CHARGING INFRASTRUCTURE

Prof. Apurv Kumar Yadav

Department of Electrical Engineering

Indian Institute of Technology Roorkee

Week-07

Lecture-34

Lec 34: Soft Switching In Half Bridge Configuration

Hello everyone, welcome to lecture number 34 of this NPTEL lecture series on charging infrastructure. In the last lecture, we discussed switching losses. In this lecture, we will carry forward our discussion related to that and understand the concept of soft switching. Now, if you look carefully, we have defined our circuit to be something like having a switch and a diode, and it is actually supplying a constant current load. What it means is it is actually supplying what you can say an inductor. And let us say either R or you can say the parallel combination of R and C as a load. So this is what we have assumed. This particular circuit we have assumed to be something where the output is actually I_0 with certain ripple over it, and this is R_L, this is C, and this is L. So we can assume that since the ripple component is very minimal, we can say our system was something like this. There, we have seen that we have the constant current. You know, we can determine the load as drawing a constant current at the output of the combination of the switch and the diode bridge.

So, then we have seen that we have derived our switching loss for this particular scenario, and we have seen our $P_{SW} = V_{in}.I_o$, V_{in} is the voltage which is applied.

Across the bridge comprising the switch and the diode, and the current which is coming out of that half-bridge multiplied by the period during which the switch is turning on, which is nothing but T switch on, which is a combination of the rise time of current and fall time of voltage plus. You know, the loss which will occur during the switch-off time, which is $\frac{V_{in}.I_o}{2}.t_{sw}$.

Then, $t_{sw,(off)}$ is the period during which the voltage rises up across the device across the switch S1 and the time during which the current also falls down. So, we have the C and $t_{sw,(off)}$. So, we can write

$$t_{sw,(off)} = t_{ri} + t_{rv}$$

And we can also write $t_{sw,(off)}$ as nothing but the rise time of voltage plus the fall time of current. And the switching frequency f_{sw}. This is primarily because we have assumed that we have connected an inductor at the output of this particular bridge. However, in case we have just the resistive load, this term will not be in this switching loss. I mean, the loss occurring due to this transition will not be this much. It will be I_o by six times in case when we have a resistor. However, in this particular case. Since we are only concerned about the voltage source converters and most voltage source converters have the inductor kept at the pole of their bridges, we have only considered this particular case. Here, if you look carefully, the switching loss depends upon the switching frequency, the number of times the transition is happening, the blocking voltage of the device, or the voltage which it will block once it is off, and the voltage which will be coming from a non-zero value to zero when it is turning on. So that's the blocking voltage and the current which will be flowing through the switch when it is on. And finally, the time required for turning on and turning off these devices. So our switching loss depends upon that. Now, let us see how our system looks like if we just take our switching transitions we have taken over here. Now, if you look carefully, the overlapping period, I mean the period during which the current is rising and the voltage is falling, is the time during which you will actually be having, some losses which is happening across the device and that is during the$t_{sw(on)}$ period and $t_{sw(off)}$ period. So, we can say that in this particular thing the during you can say that during$t_{sw(on)}$ period and $t_{sw(off)}$ period that means you can say the instance during which this voltage and currents are overlapping during this period there are two things which is happening first is obviously the loss And this loss, we know that is

$$P_{sw} = \frac{V_{in}I_o}{2}\left(t_{sw(on)} + t_{sw(off)}\right)f_{sw}$$

That is happening during this switching period, during $t_{sw(on)}$ and $t_{sw(off)}$ period. So, during this thing, following takes place. So, it is the losses.

Now, these losses lead to reduced efficiency. and this will also you know in other words it limits the switching frequency if you wanted to have the improved efficiency you must limit your switching frequency so this is the first thing which is happening the losses which is one of the important considerations, let's say if you're switching at very high switching frequency because you go for switching higher switching frequency. So that your sizes of your passives come down because sizes of passes are inversely proportional to switching frequencies, so that losses are one thing which is happening the second thing which is which is another important thing which is happening in the system whatever the circuit we have something like this system this is D this is S1 and this was going I not at the output. So here what we have seen that during when you are turning on this S1 switch during this period the current through the S1 switch start flowing through the S1 switch suddenly when the moment to turn on the S1 switch the current which was previous to that it was going through this will then shift to the S1 switch and the moment at that point what we see is that if you mark this at the output of the this bridge that a point and let's say this is N point then what you will see is that the V_{AN} if you draw this van on this particular thing what you see is that the V_{AN} at mean the V_{AN} will start having V_{in} voltage will come at V_{AN}. So, that means this V_{AN} voltage goes from 0 initially because when the diode was on it was 0 so this V_{AN} actually goes from 0 to V_{in} there you do not have any control that happens how fast you are turning on this S1 switch. So, during this time you have certainly certain $\frac{\Delta v}{\Delta t}$ which is appearing at the output of this bridge between point 'A' and 'N' and this this $\frac{\Delta v}{\Delta t}$, if you look very carefully this is actually nothing but mostly it is V_{in} and this Δt means how fast the switch S1 is getting on. So, this has good amount of $\frac{dv}{dt}$ and you can say in other words you can say that it has good amount of $\frac{dv}{dt}$ which is coming at the output of the bridge. At the same time, we also have good amount of $\frac{di}{dt}$, because suddenly the current was not there in the upper branch and suddenly when you turn on the S1 switch suddenly i mean which was flowing through the diode will suddenly move to the S1 switch. So it will also have a good amount of $\frac{di}{dt}$ and some small period of time So it will also have some $\frac{di}{dt}$ previously it was zero current. Now it is I_0 current, so it has good amount of $\frac{di}{dt}$. So, we can say that here we have this $\frac{di}{dt}$ and that actually There is good amount of electromagnetic interference due to $\frac{dv}{dt}$ and $\frac{di}{dt}$. and this on one hand you wanted to have this switching the $t_{sw(on)}$ to be as small as possible such that your switching loss is small on the other hand the moment to go for a smaller $t_{sw(on)}$ that means you have a smaller t_{ri} and t_{fe}, so when you have t_{ri} and t_{fe} then your $\frac{d}{dt}$. values in both the things become very small and that's when you have good amount of or very high $\frac{dv}{dt}$. and $\frac{di}{dt}$. which will be imposing at the output terminal of your half bridge or the bridge comprise in this case bridge comprises of S1 and D diode this is also another thing which is taking place and because of high or you can say uncontrolled you know because of high dvdt and di dt there are di dvdt related problems there are $\frac{dv}{dt}$. and $\frac{di}{dt}$, related problems. Now those problems are you know those problems are like false turn on which takes place because of high $\frac{dv}{dt}$. and because of high $\frac{di}{dt}$, you have you know in gate to source voltages you have sudden oscillations which appears and that may damage your devices.

You may take your devices to operate at certain unsafe region of operation. So, these are the problems which we see which happens whenever we have during $t_{sw(on)}$ and $t_{sw(off)}$ and to reduce P_{sw} or loss during switching the $t_{sw(off)}$ and $t_{sw(on)}$ time need to be reduced. However, it leads to IR, $\frac{di}{dt}$ and $\frac{dv}{dt}$. And because of high $\frac{di}{dt}$, $\frac{dv}{dt}$ your EMI performance or electromagnetic interference performance reduces and you have certain $\frac{di}{dt}$, $\frac{dv}{dt}$ related problems appear in the circuit which is nothing but false turn on and oscillations on your gate to source voltages. So, $\frac{dv}{dt}$ actually lead to false turn on of the devices and $\frac{di}{dt}$ actually leads to you know oscillations in your gate to source voltages.

So, these are the problems which we have. So, what we want? We want to have, on one hand, we wanted to go to high switching frequency such that size of passive goes down. On the other hand, we want our switching losses to be as minimal as possible because, you know, high switching, since we are going to high switching frequency, that means this is fairly good amount of switching frequency. V_{in} an I_o, you cannot change because that is not in your control.

That is given in the specification. So, what is in your control is it? time duration during which $t_{sw(on)}$ and $t_{sw(off)}$ that is something which as of now you have the control. Now since you have the control on these two things you want would like to have as these two numbers to be as small as possible but the moment to go for this number to be as small as possible that means the transition during which the current switches and the transition during which the voltage switches will actually be very less and since the those transition the time duration is very less the $\frac{dv}{dt}$s and $\frac{di}{dt}$ are very high and because of that there are problems related to high didts and $\frac{dv}{dt}$s like my performance get problematic or you have false turn on of the devices and that leads to the short circuit and the oscillations in your gate to source voltages.

So to avoid this thing people start using a method by which they can eliminate or they can at least reduce the impact of this particular effects and those that particular phenomenon is called the short switching. Now before I start going to that let me also say, so $\frac{dv}{dt}$s actually leads to you know false turn ons or false turn on of the devices because you know your voltages on the gate to source will go above the you know threshold voltage when the switch is off and other switch is turning on that's when the false turn on of the switch which is already which is off. So, both the switches are on in the hub bridge and then that leads to the first turn off and $\frac{di}{dt}$ actually lead to oscillations in gate to source voltages. So again, these are things which which we are not going too much in details primarily these are the problems which occurs because of these things, so let us see how we can avoid these things. Now to go ahead with this we have till now we have been discussing converters like this where we have a switch S1 and D connected in this fashion and it is supplying to the I_0 current that we will in more generalized manner we can define this to be a two switches having the you know if let's say these two switches are realized using MOSFET then they are the body diodes if they are realized using IGBT then they are the freewheeling diodes to those so that we can get the fundamental building block of any because this particular structure is fundamental building block of any voltage source converter and having the inductor connected at i mean at the pole so it's a fundamental building block of any powertronic converter. Now we can so I mean for easiness let us also take a system to be something like this where let us take we are using a MOSFET S1 this is S2 this is V_{in} this is let's say D1, D2 and since we have a MOSFET we will also have you know every MOSFET has a parasitic output capacitance and let us define this as C1 and C2 and this is actually supplying to the output current I_0 coming to the load $I_0$and this C1 and C2 are the you know output capacitance of MOSFETs S1 and S2. So we will now from now on we will consider this particular structure and we will try to see the concept of you know soft switching.

Before understanding how we can achieve soft switching in this particular conventional building block of any voltage source converter. Now, let us consider this particular converter architecture and these waveforms, which we have already drawn in the last class while discussing the switching loss concept. So, in this So, whenever we are turning on this S1 switch, what is happening is before when S1 was off, the current was actually flowing through the body diode of D2 or maybe if you turn on the S2 switch, the channel of the S2 switch, it is flowing through that. In this way, it is flowing, and then at that point, my current through this S1 switch is zero because the entire current is going through this loop. Now, during that time And since this switch is on, the voltage across the bottom switch is 0.

So, the voltage at V_{AN}, we can say that it is nothing but 0 voltage. And the entire voltage is coming across the switch S1, which is what? Which is nothing but V_{in} across switch S1, which is coming across this one. Similarly, on the other side, when it was off, when the switch was given an off signal, during the off signal, the current will start shifting from the S1 switch to the bottom switch. Let's say the bottom switch, through the diode D2, it will start going through the diode D2. Since the switch current is going to D2, the voltage across D2 will start falling, as a result of which the voltage across S1 will start rising up. And because the moment it reaches the V_{in} voltage, the current which was somewhat going through here will now fully go to zero afterwards, and the current will then be fully going through the diode D2.

During this time, if we look very carefully here, during when it is turning off, the current is going from I_o, some non-zero value, to zero value, and the voltage across $V_{S1}$is going from these zero values to the non-zero value. While during the turn-on period of the S1 switch, the current through the S1 switch is going from zero value to non-zero value, and the voltage across the switch goes from non-zero value to zero value. Now, if we look, the power loss is happening in the $t_{sw(on)}$ and $t_{sw(off)}$ periods where the current rise or fall and voltage rise or fall through switches are overlapping. If we are avoiding this overlapping, then we can reduce the switching loss nearly to zero. Now, let us see how we can do that, and let us see during the turn-on period of S1, since the I_o is zero before, and if I can somehow ensure that this voltage goes to zero this voltage goes to 0 before the current starts rising, then I can ensure there is no power loss during this time.

That I can ensure. Similarly, if I can somehow ensure that if I delay my I_o rising in such a manner that After it occurs, after the voltage falls down, then also I can, avoid having any overlapping. So, you can say I_o I am delaying and V you can say that I am leading, or you can say somehow, I am ensuring this falling is happening before the current starts rising. Somehow, I mean, there could be many means: you can connect some external circuits, or by the operation of the converter, it may happen.

So, during that time, I can do that. Similarly, during the turn-off case, if I can somehow ensure—I can, you know, make sure the current goes to 0 before the voltage starts rising—that I can get it by either, you know, leading or you can say pushing the current fault before the voltage starts rising. If I can ensure that, then I can avoid having any overlapping. Similarly, I can delay my voltage rising after my current falls down. That also I can do. That can also avoid this overlapping of rising current and falling voltages or falling current and rising voltages. And that's when I can avoid this $t_{sw(on)}$ and $t_{sw(off)}$ period. And since if I avoid the $t_{sw(on)}$ and $t_{sw(off)}$ period, the losses will also help in reducing sharp $\frac{dv}{dt}$ and $\frac{di}{dt}$, as the voltage or current transitions are now governed by the arrangements we have done. To make the voltage fall to zero before the current rises during turn-on and making the current fall to zero before the voltage rises during turn-off, I can avoid.

So, we can write that we can write two important points out of this. The first point is during turn-on, if somehow, we ensure that the voltage falls to zero before the current starts rising, then the $t_{sw(on)}$ period can be avoided, or you can say the overlapping period—overlapping of current rise and voltage fall—can be avoided, okay. be avoided, and that will lead to, you can say, that actually this will give the P_{sw} during on to be equal to zero. So, we can say that if during turn-on, if I can somehow ensure my voltage goes to zero before my current rises, we can completely eliminate the T_{sw} period which is overlapping of current rise and you can say the voltage falling and that is when we can ensure that there is no switching loss which is happening during turn on. Now, this particular scenario since we are ensuring the voltage goes to 0 before current rises is called as the 0 voltage switching. And it is abbreviated as ZVS. Since we are switching with the zero voltage. And that primarily occurs during turn on.

And because you know during turn off the voltage is already zero. So there is I mean you do not have to bother about having ZVS during turn off case. Because before when you are going for turn off case your voltage was already zero. And then you are going to some non-zero voltage coming across it. So, voltage was already 0.

Here, we are somehow ensuring that voltage goes to 0 before current is start rising. Similarly, we can on the same line, we can write down during turn off case. If somehow we ensure that current goes to zero before if current goes to zero before voltage start rising then the $t_{sw(off)}$ which is nothing but overlapping now you can overlapping voltage rise can be avoided

And this will lead to P_{sw} off to be equal to zero. And that particular scenario is called as a zero current switching. And it is abbreviated as ZCS. And this primarily happens, this zero voltage switching happens during turn on. It is important and this is happening during turn off.

Because you know during that time we are making those things to goes to 0. Now in this particular you know since we are having the voltage source converters. Having driven by the voltage source and having kind of constant current at its terminal. Because most of the time at the output of the terminals of half bridge you are connecting huge inductor. Followed by load or followed by source.

So you are actually drawing the constant current from the output of half bridge. So, now conventionally this particular converter structure because of the operation of the converter it has the scenarios in which at least one of the device goes to the zero voltage switching during turn on and that is when we achieve ZVS operation and we can say during that transition our T switch on is nearly zero and that is when we can have a you know a soft switching scenario. So, let us take our system to be you know half bridge made up of let us take whether we can achieve our ZVS and ZCS in our conventional half bridges or not. And without adding any, you know, additional circuitry. So, let us take this.

This is our C. This is S1. This is S2. This is D1, D2. And the capacitance, output capacitance C1 and C2, this is actually given by this, you know, current source, something like this. Now in this thing we know that since they are the conventional hub bridges S1 and S2 are complementary to each other.

That means when S1 is on S2 is off and when S2 is on S1 is off. Both can be off but both cannot be on simultaneously. So we have to provide I mean at that time and there is that time during transitioning during transition from from off to on in both the cases from off to on there will be that time will be provided and during the dead time then both the switches will be given 0 signal, so what we have is we have $S1 = 1$ and during that time $S2 = 0$ and then we have $S1 = 0$ and since because of the operation we will make $S1, S2 = 1$ but going from this transition to this transition you we will put we will insert some dead time in between them such that we will allow our switch to turn off completely before the other switch turns on otherwise if the switch let's say we are going from S1 switch to S2 switch. So we have turned off our S1 switch and we are now turning on our S2 switch if S1 switch does not turns off fully then there will be short circuit of this voltage source So, now let us see during this transition whether we can get the ZVS or whether we can get ZCS but here we do not connect any other circuitry externally how this conventional half-bridge in what scenarios it will achieve because you know if you look very carefully there are four instances. One instance is when S1 is turning on another instance is when S1 is turning off or S1 is turned off turned off. You can say it is turned on.

Another instance will be when S2 is turned on. And then the other one will be when S2 is turned off. There are only four transitions which take place in this conventional, or you can say the half bridge, which is one of the building blocks of any voltage source-fed power converter. So, let us take one of the instances when my S1 is turned off, and after turning off my S1, I will go to turning on the S2 switch. So, S1 is turned off.

That means we can say that S1 goes from on to off. Now, let us see how our system looks like. So, since my S1 is going from on to off, initially So, since S1 is on, the current is actually going from here to switch S1 and going here, and then coming back here. And the S2 was off, and that's when my S2 is actually blocking the V_{in} voltage of this MOSFET. The output capacitance of S2 MOSFET, which is nothing but C2, is actually blocking the V_{in} voltage. Now, after this, what happens is that the dead time occurs, during which what happens is that you have removed the pulse from the S1 from the gate to source of the S1 switch. That is when what happens is that we will see what happens during the dead time. At that time, S1 is off and S2 is also off. Both are off during this time. So, during this time, in order to ensure the current remains I_O, what happens is that now there is no channel which has been formed in S1 because you have now removed the gate-to-source voltage or made the gate-to-source voltage correspond to turning off of the devices. During this time, my S1 will also be off. The channel which was conducting will no longer exist and there is no pathway from where the current can flow through the S1 switch and the S2 switch. So, this is D1, D2, and now what happens is this: we all have a C1 and we have C2, and it is actually giving. But during this time, since this current has to be there, so we must ensure that this current I_O still persists. And during this time, what you will see is that there is a current, some current is actually flowing through this C1 flowing like this. Some current will be flowing through C2, and some current is coming over here, and some current goes over here. Now, this, let us say, this is i_{C1}, i_{C2}.

So, we can say that $i_{C1} + i_{C2} = I_o$, which is going at there. And if you look very carefully, the voltage which was there across C1 is actually. Now since the current is coming out of the capacitor C2 so the capacitor C2 is discharging we can say C2 is discharging and because of the current direction C1 is charging so C2 and C2 is discharging C1 is charging and so that means we can say that V_{C2} is reducing and V_{C1} voltage is increasing and that is when we will see that so in during the dead time what happens is that this voltage will keep on reducing which was at V_{in} which was keep on reducing this voltage will keep on increasing and what we will see that now since this will keep on going until the voltage across this becomes zero and the voltage across this becomes V_{in} and that is when since the voltage across this is zero this diode

D2 gets forward bias and that's when the current will now start flowing through the D2 , so $I_O = I_{D2}$ entire current will be going through the diode D2 and $V_{C1} = 0$, $V_{C1} = V_{in}$ And we can say that since the entire current is going through the D2, we can say that the V_{S2} is actually nearly equal to 0 if we assume the forward voltage of the diode is negligible. So, we can say voltage across the switch S2 is actually 0. Now, if you look very carefully, we have not given turn on pulse to switch S2. We have only removed the pulse from S1 switch.

So we have here we have S1 switch was is on and during this time my S2 is off already it is off then you have removed the pulse from the s1 switch that's when the S1 is off and S2 is off and that's a dead time in that time what happens the C2 gets discharged fully is getting discharged and c1 is getting charged and this will continue until The voltage across C1 reaches V_{in} because beyond that it cannot go and voltage of $V_{C2} = 0$ and that is when you will see that since the $V_{C2} = 0$, the diode D2 will start conducting and that is when the voltage across $V_{S2} = 0$and the current is actually flowing through the i_{D2}. and now we have understood during turn on case if we somehow make the voltage goes to zero before the current start rising through the device we will get the zero voltage switching so here we have made our voltage goes to zero and now when we give pulse to S2 switch to turn on the channel to form the channel through S2 switch the device will achieve the zero voltage switching and which which will actually have negligible loss or you can say zero loss or due to the overlapping of voltage falling and current rising and we will get the zero voltage switching off during this time . So now what will happen is that at this point we can also say one more thing here since this I_0 current is there we can say that the voltage or you can say the voltage V_{AN} voltage if I write V_{AN} voltage here the V_{AN} in this case was since the S1 was on it is nothing but V_{in} here the V_{AN} voltage is actually is reducing or is reducing with V_{c2} and here van is actually zero. So we can say that our V_{AN} goes from V_{in} to V_O and if we look very carefully the rate with which this voltage is falling is not dependent on how fast you are turning off your S1 switch it only depends upon this capacitance C1 and C2 and this current I_O so we can say that in this case my $\frac{dv}{dt}$ actually nothing but limited this $\frac{dv}{dt}$ is limited and this value we can get either

$$\frac{dv}{dt} = \frac{I_0}{C_1+C_2}$$

it only depends upon the external current which is flowing out of the half bridge and the output capacitance of of the devices S1 and S2 . Now after this so what we have done we have ensured our V_{S2} goes to 0 and the $\frac{dv}{dt}$ is limited which is given by C1 plus C2 by I_0. However this capacitance are non-linear capacitance depends upon the voltage to across these devices so but they are limited they are you know they are not depends upon how fast you are turning on and turning off S1 and S2 switch I mean it is independent of your gate to source circuit or your gate to source loop So, what we have?

We have got V_{S2} goes to 0. We have got that and we have limited $\frac{dv}{dt}$ which actually lead to good EMI performance. You will not find any sharp edges or you know any oscillations during the across the voltages of these devices. So, what we have is we have $V_{S2} = 0$ and when you are now turning on S2 after after the voltage across $V_{S2} = 0$, so what you will get is you will get when S2 is on turning on S2 means you are giving gate pulse gate pulse to S2 you know some gate pulse to S2 during that time if this is my I_0, so i can say the current will now start flowing through the S2 switch however the voltage across this was alreadyV_{S2} is actually equal to 0 and this current we can say i_{S2} is nothing but equal to I_o . So we can get $P_{SW(ON)} = 0$, in order to ensure this is 0 we must ensure that sufficient that time is provided such that, such that $V_{C2} = 0$ and simultaneously, simultaneously $V_{C2} = V_{in}$ and here it is V_{in} voltage to be coming over here. So, we can get P switch on equal to 0 and along with that we have limited $\frac{dv}{dt}$ which is

$$\frac{dv}{dt} = \frac{I_0}{C_1+C_2}$$

and if you look very carefully in this case since we are ensuring our C1 is charging. to V_{in} voltage from zero voltage and C2 is discharging from V_{in} voltage to zero thus we can say that the energy which is there in this one is nothing but energy in capacitance is

$$energy\ in\ capacitance = \frac{1}{2}V_{in}^{2}C_{1} + \frac{1}{2}V_{in}^{2}C_{2}$$

and if we can say energy associated with with I0 flowing through flowing through inductor L because generally this indicates we have at the output of this bridge we have L and then some C, R_L or you can see here we can also have load or i mean we can also have any voltage source or R_L whatever, so this L is there and which is having the i naught this is s1 this is s2 this is the actual circuit this was the derived circuit we have got here but this is the actual circuit so we can say the energy associated because since I_O is flowing through L we can say it is half $L = \frac{1}{2}LI_O^{2}$ and the $V_{C1} = 0$ and $V_{C1} = V_{in}$,whenever the S1 turns off and during the dead time when S2 is turning on and after that S2 is turning on so during this time this energy whatever is there must be sufficient that this energy whatever which is there because of changing the states of C1 and C2 this particular energy must be greater than this , so we can say the necessary condition is my

$$LI_O^{2} > V_{in}^{2}C_{1} + V_{in}^{2}C_{2}$$

this is the necessary condition and this is this particular condition is your you know this is the necessary condition then this is the required condition that means That means the necessary condition this energy associated or energy with the inductor must be sufficient enough to take out the required charges from C1 and C2 in such a manner that the C1 goes from 0 volt to V_{in} voltage and C2 goes from V_{in} voltage to 0 voltage.

This much energy has to be taken out by this current which will be flowing through inductor L. So that's when that is the necessary condition. However, once the necessary condition is met, then one must ensure there must be required dead time is there such that the voltage across these two gets to 0. So, this becomes the required condition or you can say that the condition which is a sufficient condition for the voltage across these devices to goes to 0 or you can say that ZVS of switch S2. So, we can say that Here in this particular case we have ZVS of switch S2 we are having during turn on of S2.

So, we will get our this thing here. So, this is the first condition we have seen that out of four condition in one of the conditions we are getting ZVS. Now when the next thing is happening when S1 is turning ON that means going from OFF to ON during that period what happens is that S1 is off since S1 is off we can say that the current was going through S2 because S2 is on if S1 is off S2 is on. So current is going through here and we can say that the voltage across this is nothing but $V_{S1} = V_{in}$. Now what happens you are now turning off, so now you will do S1 is on or you can say S1 is off and S2 is also off that means during that time so here we can also see the turning off of S2 as well so during that time.

Since you have turn off your S2 switch, so channel is not been there because you have removed the gate pulse. So now what happens is that the current if let us say D1, C1, D2, C2. So current will now because in order to find the path through the circuit, it will now start flowing through. Switch to D2 and we can say I_0 is nothing but I_{D2}. Here the I_0 is nothing but equal to I_{S2}.

And because of this thing, here we can say here it is 0 and here still it is 0 because the current is going through there and here it is still V_{in} voltage. So, this is my dead time. This is the dead time. you are now giving pulse to S1 switch so now what you are doing is you are now S1 is on and S2 is off so now during this time what happens because there is no other way because of the direction of the current the current will start flowing through the diode D2 there is no way by which i will reduce this this capacitance voltage because the current is going through the diode D2 D2 . So D2 is forward bias the voltage of C2 is nearly zero since the voltage across C2 is zero since we have been a voltage across here so that wind will be coming across the C1

So there is no way by which we will be able to discharge capacitor C1 voltage from V_{in} to 0 before the gate pulse to S1 is given to turn on the S1. So that's why when we gave pulse to S1 to turn it on the C1 will discharge through the switch S1 and then the voltage across C1 will go to 0 and that's when we can say we have. Now suddenly the channel has been formed and the current will start flowing through this and that's when the voltage across this becomes zero and the voltage across this becomes V_{in} and this voltage which was there in C1 will now actually get this will get discharged through this S1 switch so that extra charge which was there in C1 will also get discharged through this channel and that's when we have good amount of losses in this one so here we can say that I_0 is nothing but equal to I_{S1} and some non-zero $P_{SW(ON)}$ is there we can say some non-zero we can say some non-zero $P_{SW(ON)}$ will be there, so we can say that we have since now as in the case when S2 is turning on we have zero voltage switching or ZVS of switch S2 so we can say that there we have short switching because we were softly turning on the S2 during turn on because we are softly turning on the S2 because we have make sure the V_{S2} goes to zero voltage across S2 goes to zero and the transition is soft because you can say transition is limited by the output current and the capacitance of this devices so that you can say that we have softly turning on the S2 switch and here we can say since the some non zero $P_{SW(ON)}$ is there and high $\frac{dv}{dt}$ is there high $\frac{dv}{dt}$ because you suddenly form the channel whenever it was blocking the voltage V and you suddenly turn on you have suddenly created the channel that the entire voltage across the C1 get discharged to S1 switch and the another V_{in} will start appearing across C2 and for that it will again take extra current through the through the channel of the S1 itself to charge to V_{C2} will get charged to V by taking additional current from the V_{in} voltage itself from here itself and so here if we write V_{AN} voltage it is it is zero here again it is V_{AN} voltage is equals to zero if you write V_{AN} here voltage zero and here if we write here V_{AN} it suddenly goes to V_{in} there it was slowly going to zero voltage here it has suddenly you can say that this transition goes from this V_{in} voltage goes from 0 to V_{in} is only depends upon how fast you are creating the channel in this switch S1 that's when you can say it all depends upon how fast is your gate drive circuit is and you know the time period of going from voltage of V_{in}goes from 0 to V_{in} only depending upon the gate to source circuit I mean how fast the gate to source forms the channel and the current which was flowing through the D2 moves to the channel S1 it only depends upon that, so high $\frac{dv}{dt}$ and you can see some non-zero power loss and this system is called as this type of switching is called as the hard switching so hard switching of S1 we can say so what we have seen if if we take this particular circuit then we can say that yeah i mean in this circuit we can say that S1 turns on with hard switching we can say that S2 turns on with soft switching we can say which is nothing but a ZVS we will get. So, we can say that the S1 turns on with hard switching and S2 turns on with soft switching which is nothing but the ZVS operation we get. However, if we think about turn off case we would like to have the current goes to 0 before my voltage start rising up during the turn off case during the turn off case in this kind of circuit is quite difficult because we are not adding any additional circuit to it since we have connected an inductor at the output of the current. So we can say that we have the current which is kind of constant current coming out of this half bridge so there it is difficult to make the current goes to zero since we have inductor coming out of it so that's why in this kind of circuit we can only have the soft switching during one of the turning on of one of the switches uh while we we will have the hard switching when we are turning on with the other switch we can say that gcs is difficult for voltage source when we convert difficult for voltage source but half bridge converter since they have non-zero current coming out of its pole pole which is between A and N. So, it becomes quite difficult. However, there are possibility if the I_0 current itself goes to 0 because of the operation of circuit after this particular half bridge if there is certain circuit where because of the operation of the circuit the current goes to 0 then in that case you will achieve the ZCS during turn off case as well.

So, in these kinds of cases where we have the voltage source converter and we have a constant current, then we will only achieve the ZVS during the turn-on instead of one of the switches. However, if the current direction is reversed, then we will see the vice versa case, which means my S1 goes to soft switching while my S2 is hard-switched turn-on whenever these devices are turned on. So, it depends upon the direction of the current which is coming out of the source. However, there are certain scenarios where we have, you know, discontinuous conduction mode. So, there again, you are turning, you know, your current goes to zero when you are, and then you are turning off your devices.

So, you can say we have, you know, ZCS operation during that time. This ZCS is only possible if during during the operation of the circuit, i naught goes to zero—for example, you know, your DCM operation, or you can say that, for example, one of the cases is DCM. Sometimes during the operation of full-bridge converters, during that time also, these conditions may arise. So, that is what ZCS only.

So, ZCS is difficult to achieve in this kind of system, but you know, ZVS we can easily achieve by doing this thing. So, in this thing, we have particularly understood how the short switching can take place in the half-bridge converter, which is the building block of any voltage source-fed power converter. We will use this understanding because, in subsequent slides, when we discuss the pulse modulation of the full-bridge converters and the phase-shift modulation of full-bridge converters, this understanding of these concepts is essential, which you will be using to understand the concepts going ahead. So, thank you very much for patiently listening to this lecture.

Thank you.