CHARGING INFRASTRUCTURE

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Week-07

Lecture-35

Lec 35: Modulation Strategies for PWM Full Bridge Converter

Hello everyone, welcome to lecture number 35 of this NPTEL lecture series on charging infrastructure. In the previous lecture, we have seen the concept of short switching, and we have also seen the switching losses. Before that, we revisited some of the isolated DC-DC converters. Now, in this lecture, we will study in detail the different modulation strategies for PWM full-bridge converters. Obviously, I am talking about the full-bridge isolated DC-DC converter here.

So, if we talk about the last lecture, we understood that when we have the half-bridge, which is nothing but the fundamental building block of any voltage source converter. There, we saw that depending upon the direction of the current coming out of the half-bridge, one of the switches will go through soft switching. In this case, if the current is coming out of this half-bridge because of the current direction, when S1 is off, there will be some dead time before S2 turns on during that time. First, the current I_0will flow through C1 and C2 in such a manner that C1 charges from 0 to V_{in} and C2 discharges from Vin to 0. Then, D2 will be on, and once D2 is on, the current will flow through this diode D2. Since the current is flowing through diode D2, the voltage across the device will be zero. Then, when you turn on the device, you will see the zero-voltage switching turn-on of this device S2. As a result, the switching loss on the S2 switch is nearly zero during the turn-on period.

And because, during the dead time, the dV/dt—that means the voltage between points A and N—is actually limited depending upon C1, C2, and the I_0 current. So, we can also have less EMI—what you can say—electromagnetic interference to nearby systems. And then, we have also seen that, I mean, this particular circuit—we can say that instead of R, L, N, C, we could also have the voltage source on this side, and here on this side, we could have resistance and capacitance. This scenario we know, that the output of the half-bridge will always be connected to the inductor 'L', and the current in the inductor cannot stop abruptly, so it will find a path. That's why it has to connect at the pole of this half-bridge. So, because of that, the necessary condition to ensure that C1 charges from 0 to Vin and C2 discharges from Vin to 0 is nothing but LI_O^2 must be greater than—that means the energy contained in this must be greater than $V_{in}^2C_1 + V_{in}^2C_2$, where C1 and C2 are the device output capacitances.

$$LI_O^2 > V_{in}^2C_1 + V_{in}^2C_2$$

These are the necessary condition. However, once this condition is met that means there is a possibility of soft switching off during turn on of this S2 switch. However, now the required condition that means the condition which must be there is nothing but you have to provide the sufficient dead time That means you have to provide sufficient time before sending the gate pulse to S2 switch such that the voltage of this C2 goes to 0 from V_{in} voltage and simultaneously the voltage of V_{C1} goes from 0 to V_{in} voltage. That means the desired condition to obtain the zero switching loss we must ensure that sufficient dead time is provided between the turn off of the gate pulse S1 and turn on of the gate pulse of S2 switch.

this we have also studied in the last class then we have seen that whenever the S1 is turning on the S1 is turning on with the fixed I mean voltage across it I mean there is no way by which the capacitor gets discharged from V_{in} voltage to 0. So, the channel is formed and this V_{in} voltage which was there will actually be discharged through this channel so since the V_{in} will be directly imposed upon the switch whenever the channel is formed that means or you can say whenever the gate pulse for S1 is given. So, during that time what you have is you are having a finite losses turn on losses of S1 switch and that is and you will also see that there is a dV of this voltage V_{AN} where I mean the or the $\frac{dv}{dt}$ at terminal A is not in under control it is depend upon how fast you are turning on S1 that means that the rate of excitation of gate to source voltages it depends upon that. So, that's why this particular the S1 switch here turns on with the finite losses as well as good amount of $\frac{dv}{dt}$ between point A and N. So, that's why you will see that this switch receives or achieves the hard switching. However, the S2 switch achieves the short switching during turn off.

So, these are the things we have studied in detail in the last session. Now, let us see how this particular concept we will be using to understand the operation of full bridge converter. but before starting that let us recap or let us understand what we have studied about full bridge converter in full bridge converter we know that we have four switches which are actually exciting the primary winding of the transformer secondary side we have two diodes and which is leading to L and C and V_0 output will be there and we know that in this particular scenario we have V_0 to be nothing but 'n' which is nothing but 'n' is nothing but $\frac{N_s}{N_p}$,So we know that V_0 is nothing but n being duty ratio D where duty ratio D is the fraction of the time of half the switching cycle so this is actually half the switching cycle $\frac{T_s}{2}$ and this is another $\frac{T_s}{2}$ period during this $\frac{T_s}{2}$ period for some portion of the $\frac{T_s}{2}$ period the S1 and S2 is on and then during which you know we have seen that how the flux rises and then how the DR1 is conducting during this time and whenever the S1 and S4 is off the current of the inductor I_{L1} mean the current through the inductor I_L is such that it ensures both the diodes turned on since both the diode turns on what happens is that the current through this inductor L is actually going through this IDR1 and IDR2 it is going through these two devices and that is when you know we see that voltage across this primary winding becomes zero and different operation of this converter we have seen however if you look very carefully here we have not discussed any parasitics of the of the devices which are present and also parasitics of these you know transform because you know every transformer you do you have good amount of this inductance which is good amount of leakage inductance which comes in series on either side on the primary side on the secondary side and this leakage is because of the when you excite this winding some of the flux gets links with itself and corresponding to that there is the inductance which is called as a leakage inductance so the flux which does not get coupled to the secondary side winding the fluxes which links with the coil itself and inductor corresponding to that fluxes are called as a leakage fluxes because that got leaked out it does not gets coupled through the core to the other winding. Now so these are what this is some of the L_{lkg} of this finding we have we also have you know every mosfet you take or even if you take the you know igbt across the drain to source what we have is we have the capacitor C1 let's say we have the output capacitor let's say output capacitor C1, C3, C2 ,C4 and these are D1 D3 D2 and D4 these are you know since we have considered this is MOSFET we are considering this D1, D2, D3, D4 are the body diode of the MOSFET.

So now we know that we can control our output voltage by just controlling the duty ratio of S1 and S4 switches. along with we can also adjust the turning on or turning off instances of switches S1 and S2 in first leg and S3 and S4 in second leg and this will have some advantages like we will achieve a soft switching of this converter and accordingly we can ensure our operations so let us see how we will obtain the different what are the different possibilities of modulation strategies Now, if you look very carefully in this circuit, this is nothing but our $\frac{DT_s}{2}$ period and this is nothing but our $(1 - \frac{D)T_s}{2}$. And we know that during this time, my S1 and S4 is on and then after this S1 and S4 turns off, it is you know the current which was there in order to ensure the output current output inductor current remains there their current will get divided into two diodes and both the diodes DR1 and DR2 conducts so since here both the diodes are conducting the voltage across this winding is zero if across entire winding is that's when the voltage across these points you know the points is zero however there is L_{lkg} you know inductor which are present so now what what happens is that

Since in $(1 - \frac{D)T_s}{2}$ period S1 and S4 turns off and S2 and S3 was already off. And then only after $\frac{T_s}{2}$ period the S2 and S3 is turning on. So, during that time what happens is that the voltage across AB will be when your S1 and S4 is on it is V_{in}. And when S2 and S3 is on, is your minus V_{in}. Because when these two are on, the positive terminal of DC link is actually connected to B point.

And when S2 is on, the negative terminal of the DC link is connected to point A. So, we have minus V_{in} voltage appearing across V_{AB}. However, there are some possibilities we have. So, for the possibilities, what we do is define the two bridges, the two half bridges that we have. As you know, one bridge we define as the leading leg, and another bridge we define as the lagging leg. Now, I will tell you why we call this the leading leg and the lagging leg. In this, what we are doing is, for the leading leg, we can change the turn-on time of these leading leg switches, which are S1 and S2, by a certain duration.

Now, let's say we increase this one. Let's say S2 goes to this point, to this particular point, and let's say my S1 also goes to the same point, this particular point. Now, if my S2 switch is on during this period, during this period, my S3 is off, my S4 is off. You know, I'm just increasing the T1 period of this S2 switch in the forward direction. So, what we are doing here is that we are actually increasing the turn-on time in the forward direction, in this direction. As a result, what happens is, since my S1 is already off, my S4 is off, and my S3 is still off, even if I turn on my S2 also, the voltage across V_{AB} will still be zero because what is happening is this is off, this is off, this is off, and we are just turning on this S2 switch. So, even though we turn on the S2 switch, it does not make much difference to the V_{AB} voltage. So, the V_{AB} voltage will still be zero. Similarly, if we increase the turn-on period of my S1 switch in the forward direction, that means in this direction, So, since during this portion of time, only S1 is on, and all the rest of the switches are off, there is no impact you will see on V_{AB}. V_{AB} will still be zero.

At the same time, if in the lagging leg, if we are in the backward direction, lagging means we are in the backward direction, increasing the turn-on period of both S3 and S4 switches in the backward direction. So, during that period also, that means during this period, all these three switches are off. Only for the S4 switch, we are delaying its turn-off for a certain period. Similarly, during this period, we are actually delaying our S3 switch turning on in the backward direction. So, still, the other three switches are off. That's when we will see that there is no impact we will get on the V_{AB} voltage. So, what we are doing in the leading leg is just increasing the turn-on period of these leading leg switches in the forward direction by some small amount without changing anything on the leading edge of your lagging leg switches. So, when we are increasing during this portion, the other three switch states are still the same. So, there is no impact we are getting on V_{AB}.

similarly in the lagging lag we are actually increasing the turn on period of the lagging lag switches by delaying or by increasing the falling edge in the backward direction by some amount and during this time the V_{AB} voltage will still be zero so during this time the voltage is still be zero during this time it is still zero during this time still zero during this time it is still zero since we are not impacting anything on the V_{AB} voltages We get the output voltage to be $V_{AB} = n * V_{in} * D$, we are also not changing anything on the output voltage because the volt second of inductance L will still be the same as we are not changing V_{AB}voltage and the voltage which is appearing across V_{AB} will only be rectified after this diode DR1 and DR2 and still during $\frac{DT_s}{2}$ period. I am applying voltage across inductor as $V_L = (n * V_{in} - V_o)$ and during $(1 - \frac{D)T_s}{2}$ period the $V_L$voltage will still be just minus V_O. So, because even if we are changing just turn on instances of one of the switches we are not in actually impacting any you know change in the V_{AB}voltages which is applied at the primary winding of this full bridge you know transformer. So, in this kind of modulation strategies or methods we are not changing the output voltage as our V_{AB} is same.

However, we are just adjusting the turn on or turning off instances of leading lag and lagging lag switches which will help us in achieving short switching of the switches in the full bridges. So, based upon that we can say there are certain possibilities. First possibility is obviously in the leading lag which is you know this is the leading lag The leg comprises of switch S1 and S2. In the leading leg, what we are doing is we are actually increasing the turn on period of this S1 and S2 switch by actually changing this switching instant in the forward direction.

Then rising edge we are increasing in the forward direction or we are adjusting in the forward direction. So, let us see how the, you know, in the leading leg what takes place. So, there are three possibilities. One possibility, you are not doing any change. Obviously, the on time is still be $\frac{DT_s}{2}$period for, you know, for S1 and S2 switches.

You are not changing the leading leg. Again, when we are discussing about the leading leg, we are not touching anything on the lagging leg. We are not doing any change on the lagging leg which comprises of S3 and S4 switch. Now, the second possibility could be your turn on period of this S1 and S2. You are adjusted forward, you are adjusting in the forward direction.

However, you are doing the adjusting, you are changing the, you know, you are changing the turn on period of S1 and S2 switch. But still that on time is less than $\frac{T_s}{2}$. If we say this is $\frac{DT_s}{2}$, this is $(1 - \frac{D)T_s}{2}$ period. So, this period from here to here is $\frac{T_s}{2}$. So we are not going from this point to this point.

Because even if you go from this point to this point also there is you know the V_{AB} will still be the same. But you are not doing that. You are just adjusting the turn on period in the forward direction. But that for on time is still less than $\frac{T_s}{2}$ period. And the third scenario when you have adjusted this thing in such a manner that the turn on period of this S1 and S2 switch in the leading leg.

goes to $\frac{T_s}{2}$. So, there are three possibilities. One, you are not changing the turn on time. In the second, you are changing the turn on time. You are adjusting the turn on time by adjusting in the forward direction, but still the on time are still less than $\frac{T_s}{2}$.

So, here what you are doing, you are $\frac{T_s}{2}$ period plus delta T you are doing. However, $\Delta t < (1 - \frac{D)T_s}{2}$ period, you can say. So, this you can say from here to here is delta t, that delta t which you are adding up here. Similarly, in the third point, you are increasing this thing such that $D\frac{T_s}{2} + \Delta t$ you are doing and such that this is $\Delta t = (1 - \frac{D)T_s}{2}$. That is when you can make the turn on period of S1 and S2 switch to be equal to $\frac{T_s}{2}$.

So, this is the third scenario. Similarly, in the lagging lag case, so here we can say this is the leading lag. This is the lagging lag. In this case again, the lagging lag switches which are S3 and S4. you are not changing that makes the first possibility keeping the turn on time remains same the second thing you are changing you are adjusting this time you know falling edge or you can say the turn on time of S3 and S4 in the backward direction in this direction and such that the turn on time is still less than $\frac{T_s}{2}$ that means what you are doing is you are doing adding a Δt time however $\Delta t < (1 - \frac{D)T_s}{2}$.

And in the third point what you have is we have that $D\frac{T_s}{2}$ we are adjusting the turn on time and such that you know such that $\Delta t = (1 - \frac{D)T_s}{2}$ and that's when you are you are turning on for the entire $\frac{T_s}{2}$ nearly $\frac{T_s}{2}$ period you are turning on your Why we are saying this one? So let's say we are increasing this to this place point. So the entire $\frac{T_s}{2}$ duration because this is $D\frac{T_s}{2}$. This is $(1 - \frac{D)T_s}{2}$ for the entire $\frac{T_s}{2}$ duration.

We are turning on S3 and S4 switches. So here in the lagging case, we are defining the three possibilities as A,B,C. In the leading leg case, we are defining the three possibilities as 1, 2, 3. in both the cases my $V_o is\, V_o = n * V_{in} * D$ because if you see even if you are adjusting here During the adjusting period, during this period, Δt period, I am still applying the V_{AB} to still be the same which is 0 from, I mean at this point which is actually imposed upon the primary winding of your isolated transformer.

So, still what we have is we are not actually changing the V_{AB} voltage. So, that is when we are not actually changing the output voltage. We are still the output voltage, we are keeping it intact. even though we are adjusting the you know turn on time of lagging lag switches and leading lag switches but still the voltage which will be appearing at the a and b will still be the same if this voltage are same then the voltage applied across i mean at the inductor l will still be the same and we are doing the volt second balance of this inductor to find the relationship between the input voltage and the output voltage so thus our output voltage the output voltage will still be the same so now because of this three possibilities from the lagging lag and three possibilities from the leading leg there are several modulation methods which are possible in the first modulation method what we are doing is we are not changing anything, so we are using one a so one corresponds to whenever there is no change in the leading leg S1 and S2 turn on time this is our leading like this is our lagging leg for lagging leg there is no change in the turn on period that's when you will see that there are no change in the turn on period and V_{AB} will still be the same and here we see that the diagonal switches the diagonal switches which are S1 and S4 they are switched off at the same time similarly for S2 and S3 switches they are switched off at the same time. So this is another important thing which actually defines different kinds of modulation we will see that how it impacts and these are (1a) possibilities (1a) possibility or method number one which has the possibilities one and a one from the leading leg side and a from the lagging leg side now in the second modulation method what we are doing is we are adjusting the turn on period of leading leg and we are adjusting the turn on period of the leading leg which is defined in the you know the second number possibility in the leading leg side but we are not changing anything on the lagging leg. So what we are doing we are actually increasing the turn on period of this only the leading like by adjusting the turn on time in the forward direction. However, the turn on time is still less than $\frac{T_s}{2}$ period.

So, still less than $\frac{T_s}{2}$ that means if we say this is $\frac{T_s}{2}$, this is $\frac{T_s}{2}$ and this is again your $\frac{DT_s}{2}$ and this is your $(1 - \frac{D)T_s}{2}$. So, here we are increasing by delta T This delta t and this delta t is less than 1 minus d Ts by 2. That is when we are adjusting the turn on period. So, we can say the turn on period of S1 is nothing but becomes $\frac{S1=(DT_s}{2}) + \Delta t$ of S1 and S2 switch sorry both the switches S1 and S2 switch, the period during which the turn on period is adjusted if we check in this portion in this portion although i have adjusted my S2 switch turn on time but my S1 S3 and S4 switch are still off during this time. So still i am applying zero voltage from the vab since i am applying zero voltage from the vab my output voltage is still $V_O = n * V_{in} * D$. So this is the thing we got the second modulation method and in this method if you look very carefully the diagonal switches which are S1 and S4 switches and S2 and S3 switches diagonal switches are turning off at the same time then the third possibility you know you can adjust the turn on period of S1 and S2 switch in the leading leg such that you adjust it up to the TS by 2 period. So, if you take this is entire period is $\frac{T_s}{2}$ you adjust it such that this will now turn on for the entire $\frac{T_s}{2}$ period. In the entire period you are turning it out. Here you are kept $\Delta t = (1 - \frac{D)T_s}{2}$. That's when your t_{on} of S1 and S2 is

$$t_{on} = \frac{DT_s}{2} + \frac{(1-D)T_s}{2} = \frac{T_s}{2}$$

And if you look very carefully during the adjustment period, Δt adjustment period, the turn on adjustment, during this period, your V_{AB}voltage is still not changing. That's when your V_O is $V_O = n * V_{in} * D$, because you are not changing the output, you know, the voltage at V_{AB}, which is actually get imposed after this rectifier onto the inductor L for $\frac{DT_s}{2}$ period. And during $(1 - \frac{D)T_s}{2}$ period, it is the V_O which will be freewheeling through the DR1 and DR2. And the possibilities what we have, if we number the possibilities, so it is 3 from the leading lag and it is A from the lagging lag because still we are not changing anything on the lagging switches, S3 and S4, the lagging switches, the switches in the lagging lag, the turn on period is still not changed. So in this, if you look very carefully, the turn on period of S3 and S4 is still not changed.

We are not touching it. That's when we have A possibility from the lagging lag. This is my lagging lag. we know that this is our leading leg and if you look very carefully during the turn of the diagonal switches are turning off you know s1 and s4 and you can say S3 S2 and S3 they are switching off at the same time or they're turning off at the same time then comes the fourth possibility in the fourth possibility what we are doing is we are now keeping the leading leg which is S1 and S2 switch we are not touching anything from the leading leg however we are we are actually increasing the lagging lag time by adjusting the turn on of S3 and S4 switches in the backward direction in the backward direction by Δt and this $\Delta t < (1 - \frac{D)T_s}{2}$. Now, because of that what happens is that my turn on period of S3 and S4 is now actually my $\frac{((DT_s}{2}) + \Delta t) < \frac{T_s}{2}$ because this is entire $\frac{T_s}{2}$. This is from here to here $\frac{DT_s}{2}$ from here to here $(1 - \frac{D)T_s}{2}$ period. Now, if you look very carefully during the delta T period during this period the all the other switches are still off.

So that means the V_{AB}voltage is still be 0. And that means the voltage applied on the primary one does not change. That's when my $V_o = n * V_{in} * D$ which we obtain by doing the volt second balance on the output inductor L. So that's a you know when my $V_{in} = 0$. So during that time they are actually freewheeling across this point. That's when applying during $(1 - \frac{D)T_s}{2}$.

We will apply $(1 - \frac{D)T_s}{2}$. period. we will apply $V_L to\ be\ V_L =- V_O$ to be equal to minus V0 and in DTS by 2 period, we apply $V_L\ to\ be\ V_L = (n * V_{in} - V_O)$, which actually give us and when we do the whole second which we have done in 2-3 lectures back, we will get V_O to be $V_O = n * V_{in} * D$, and the possibilities if we talk about the possibility numbers so it is first from the leading leg side and we are now started adjusting the lagging leg time and here if you look very carefully the turn off instances of diagonal switches. So if you look the turn off instances of S1 and an S4 is now not at the same time they are at a different time so you can say the turn off stress of s1 and s4 and s2 and s3 are not at the same time so these diagonal switches you can say S1 and S4 or S2 and S3 they are not turning off at the same time then comes in modulation method 5 in this modulation method 5 what we are doing is we are now adjusting both the leading lag as well as lagging lag so this is our leading lag comprises of switches S1 and S2 and we have the lagging lag comprises of switches switch S3 and S4.

In both the legs we are adjusting the turn on time and the turn on time are adjusting in such a manner that the turn on period of the lagging leg and leading leg is still not equal to $\frac{T_s}{2}$. So, this is the Δt we are doing changes. In the leading leg, we are adjusting the turn on period in the forward direction. In the lagging leg, we are delaying the turn off instances in the backward direction. So, by Δt period and with this $\Delta t < (1 - \frac{D)T_s}{2}$. That's when we can say that my turn on periods of both S1, S2, S3, S4 is actually nothing but $\frac{Turn\ on=(DT_s}{2}) + \Delta t < \frac{T_s}{2}$. Here from here to here it is $\frac{T_s}{2}$.. It is still less than $\frac{T_s}{2}$, and during this you know adjustment period delta t what we see is that the vab voltage is still the same because the other three switches operation are not same only one switch we are changing at one time so that's when the vab will still be the same since the vab will still be the same the output voltage is still the same we are not impacting anything however we will see in subsequent lecture this methods will help you all to achieve the short switching of the switches which will impact the switching losses and the losses of the entire converter and that's when the you know these methods are being used to achieve the very high efficiencies in this particular converter because generally we are switching this converter at a very high switching frequencies such that the size of this inductor and passives are smaller So here the possibilities what we have is the second possibility from the leading leg side and B possibility from the lagging leg side. And here if you look very carefully the diagonal switches which are S1 and S4 or you can say S2 and S3 they are actually switches at a different instances. They are turning off at a different instances. Then in the modulation method 6 what we are doing is we have

In the leading leg side which comprises of S1 and S2 switch we have adjusted the t_{on} period by the the time You know $(1-\frac{D)T_s}{2}$which is nothing but here it is $(1-\frac{D)T_s}{2}$ and which will actually give you t_{on} of S1 and S2 to be $\frac{T_s}{2}$. However, T on of S3 and S4 is still $\frac{Turn\,on=(DT_s}{2}) + \Delta t$. which is and this $\Delta t < (1-\frac{D)T_s}{2}$. So in this period the adjustment period during which we are adjusting the turn on period of lagging and leading lag at this point if you look at this point during this point what happens is that during this point what happens is that my s1 is off my s3 is off this two are off and you are now turning on S2 and S4 both the S2 and S4 is on since both are on so in the circuit this is on this is on so in the circuit this the vab voltage is still be zero which is what you know so that means we are still vab we are not changing similarly during this instance during this instance what happens is that the S1 is on doing this insert the S1 is on and you know at this point my S3 is on so during this time again this in this in this entire in this entire circuit the V_{AB} voltage is still zero so during this time still the V_{AB}voltage is zero and remaining period. The time during which the S4 turns, you know, during this period, if you talk about during this period, during this period, since all the three switches are having the same state with just changing the timing for one of the switches, it will not impact anything on the $V_{AB}$and that's when we can say $V_O = n * V_{in} * D$. So this method this particular method is comprises of possibility number 3 from the leading leg side and possibility number B from the legging leg side and here if you look very carefully these turn off period of the diagonal switches are actually not at the same time they are at different time this is the modulation number 6 similarly the modulation number 7 in modulation number 7 which actually is nothing but (1C) where we are not changing anything on the leading leg but on the lagging leg which is comprises of S3 and S4 what we are doing is we are changing the turn on time by 2 period by this much period And that's when my, you know, the turn on period of S3 and S4 goes to $\frac{T_s}{2}$.

However, during this time, the V_{AB} voltage will still be unchanged. So, our$V_0 is\ still\ be$ $V_0 = n * V_{in} * D$. And we are doing the same operation. Now, in this one, if you look very carefully, the diagonal switches S1 and S4 and S2 and S3 are actually turn off at a different times similarly there is another possibilities which is we are adjusting in the you know the lagging leg side which comprises of S3 and S4 we have increased the turn on period to $\frac{T_s}{2}$, we can say $t_{0n}$of S3 and S4 is actually $t_{0n} = \frac{T_s}{2}$, however we are adjusting the turn on period of leading leg by delaying or by adjusting the forward direction of the rising edge of this turning on period so that's when we will get t_{0n} S1 S2 is $t_{0n} = \left(D\frac{T_s}{2}\right) + \Delta t$ where $\Delta t < (1 - \frac{D)T_s}{2}$. Now because of that if you look very carefully this we have extended here during this time during let's say during the Δt time when both the S2 and S4 is on the voltage across $V_{AB} = 0$ will still be zero at this point. Similarly, during this period of time what we have is our S1 and S3 is on so $V_{AB} = 0$ here. However, in other times, you know, during this period of time from here to here, during this time period of time, what we are seeing is that only one of the switches turn on time is changed. However, other switches turn on time is not changed.

So that's why the $V_{AB} = 0$. So we can say that the V_0 is unchanged, which is $V_0 = n * V_{in} * D$. The possibility is possibility number 2 from the leading leg and possibility number C from the lagging leg side. And here again if you see the turn off instances in diagonal switches S1 and S4 they are at different time. S2 and S3 they are at different times.

Similarly, if we see the modulation method 9, we are having the (3C), where what we are doing is we are delaying our lagging lag by $(1 - \frac{D)T_s}{2}$period. However, we are also adjusting our turn-on period of S1 and S2 switch by $(1 - \frac{D)T_s}{2}$period. So, you know, by adjusting in such a manner that... we are resisting such a manner that for the entire th by 2 period both the both the devices are on so we can say that the turn on of all S1 S2 S3 S4 is actually nothing but $\frac{DT_s}{2}$ period since the adjustment Δt is nothing but is $\Delta t = (1 - \frac{D)T_s}{2}$, so during the adjustment period if you look carefully during this period your S2 and S4 is on your S2 and S4 is on so obviously the $V_{AB} = 0$.

And during the next time, when the turn-on time of S1 is adjusted to $\frac{T_s}{2}$ periods and the turn-on period of S3 is adjusted to $\frac{T_s}{2}$ periods. So, where my S1 and S3 are on during this period, my $V_{AB} = 0$. So, my output voltage $V_O = n * V_{in} * D$. And there is no change in the output voltage. So, if you look very carefully, the turn-off instances of S1 and S4 are turning off at different times, and S2 and S3 are turning off at different times. So, these are the nine different modulation methods we get by just adjusting the turn-on period of either the leading leg or the lagging leg.

So, we can finally say that we have, in total, actually nine PWM modulation strategies, and these modulation methods or strategies can be grouped into two types. Type 1, where the diagonal switches turn off at the same time, which we get from methods 1 to 3, and there is a second type where the diagonal switches turn off at different times. Which is nothing but modulation methods 4 to 9. These are the nine different methods which you will get, and you can use them without changing any output voltage or any variation in the output voltage. You can use them to achieve the soft switching of these devices, which we will discuss in the next lecture—how these different modulation strategies can be employed and how this will help in achieving the soft switching of the leading leg and the lagging leg. We will see this in the next lecture.

Thank you very much for patiently listening to this lecture, and we will see you in the next lecture.