CHARGING INFRASTRUCTURE

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Lecture-42

Lec 42: Dual Active Bridge Converter-I

Hello everyone, welcome to lecture number 42 of this NPTEL lecture series on charging infrastructure. Today, we will talk about another isolated DC-DC converter, which is the dual active bridge converter. Now, if you recall our previous discussions, we were discussing the full bridge isolated DC-DC converter in detail, where we have seen that the circuit will look something like this. It comprises two half bridges called the leading leg and the lagging leg. The leading leg and the lagging leg, and because of this particular structure, we have seen different schemes of that full bridge converter. Then, we moved to a more detailed discussion on the PSFB, which is the phase-shift full bridge converter, which is nothing but a full bridge converter operated with a phase shift between the turning off of the diagonal switches.

Then, for the phase-shifted full bridge converter in detail, we have seen different operating modes. We have derived different conditions where we can achieve zero-voltage turn-on of the leading leg as well as the lagging leg, and that's when we can achieve very low switching loss during the turning-on instances. At the same time, we will get the controlled dv/dt at the output of these half bridges, which actually improves the EMI performance of this converter. Then, we have moved our focus to small-signal modeling of this phase-shifted full bridge converter. With this small-signal model of the phase-shift full bridge converter, we have also seen how we can do the closed-loop control of this phase-shift full bridge converter, with the control objective of regulating the output voltage at a desired value. One can also introduce another control scheme, like peak current mode control, where one can sense the transformer primary current and then ensure the peak current of this transformer on the positive side as well as the negative side is the same. That's when it will help in avoiding the flux walking of this transformer because if the flux in the transformer does not reset to its initial value, it keeps on having some DC offset, and that offset will keep growing either in the positive or negative direction, leading to the saturation of this transformer. This DC offset may arise due to the non-ideality in the devices, like different $R_{ds(0n)}$.Thus, the voltage drop across these devices will be different. Also, sometimes due to the delay introduced in the gate driver circuit, the average voltage applied will be different, and that's when we will have different voltages applied along the transformer when the diagonal switches are on. They are not equal and opposite.

And that's when it leads to some DC residual flux, which keeps growing during the operation of the converter. So, that also has to be addressed, and one can address it by using peak current mode control by measuring the transformer primary current. So, these were the things we have discussed in detail. We will now move ahead with our discussion toward another isolated DC-DC converter called the dual active bridge converter. But before starting that, let us also try to write down the disadvantages of PSFB. Now, these disadvantages include the first thing: because of this diode rectifier at the secondary stage, the There is no possibility of bidirectional power flow. So, no bidirectional power flow can be achieved.

That is the thing, you know, power can flow only in one direction from this side to this side. However, because of the presence of this secondary side diode bridge rectifier, we will not have any bidirectional power flow. Only the power flows from input to the output. now the next thing is you know we have already seen we have limited range of limited range of short switching because we have also seen that for the leading leg it is not a problem the leading leg switches will go for soft turn on however the lagging switches will require the circuit operation in such a manner that L_{lkg}will have enormous amount of energy to discharge the C3 capacitor to zero and C4 capacitor to V.

So, we have limited range of the soft shifting especially in the light load conditions the achieving the gbs in the lagging lag is a quite a difficult task then third point what we have in this one is that we have large inductive filter and secondary side large inductive filter in the secondary side that is again one of the one of the concern you know this is also takes good amount of area it also impacts the power density of this as well as dc-dc converter then another point you know we have already discussed you know this is flux walking which will take place however this can be arrested by you know solved by peak current mode control. They will slightly change the duty ratio from its nominal value to either less or more and that's when they can control the peak current of the transformer in the positive and negative side to the nominal values. That is also one disadvantage which one need to address. Now let us try to see how one can you know address this thing in DAB converter which is again one of the very commonly used dc dc converter especially for high power application going up to 20 to 25 kW power range so let us try to see our dual active bridge .Now as the name suggests dual active bridge it is also called as the DAB in the short form I mean a very famous abbreviation as the dual active bridge and one can then make this dual active bridge in the modular fashion and can obtain a very high power charges by connecting them in series and parallel according to their requirement.

So let us try to understand what is a DAB converter. Now if you look very carefully dual active bridge as the name suggests it has a dual that means two active bridges which are present in the converter. So let us try to draw the converter this thing. I am taking a liberty to draw the generalized switches. So this switch, generic switch is nothing but one can achieve using MOSFET with a body diode or it could be achieved using IGBT with the freewheeling diode attached to it.

So in both the ways one can achieve this generic switch which I am drawing over here. So this is the generic switch. So, it is having one bridge. So, let me define this as V_{in} as we named and as our nomenclature says S1, S2, S3, S4. Now, this again from the point 'A', let us say defined as A1 is actually we will then take the inductance and then B1 from the other leg.

This is, you know, this is the L. I am just writing L. This L could be achieved either using the leakage inductance of the transformer or by putting the additional inductance in series with the one of the winding, either primary winding or secondary winding. Now, this is the primary side. Let us define Np. And on the secondary winding, we define as Ns. And on the other side also, we have something similar to that.

Let us say A2 B2 this particular thing I mean let's say if we have the capacitor we can connect it to the load C, R_L and we have here we can define S4 S5 S6 If you look very carefully, we do not have any inductor kept at the output of the bridge. This inductor, we can assume that this inductor is being incorporated in the inductance L. However, that inductance value of inductance

L, that we will understand when you see the operation of this converter how it works and we can put the c and R_L. So here if we assume this we have a good amount of c with the less voltage ripple so we can also draw this converter to be something like V_{in} my S1 and we can just draw voltage with V_0if we assume the C is sufficiently higher enough to keep the voltage at the constant value V_0or with a very small ripple now if you look very carefully.

In this converter, we have S1, S2, S3, S4, S5, S6, S7, and S8. If you look very carefully at this particular converter, this is a dual active bridge because we have one active bridge from one side of the transformer winding and another active bridge from the other side of the transformer winding. These two bridges are actually the active bridges, the reason being both bridges can apply any value of voltages between zero and V from A_1, B_1, and eight, and any value between zero and V naught from. A to B to in between that they can apply voltages, obviously in a switching average sense. Now, in this particular structure, we can represent this transformer in the form of a T-model, so we can make this transformer and P and S to be looking like. Something like this, where this is the L_{lkg} on the primary side, L_{lkg}on the secondary side, and we have this magnetizing component of inductance Lm. If we assume if L_p, L_s, the leakage of primary and secondary are small. And less than you can say that L value, and if L_m is large enough or is large, now this transformer we can define in this manner, considering we have a T-model of the transformer. Now, if you look very carefully when you know this particular system, we can here we can apply, you know, any voltage between 0 and V from A_1, B_1, and any voltage between 0 to V_0.

From A_2, B_2, obviously in a switching average sense. So, since A_2, B_2,, we can apply any value between 0 and V_0, so we have to then take the A_2, B_2, voltage referred to the primary side, and that is when we can then define the equivalent circuit. We are applying any voltage from A_1, B_1, and this V_{A1}, V_1 is in the. Switching average sense. That means the average voltage applied from the V_{A1}, B_1 in the switching period. So, in a switching average sense, and we are now applying a voltage across L, and this voltage is nothing but again applied from the other side, which is V_{A2}, B_2, and this has to be referred to the primary side, so we can then write by n. So we can write in this way. Now again, this is in the switching average sense, so thus what we can say is that we are now by changing any value from A_1, V_{A1}, B_1 and any value from A_2, V_{A2}, B_2.

We can then allow the current to either flow in this direction or flow in the other direction. Obviously, in a switching average sense, we are defining that power flow to go from either from V_{A1}, B_1 to A_2, B_2or from V_{A2}, B_2.to V_{A1}, B_1. And that is how we can achieve the power flow to go from. V_{A1}, $B_1$to V_{A2}, B_2.or fromV_{A2}, B_2.to V_{A1}, B_1. Now, if you look very carefully, you know our this circuit what we have drawn, let us take that circuit. If you look very carefully in this circuit, now here we can do several, you know, we can control this voltage applied from A_1, B_1 by actually changing the phase shift between, you know, half-bridge compressors of S1, S2 and half-bridge compressor S3, S4. Let us define this angle to be θ_1 that we can control the phase shift.

Of turning off the diagonal switches, as we discussed in the case of a phase-shifted full-bridge converter. Similarly, from the other side, we can also control the voltage applied from A_2, B_2, by giving the phase shift between the diagonal switches in the full bridges, which comprise two half bridges: S5, S6 and S7, S8. That phase shift we can give to be θ_2. Along with that, we can also control the average voltage applied from A_1, B_1or from A_2, B_2 or from A_2, B_2 or from A_2, B_2 or from A2 B2 by giving the phase shift between these two full bridges by a phase angle, δ by giving the phase shift between these two full bridges by a phase angle, δ by giving the phase shift between these two full bridges by a phase angle, δ, by giving the phase shift between these two full bridges by a phase angle, delta. So, if we see, we have three control variables: delta, theta 1, and theta 2. Delta is actually doing the phase shift between the two full bridges. One full bridge comprises S1, S2, S3, S4, and another one comprises S5, S6, S7, S8. The other phase shift is between the two half bridges in full bridge 1. Let me say this is full bridge 1, and let me define this as full bridge 2.

So, $\theta_1$is actually the phase shift given in the half bridges of full bridge 1. While there is another possibility to provide the phase shift between the half bridges of full bridge 2. So, with these three phase shifts, we can achieve different kinds of modulation schemes. By giving delta, we are actually changing the phase shift of the voltages applied from V_{A1}, V_1, and voltages applied from V_{A2} V_2. While giving theta 1, we are actually changing the duty ratio of the voltage applied from A_1, B_1.

That means, for how much time we are applying plus V in voltage and for how much time we are applying minus V_{in} voltage from A_1, B_1. Similarly, by theta 2, we are actually changing the duty ratio of the voltages applied from A_2, B_2. You know that duty ratio means for how much time we are applying positive V_0 in one switching period. Similarly, theta 1 actually impacts the duty ratio of the voltage applied from A_1, B_1, meaning the time for which we are applying plus $+V_{in}$ one switching period. So, by doing this, we have different kinds of modulations possible. The moment we control the voltage of A_1, B_1 and A_2, B_2, we can either control the magnitude of the voltages applied from A_1, B_1 and A_2, B_2, or we can provide the phase shift between A_1, B_1 and A_2, B_2. In both cases, we can control, the power flow from going from A_1, B_1 to A_2, B_2. or from A_2, B_2. to A_1, B_1. So that is why there are so many modulations are possible in these dual active bridges, so let us define different modulations possible different types of modulation. Now the first type of modulation is called we can also call it as a single phase shift modulation which is also called as a short form as sps modulation now in this only one phase shift will be changed mostly it will be delta which is being changed and that's when by controlling this delta value one can control the power flow going from one side going from A_1, B_1 to A_2, B_2 or from A_2, B_2 to A_1, B_1. Now second modulation dual phase shift and dual phase shield modulation also called as DPS there are either along with delta you can either do with change you can also change the theta or along with delta you can change the θ_2 or one can also do θ_1,θ_2. Again it depends upon the designer who is designing that what kind of modulation they wanted to implement in their controlling scheme. then the third one is you know comprises of since we have three modulation scheme presents, so they can also say that triple phase shift modulation also called as a TPS modulation.

Here we are changing all the delta θ_1 and θ_2 and that's when we can control the output voltage or we can say that control the power flow going from A_1, B_1 to A_2, B_2 or from A_2, B_2 to A_1, B_1

. We can do the power flow control using that by changing all the three δ, θ_1 and θ_2 phase shifts. And however, here if we see when we discuss one of the modulations, simplest modulations, SPS modulator, you will see the current waveform changes by introducing this, you know, δ, θ_1 and θ_2 and that is when one can achieve the lesser RMS value of the currents in the circuit and that is when the conduction loss in the circuit can be reduced. Now another kind of modulation is also possible is you know along with this if you look very carefully in this circuit the power flow can be either from A_1, B_1 to A_2, B_2 or from A_2, B_2 to A_1, B_1 by either giving the phase shift between these two voltages or by changing the magnitude of voltage which is coming on this two side along with that we can also change the impedance offered by this. This inductance and that impedance is nothing but we can say ωL and that omega in this particular circuit $\omega = 2\pi f_{sw}$ because we are applying the square pulses from A_1, B_1 to A_2, B_2.

so now this ω what we are writing over here this particular ω we can also change that particular frequency fsw and that's when we are changing this impedance ωL and that's when we can control the amount of current which is flowing from one voltage source to another voltage source or from second voltage source to first voltage source. So another possibility is also could be we can have triple phase shift with variable frequency sometimes also called as the TPSVF which is also called the triple phase shift with variable frequency. Similarly, one can also achieve you know dual phase shift (DPS) with variable frequency (DPSVF) And I mean, again, this is very rarely used, but one can also use this as well. Very, very rarely used. Now, if you see in this triple phase shift with frequency control, one can do δ, θ_1 and θ_2 and switching frequency f_{sw}.

One can write δ, θ_1 and θ_2, and f_{sw}. Here, you know, either of these things— δ, θ_2, or δ, θ_1 or θ_1, θ_2—along with this, we will have, you know, f_{sw} here, f_{sw} here, f_{sw} here. However, it is very rarely used because, as per several researchers who have worked on it, we can get a very low RMS value of the currents flowing in the circuit, very low in this particular case. That's why people go for this particular approach. So, what we have—what we saw—are different kinds of modulation where we have single-phase shift, where we are just changing, you know, the phase shift angle between full bridge 1 and full bridge 2.

Dual-phase shift, where along with this δ that means the phase shift between full bridge 2 and full bridge 3— the full bridge one and full bridge 2, we are actually giving the phase shift either from full bridge one or full bridge two. That's when we can control the time period for which the V_{in} voltage is applied from A_1, B_1 and the time period for which the positive load voltage is applied from A_2, B_2. That's when controlling the average magnitude of voltage applied from A_1, B_1or from A_2, B_2 by giving either θ_1 and $\theta_2$phase shift. And then, finally, we can also combine all three phase shifts— δ, θ_1 and θ_2—that's when we can get the triple-phase shift modulation. Along with triple-phase shift, we can also introduce variable frequency operation. Further, in all these modulations, since the phase shifts are given, all the switches are turned on for half the switching cycle period and turned off for half the switching cycle period. Only the phase shifts in turning on—or, in other words, turning off—instances of the corresponding diagonal switches are given.

Since the switches are on and off for half of the switching cycle period, the phase shift given between turning on instances will be the same as saying the phase shift is given between turning off instances of the diagonal switches. Now, let us see the single-phase shift modulation for developing an understanding of how this converter works. So, let me define the single-phase shift modulation. Now, in this, if you see, Let us try to draw the waveform because, from that, we will understand our circuit.

From that we will understand our system. So, if we see our first, let us first assume that S1 and S4 are turned on at the same time and turn off at the same time. S2 and S3 are turned on and turn off at the same time. S5 and S8 turn on and turn off at the same time. S6 and S7 turn on and turn off at the same time.

So assume the first it is S1 and S4 it is on. So we are having S1 and S4 which is on. Let me quickly draw the circuit for our understanding. We have S1, S2. S1, S2, S3, S4.

now so my s1 and s4 are on at the same time so let me draw S1 and S2 are on for the same time let us take it is on for $\frac{T_s}{2}$ period and slightly take a small and then it is off for another $\frac{T_s}{2}$ period this term up till this point is $T_S$duration and this thing to this thing it is $\frac{T_s}{2}$from here to here it is $\frac{T_s}{2}$. Now the other switches if we see let us see S1 and S4 are on and immediately after that my S2 and S3 is on then let us also draw my S5 S8 and let us also draw my s6 S7 and we let us also draw after that we A_1, $B_1$to A_2, B_2 and finally at last we will draw we will draw our this the current il current which is flowing through the l so which is il Now let us try to draw S2 S3 so it is 0 and then it is turned on for $\frac{T_s}{2}$ period and again it is 0 and if we see our S5 S8 let us you know this there is a phase shift which is given between S1 S1 and S5 which is you know delta

Here the phase shift means the angle with which the turning on instances of S5 acids switches are displaced or shifted. Now let us define an analogy. If there is an angle of 360^0 ,it indicates that we have the time period nothing but corresponds to T_S. And that means if there is a phase shift or if there is a phase of 180 degree, then that indicates the time period of $\frac{T_s}{2}$. Similarly, we can say that then giving phase shift of delta means we have time delay of delta by 180 degree into $\frac{T_s}{2}$.

That means if we give a phase shift of delta, then it indicates that we have time delay of delta by 180^0, $\frac{T_s}{2}$. And thus, we can define a term delta star which is nothing but equal to delta by 180 degree a kind of we can say which is a phase angle ratio and this we have done it for our easiness. So, we can say that if there is a phase shift of delta then the time delay corresponding to that is delta star $\frac{T_s}{2}$. So let us given one phase shift which is let us take at this point, and this period this period is let us define this period going from this and this will be nothing but delta star $\frac{T_s}{2}$ and then this period will be nothing but 1 minus delta star $\frac{T_s}{2}$ period similarly we can also draw S6, S7 because this since whatever the delta angle between S1 and S5 same δ angle will be there between S3 and S7 so S7 and S6 will be having the same phase shift as that of this so if we take you know our this thing you know at this point at this point my S6 S7 is on and it will turn off at this point and here it goes it was on and then it goes zero then it becomes zero like this similarly similarly this is also same as $\delta \times \frac{T_s}{2}$and this one is again nothing but $(1 - \delta)\times\frac{T_s}{2}$ period. Now let us try to draw this V_{A1}, B_1 , how it looks like since between 0 to $\delta\times\frac{T_s}{2}$ my S1 and S4 is on S1 and S4 is on. So, this V_{in} since my S1 and S4 is on I am applying V_{in} voltage from V_{A1}, B_1.

Then at $\frac{T_s}{2}$ period S1 S4 is off turned off and S2 and S3 is turned on. That is when I am now applying $-V_{in}$ because now S2 and S3 is on. So that is when A1 B1 is now applying the 0 or minus V in voltage from there. And then again it goes to V in. Similarly, in case of A2, B2, if you see my S6 and S7 is on, S6 and S7 is on.

Again, this particular thing we will now write here one important thing. That means it is referred to primary side so that we can then draw our i_L current referred to primary side. So, this is VA2, B2. We can say VA2, B2 primary is VA2, B2 referred to primary. primary side now if you look very carefully the A2 B2 is you know when my S6 and S7 is on i am now applying from the secondary side$-V_O$ and this $-V_O$ if it referred to the primary side it is nothing but V_O/n where n is nothing but

$$n = \frac{N_s}{N_p}$$

So, what we will get is here we are now S6, S7. So, here we are now applying $-\frac{V_O}{n}$ voltage from A2, B2 referred to primary side. And then after this my S5 and S8 is on. So, now I am now applying $\frac{V_O}{n}$ and then again it goes to $-\frac{V_O}{n}$.

from A to B to refer to primary side. Now, if you recall our phase shift full bridge configuration, here we are directly going from V_{in} to $-V_{in}$ because we are now turning off our diagonal switches S1 and S4 at the same time if we could have introduced the phase shift between S1 turning off of S1 and S4 then we could have introduced you knowV_{in} I mean zero state as well and that's when our va1 B1 will instead of looking like going from V_{in} to $-V_{in}$ it will look something like it goes from 0 , V_{in} then to 0 then $-V_{in}$ and then to 0 V_{in} , 0, V_{in}. That is when if we are applying θ_1 phase shift δ1 phase shift.

sorry $\theta_1$phase shift if we introduce in the half bridges of S1 S2 and S3 S4 that means we we now turning off my S1 and S4 diagonal switches at different times or you can say with the staggered turn off of S1 and S4 switches we could achieve this kind of waveform and that will actually reduce the average voltage which in a switching period which will be applied from V_{A1} B1 average value of voltage Now, let us see how my i_L current will vary. You know, here we are applying V_{in} and V_O. So, across this L, from here we are applying V in voltage and from here we are applying $-V_O/n$ voltage. So, that's when my i_L current will actually rise with very, very fast slope because the slope is nothing but $\frac{\frac{V_{in}+V_0}{n}}{L}$ with that slope it will rise then between this point to this point we are now applying V_{in} from this side and V_{in}/n from this side of this L .

So, our slope is now is reduced and that is nothing but we can say it is $\frac{V_{in}-\frac{V_{in}}{n}}{L}$ with that slope it is rising.

Similarly, in this instance, we are here, we are applying minus $-V_{in}$. On the other side, we are applying$-\frac{V_0}{n}$. So, we are now having a very sharp slope, which will actually be looking like this. So, sharp negative slope we have. goes like this from in this case it was we are applying $\frac{V_{in}-\frac{V_{in}}{n}}{L}$ slope and and this one and from here to here we are applying $-V_{in}$ from other from one side on the other side we are applying$-\frac{V_0}{n}$ that's when my slope is nothing but

Is nothing but. $\frac{-V_{in}+\frac{V_0}{n}}{L}$. Here, the slope is drawn in this way. Which means that. We have taken a condition.

Where us. $V_{in} > \frac{V_0}{n}$. That's why I have a negative slope. But this negative slope value. Is reduced.

This waveform is for this case. And now this is. Let's define this as. This, if we say, is I_0, which is the same as this one we take here. So, we can then draw a curve like this, you know, for better understanding. And this is, let us define this as I_0. This value to be I_1, this value to be I_2.

This value, which is going over here, is nothing but I_3, and this value we can define as I_4, which is equal to I_0 and also equal to I_4. Here, in order to ensure the flux does not have some offset, we must ensure that $I_2 = - I_0$, $I_1 = - I_3$, and $I_4 = I_0$.

We must ensure this condition to guarantee this. No offset in the transformer primary current. Or, in better words, no DC offset in the transformer primary current, because if there is a DC offset, then the flux in the transformer will keep going in one direction and it will get saturated. So, this is the simplest waveform we have drawn by giving just the phase shift between the full bridge one. And between full bridge 2, the switches in full bridge 1 and full bridge 2, here we assume that both switches are turned off at the same instances. There is no phase shift or delay in the turning off of the diagonal switches in the full bridges.

So, this is the simplest single-phase shift modulation waveform. We will derive the conditions, considering this, you know, how we can design this L value and how the current waveforms look like for different magnitudes of V_{in} and V_0. voltages. Those things we will see in the next class, and with that, we will then look into some of the important aspects of this TEV converter. Thank you very much for patiently listening to this lecture.

We will meet in the next lecture. Till then, thank you.