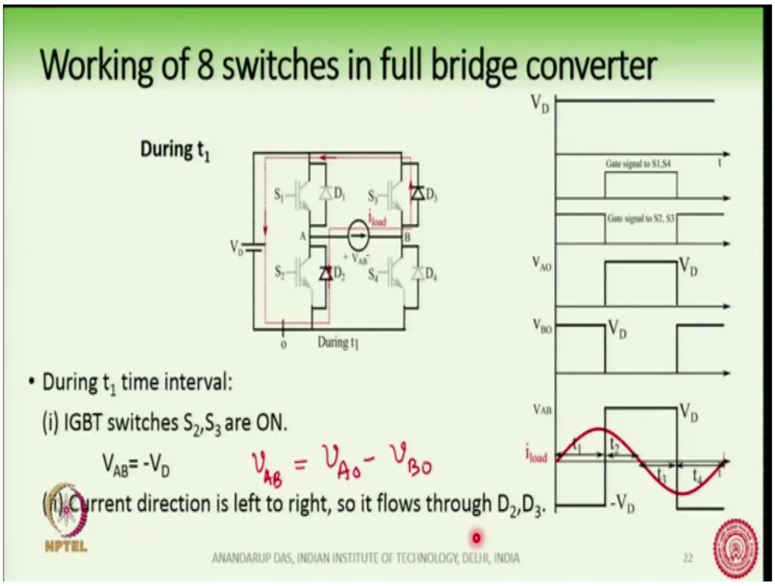

I will not go into that details, but I will only analyze 1 or 2 of them for example, so, there is a V AO voltage which is V D and then there is a V BO voltage which is shown here and it depends on how we have applied the gate signals, in this case the gate signal S 1 and S 4 is applied. So, V AO voltage becomes V D here and gate signal 2 if you apply here it becomes V BO like this. So, during this time what is the V AB voltage, V AB voltage is nothing, but V AO minus V BO, V AB voltage is V AO minus V BO I should write it here as V AB is equal to V AO minus V BO.

So, I can see that the, if I subtract V AO minus V BO in these 2 curves I see that V AB voltage fluctuates between plus V D and minus V D here. Now, the current can be again depending on the power factor, the current can be sometimes positive and sometimes negative with respect to the V AB voltage.

So, let us take the time duration t 1 where the V AB voltage is minus V D and the current is positive and so, I can find out which are the switches conducting. So, first I will see that I have applied the gate signal to S 2 and S 3. So, these two diagonal switches must be conducting at this point. Now out of them which one is conducting, whether the diode is conducting or that IGBT is conducting that can be understood from the direction of the current.

So, here the current direction is positive so, which means the current is flowing like this. So, it must flow like what is shown by the dotted line here, diode the current and through this diode D 3 and then comes back. So, this must be the path of the current here what is the voltage. So, V AB voltage so, because the diode D 2 is conducting so, O point is shorted to A and D 3 is conducting. So, B point is shorted to the positive terminal and therefore, the voltage of minus V D is getting applied across V AB here.

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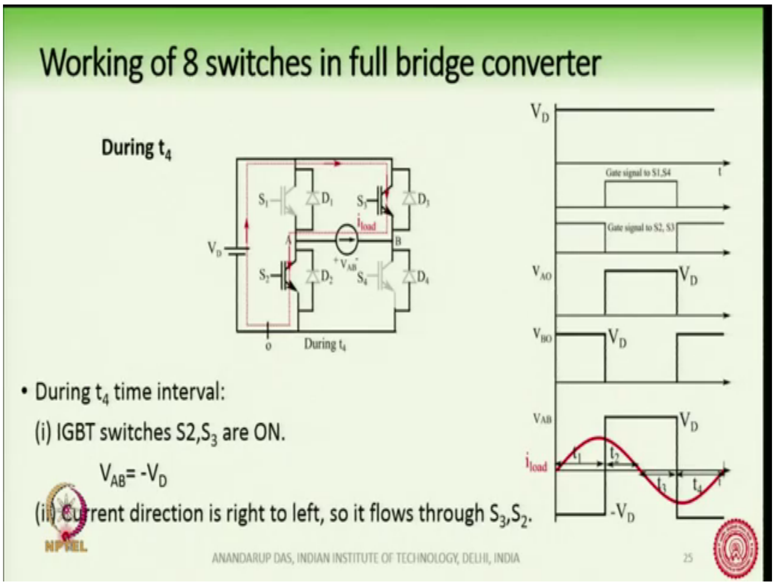

In a similar way you can also do the analysis for other durations. For example, if you take the t 4 duration you can make a similar analysis and can find out that the switches S 3 and S 2 are conducting just like how we have done with a half bridge. So, in this fashion it is possible for us to know all the 8 switches that 4 transistors and 4 diodes how they are conducting in this full bridge converter, ok.

But, remember that one advantage of using a full bridge is that in a half bridge remember that the V the load voltage was fluctuating between 0 and V D whereas, in this case in a full bridge converter the load voltage is fluctuating between minus V DD to plus V D, which means that in a full bridge converter 2 half bridges are working together and we can make them work in such a way that we get double the voltage out from a full bridge converter as compared to the half bridge converter, ok.

So, this is the other advantage of a full bridge converter as compared to a half bridge converter, although we are using more number of switches, but we are getting double the voltage across the load, ok.

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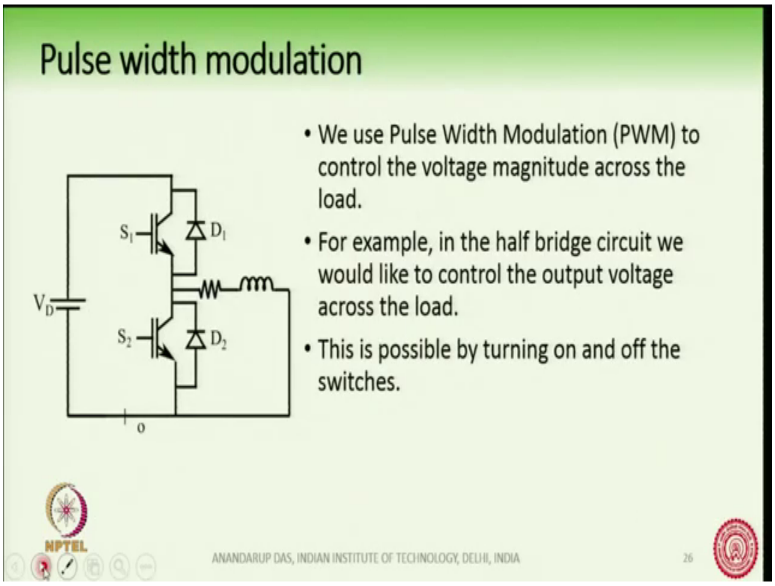

Now, before the next step in our analysis we will see what is called as a pulse width modulation. Why do we use pulse width modulation, because we want to control the voltage magnitude across the load. If you see here in for example, the full bridge the voltage magnitude across the load is always fluctuating between minus V D and plus V D and we cannot control the output voltage magnitude.

So, by introducing notches in this voltage waveform which we will do using pulse width modulation, we will be able to control the output voltage magnitude. So, let us see how we can do it. So, what we will do is, we will turn on and off these switches S 1 and S 2 repeatedly by following a specific pattern.

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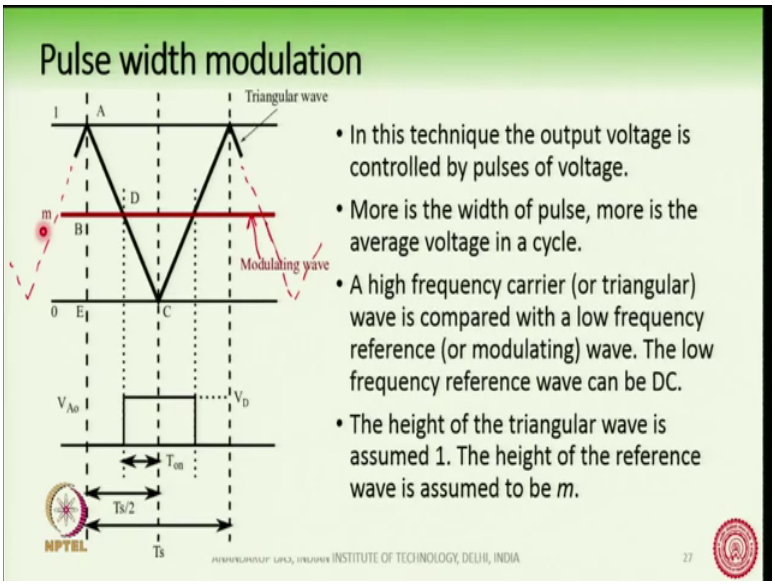

So, let us see how we can develop this pattern. So, in this pulse width modulation technique the output voltage is controlled by a series of pulses of voltage. So, if the pulse width is more, more is the average voltage across the load or more is the output voltage of the converter.

So, in this technique there is one high frequency triangular wave. So, this is the triangular wave which is part of the triangular wave is shown here basically the triangular wave exists like this, ok. So, this is the high frequency triangular wave and we also have this as the modulating wave or the reference wave.

So, there is a high frequency carrier wave or the triangular wave and it is compared with a low frequency modulating wave or a reference wave. The low frequency reference wave can also be a DC for example, in this diagram you can see that the modulating waveform here is not changing over the time interval which we are considering here.

So, the red one is the modulating waveform here it is value is m. The triangular wave is spanning between 0 and 1 as you can see here this is the 1 and there is the 0, 0 and 1 the triangular wave or the high frequency carrier wave is spanning between 0 and 1 and the modulating wave at this instant of time is somewhere in between and it is amplitude is m, ok.

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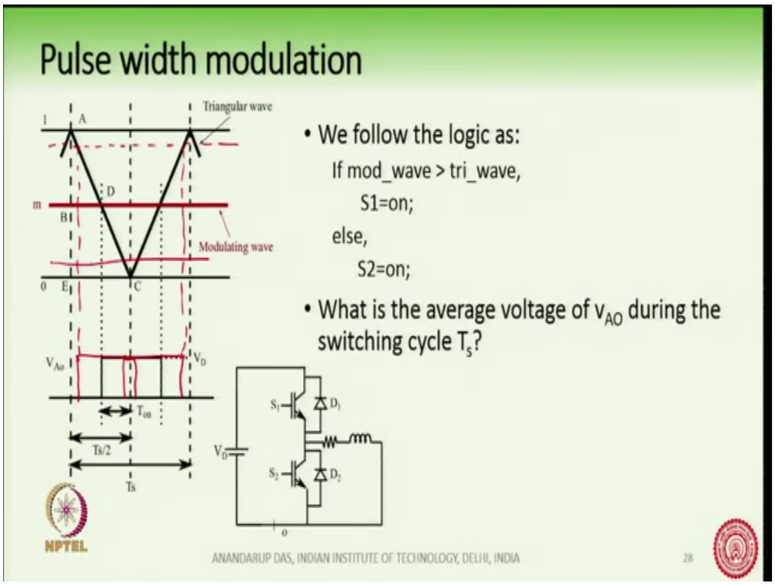

Now, we in order to control the output voltage of this half bridge we follow a logic. What is the logic? The logic is if the modulating wave is more than the triangular wave then I turn on S 1 otherwise I turn on S 2. So, let us apply this logic and see how the output voltage of the converter can be changed. So, here is the triangular wave and here is the modulating wave. So, if the modulating wave is greater than the triangular wave I will turn on S 1. So, which means that during this portion of time, during this portion of time the modulating wave is more than the triangular wave during this portion of time.

And hence I will turn on S 1 in this circuit I will turn on S 1, as I turn on S 1 the V AO voltage will be equal to V D that is the dc bus voltage. The rest of the time for example, here or here the modulating waveform is less than the triangular waveform and so, I will turn on S 2 that is the lower switch and therefore, I will get a 0 voltage here and here. So, you can now see that by changing the height of the modulating waveform in comparison with the triangular waveform height I can change the width of this pulse which is coming across V AO.

So, if the modulating waveform is lower, for example if the modulating waveform is somewhere here then I will get a very narrow pulse. So, if the modulating waveform is somewhere here then I will get a very narrow voltage waveform here or a narrow pulse and V AO you can understand the average V AO will be low in magnitude. On the other hand if the modulating waveform is high with respect to the triangular waveform I will get a big pulse like this I will get a big pulse.

So, therefore, therefore, by changing the position of the modulating waveform in comparison with the triangular waveform I can change the average output voltage V AO. The instantaneous output voltage V AO is always fluctuating between 0 and VD. However, the average output voltage of V AO can be changed by changing the position of the modulating waveform with in comparison with the triangular waveform.

So, how what is the average voltage of V AO during the switching cycle T S? So, when we say about average voltage we must specify a time period that is the time period in which we are going to do the averaging.

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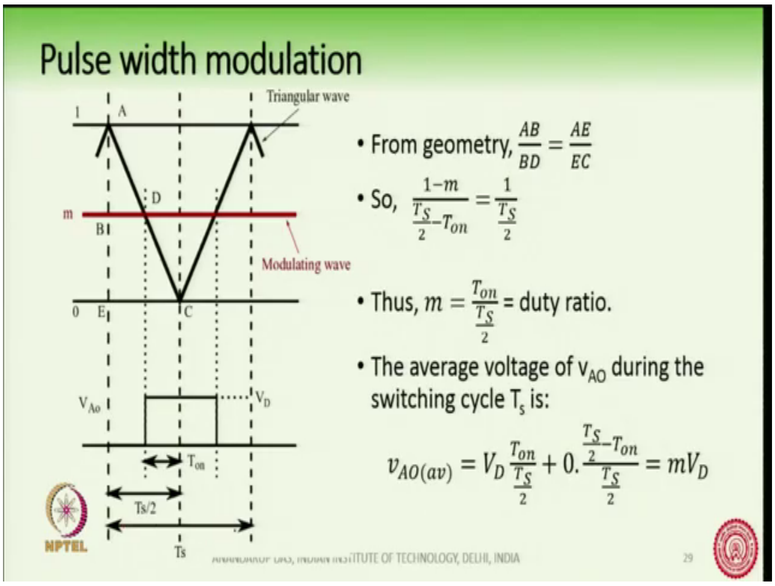

So, this time period in this case we are assuming the time period of the triangular or the carrier wave. So, this terms are used often frequently triangular wave or carrier wave, modulating wave or reference wave these terms are interchangeably used. So, in this case in the T S period time period we have the V AO waveform here shown like this and we can get what is the average V AO during this time period T S, what is the average value? So, for that we will do some very basic geometrical analysis.

So, we see that in this triangle AEC in this triangle AEC we see that AB is to BD is equal to AE is to EC, right. So, what is the height of AB since this is 0, this is 1 and this height is m. So, the height of AB is 1 minus m. What is the height or what is the length of BD? Now, in order to find out what is the length of BD we define a term T on, T on is the time for which the upper switch or S 1 is on and we are getting a voltage waveform here. So, this is the time period T S and this is time period T S by 2 and then there is a T on time period here.

So, the length BD will be equal to T S by 2 minus t on which is shown here T S by 2 minus T on that is the length of BD. What is the height of AE? Height of AE is 1 and what is EC? EC is nothing, but T S by 2. So, this is the T S by 2 here. So, if I simplify this expression I get m equal to T on by T S by 2 which is nothing, but the duty ratio so which means, the time period for which the switch is turned on over the half the switching period.

So, the average voltage of V AO the switching cycle T student, the average voltage during this time T S V AO average is equal to what will be the average, the duration of time for which the V D is on. So, the duration of time for which V D is on is V D into T on by T S by 2 plus the rest of the time it is 0. So, therefore, 0 into T S by 2 minus T on divided by T S by 2.

So, the V AO average over this time period will be equal to m times V D by substituting m is equal to T on by T S by 2 here. I will repeat this once more the average voltage of V AO during the switching cycle T S is V D into T on is the time for which V D voltage has been applied across V AO. So, V D into T on divided by T S by 2 is the period here and for the rest of the time 0 voltage has been applied. So, 0 into T S by 2 minus T on is the duration for which the 0 voltages has been applied over the time period of T S by 2.

Now, this means V AO average is equal to V D into T on by T S by 2 and this T on divided by T S by 2 which we have derived earlier is equal to m. So, therefore, V AO average is m times V D which is also understood from this figure because if m is equal to 0 we do not get any average voltage, if m equal to 1 we get the full average voltage. So, if m is 0 the modulating waveform is down here, if m equal to 1 the modulating waveform is up here, ok.

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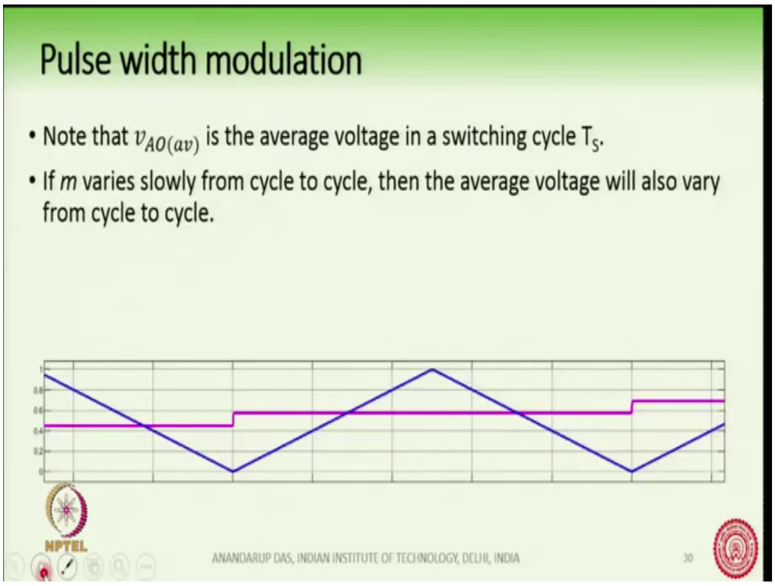

So, V AO average is the average voltage in a switching cycle T S which we have just now derived. Now, if we start to vary the value of m slowly from cycle to cycle ok. In this particular cycle which we see here the value of m is constant over the switching cycle, but suppose in the next switching cycle we just change the value of the modulating waveform slightly.

So, for example, which I have shown it here in this diagram, the value of the modulating waveform in one switching the first switching cycle is here, in the second switching cycle it has been slightly increased the third switching cycle here it has been further increased slightly.

So, if m is varying slightly from cycle to cycle then what do we expect, we expect that the average voltage will also vary from cycle to cycle, right. So, the average voltage will also change in each cycle.

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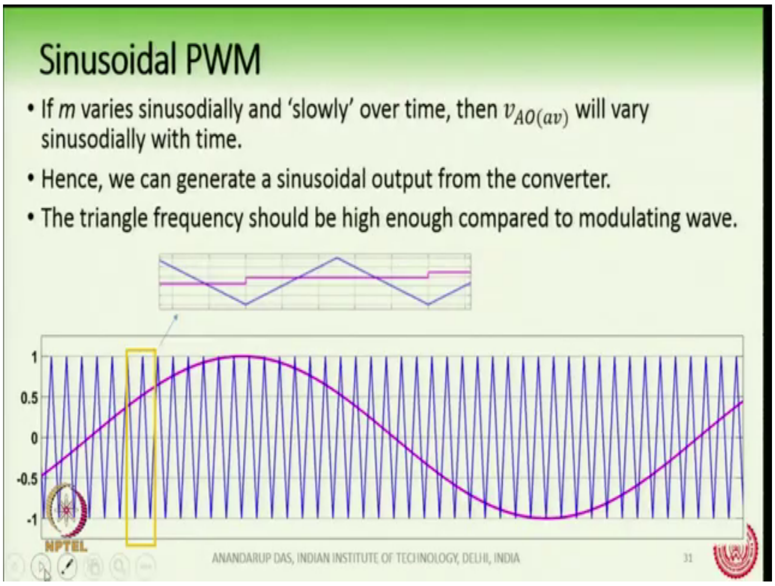

So, if now we change the value of m sinusoidally over a period of time, then the average output voltage will also vary sinusoidally and this is how we generate a sinusoidal output from a converter. Say for example, I show you this diagram here, in this diagram we see that the reference waveform is changing sinusoidally, but it is changing sinusoidally very slowly as compared to the time period in of the triangular waveform, the triangular waveform frequency is much higher than the frequency of the sine wave.

So, a small portion of the triangular waveform period, the sine wave it seems is not changing at all. So, it is more or less fixed; so, this is what we I had shown it here in this diagram. In the triangular period the modulating waveform is almost like fixed it is not changing, because the frequency of the triangular wave is very very high compared to the modulating wave. And that is what I had shown in fact, I had zoomed a small window of this waveform here and I had shown in the previous slide, this slide here was a small window of this waveform which I had which was the full waveform.

So, if m varies sinusoidally and slowly over time then the V AO average will vary sinusoidally with time. Now, you may argue what do we mean by V AO average varying. So, sometimes in order to differentiate people have used the term instantaneous average voltage in this case. Instantaneous average voltage means over a time period T S the average voltage is m times V D here.

So, this is the instantaneous average voltage whereas, months m starts to vary here then we get a sinusoidal output from the converter and it is only valid this assumption is only valid if the triangular frequency is very high as compared to the modulating waveform or the reference waveform. For example, the modulating waveform can be a 50 Hertz or a 60 Hertz signal whereas, the triangular frequency can be 5 kilo Hertz or 10 kilo Hertz or even higher.

So, during a small portion of the triangular period we can safely assume that the modulating waveform sinusoidal is fairly constant, right, yes. Now, one important thing if m does not vary sinusoidally then so which, so now, we have come to this point when we say that the output voltage of the converter can be varied and that can be varied by using the modulating waveform as a sinusoidal waveform, if I use a non sinusoidal waveform can it be done in fact, yes it can be done.

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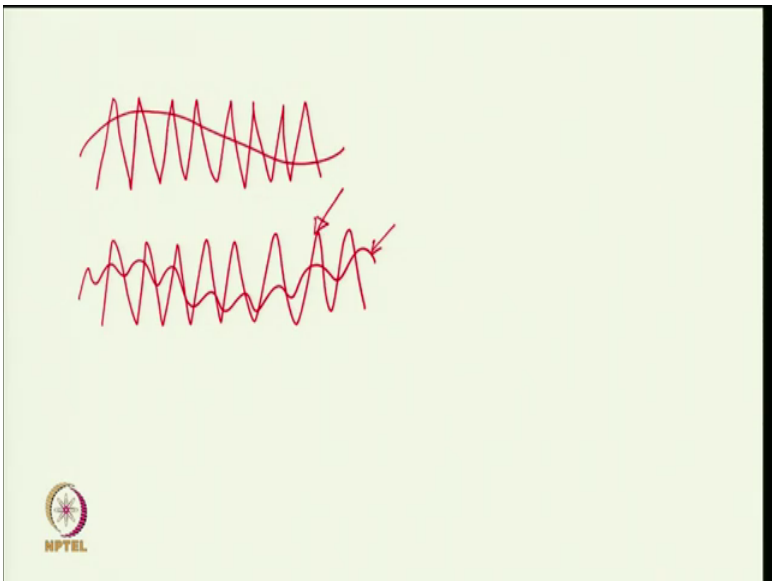

For example, suppose this is the triangular waveform and we are generating a sinusoidal waveform from the triangular wave, but the as far from our understanding the waveform need not to be sinusoidal. For example, if suppose we have a waveform like this and I want to generate something like this from the converter then it is also possible.

So, the modulating waveform need not to be a sinusoidal waveform in fact, it can be a higher order harmonic waveform also. The only condition that we have to preserve is that the frequency of the highest component in this non sinusoidal wave from which we are generating. The frequency of this the frequency the highest frequency component in this waveform must be very less compared to the frequency of the triangular waveform or in other words the frequency of the triangular waveform should be much higher than the highest frequency of the waveform that we want to generate; typically, 15 times higher, 10 to 15 times higher.

So, this kind of a non sinusoidal waveform is used for example, in active filters where the converter is asked to produce a non-sinusoidal waveform containing different harmonics. And, in that case we must have a triangular waveform which is even higher than the highest frequency harmonics that the converter is producing. So, coming back to this concept of sinusoidal PWM, we see that by changing the modulating waveform slowly and sinusoidally over time we can generate a sinusoidal output voltage from the converter and this is nothing, but called sinusoidal PWM.