CHARGING INFRASTRUCTURE

Prof. Apurv Kumar Yadav

Department of Electrical Engineering

Indian Institute of Technology Roorkee

Week-09

Lecture-43

Lec 43: Dual Active Bridge Converter-II

Hello everyone, welcome to lecture number 43 of this NPTEL lecture series on charge infrastructure. Today, we will continue our discussion on dual active bridge converters. In the last class or in the last lecture, we have seen it comprises two active full bridges connected on either side of the transformer, having a defined turns ratio. This particular converter is called active because we can actively control the $V_{A1,B1}$ voltage and $V_{A2,B2}$ voltage. Depending upon the voltage applied across this inductor, the corresponding impedance offered by this inductor determines the power flow from A_1, B_1 terminal to A_2, B_2 terminal. Or from A_2, B_2 terminal to A_1, B_1 terminal, depending upon the different magnitudes of voltage applied and the phase shift given between the A_1, B_1 and A_2, B_2 voltages.

Now, using that, there are different kinds of modulations possible with this kind of converter. So, the first modulation is simply single-phase shift modulation, where the phase shift is given between the turning on of four S1-S2, S3-S4 switches and S5-S6, S7-S8 switches. That means the turning on and off instances of the S5 switch are shifted by the phase angle delta from the turning on and off instances of S1. Similarly, the S7 turning on and off instances are shifted by a delta phase shift with respect to the turning on and off instances of S3. And simultaneously, between S6 and S2 and S8 and S4, there will be a phase shift of delta in the turning on or off instances.

Further, here all the switches are turned on and off for half the switching cycle period. By controlling this value of delta, one can control the output and the power delivered from A_1, B_1

side to A_2, B_2 side. Similarly, apart from this phase shift, one can also give phase shifts among the half bridges in full bridge 1 and the half bridges in full bridge 2. So, that means here when we give θ_1, θ_1 is the phase shift provided between the turn-off instances of the diagonal switches of full bridge 1, while theta 2 is the phase shift provided between the turning on and off instances of S5 and S8 switches in full bridge 2. And then, δ and θ_1 or δ and θ_2 or θ_1 and θ_2—one can use only two-phase angles. That's when we can get the dual-phase shift modulation. In triple-phase shift modulation, we have δ, θ_1 and θ_2—all three phase shifts are varied, and that's when one can achieve the triple-phase shift modulation.

Similarly, one can also achieve you know along with this triple phase shift one can also change the switching frequency because by changing the switching frequency the impedance offered by this inductance changes which can control the amount of current which will be flowing from A_1, B_1 terminal to A_2, B_2 terminal or from A_2, B_2 terminal to A_1, B_1 terminal or vice versa. Finally, one can also do the dual phase shift with variable frequency which is very rarely used but one can use that where you know along with this two phase shift one can also introduce you know the change in the switching frequency as well and with this kind of different modulation scheme the power flow can be transferred from A_1, B_1 terminal to A_2, B_2 or from A_2, B_2 terminal to A_1, B_1 accordingly by depending upon the kind of phase shift one is giving either the leading phase shift or lagging phase shift one is giving between these two full bridges now we were discussing about the simplest single phase modulation where we have assumed our V_{in} voltage is greater than $\frac{V_0}{n}$ voltage and $\frac{V_0}{n}$ is the voltage which can be applied from A to B to refer to the primary side and we have taken that where 'n' is nothing but ns by np and we have seen for this thing our the current waveform of the inductor the current going through the inductor will having a shape something like this. Now, let us try to find out how we can design this L value and what can be the maximum power which can be transferred between V_{in} and V_0.

Let us try to find out that particular relationship. So, in this if we look you know let us define this 4 you know this has particularly has 4 mode, mode 1, mode 2, mode 3, mode 4. if you look very carefully if we simply draw this thing in this one you know i have $i_L(t)$ it goes from if we take it goes from here very sharply rises then slowly rising then falls down falls down to this one and then finally at this point it touches and then again from here the next phase starts. So, this is the entire th duration we were having in that th duration this is this slope is given by $V_{in} + \frac{V_0}{n}$ this slope was giving $V_{in} - \frac{V_0}{n}$this slope was giving $\frac{\left(-V_{in} - \frac{V_0}{n}\right)}{L}$ okay obviously everything will be divided by L And this one will be $\frac{\left(-V_{in} + \frac{V_0}{n}\right)}{L}$ And if we see in all the three things, let us define some of the things here. Now from here to here it is $\delta^* \frac{T_S}{2}$. And from here to here we have $(1 - \delta^*)\frac{T_S}{2}$. And if we see this thing,

let us define from this point to this point. This is our T_1 point, from this point to this point is our T_2point.

And here we have taken I_0, I_1, this is I_2, this is $I_3$and this is I_4 and we have already defined my $I_0 - I_2$, $I_2 = I_4$ and $I_3 =- I_1$. Now let us try to find out the value of inductance L. Now the value of inductance L if we try to find out. So let us try to write down first thing. You know we can just write $t_1 + t_2 = \delta^* \frac{T_S}{2}$.

And then we can also write you know this slope if we see this slope this slope we have slope of this line can be given as

$$-\frac{I_o}{t_1} = \frac{I_1}{t_2} = \frac{I_2}{t_1}, \tag{1}$$

that we can write. Let us define this as equation number 1. Now what we can do is we can now find our this particular slope. If we see we have $L\,di$ which is nothing but going from 0 to I_1.

L di by dt which is nothing but t2 is nothing but the slope is V plus V0 by n. Now this is the thing let us define this as equation number 2. Where we know that our delta star is nothing but delta by 180 degree where delta is nothing but the phase shift in degrees.

Now, then after that, let us go ahead and then define my this particular from here to here. Let us try to define this thing from here to here. It is going from, you know, I0 to I1. So, I can write expression nothing but I1 minus I0 is nothing but Vin plus Vin by N by L delta star Ts by 2. and similarly we can write from this point to this point is nothing but I2 minus I1 is nothing but V in minus V naught by N by L into 1 minus Delta star TS by 2 and we know that as I naught is nothing but equal to minus I2

So, we can then write

$$I_1 + I_2 = \left[\frac{V_{in} + V_0/n}{2}\right]\delta^* \frac{T_s}{2}$$

$$I_2 = \frac{T_s}{4L}\left[\frac{2V_0\delta^*}{n} + V_{in} - \frac{V_0}{n}\right] \qquad (5)$$

$$I_2 = \frac{T_s}{4L}\left[2V_{in}\delta^* - V_{in} + \frac{V_0}{n}\right] \quad (6)$$

$$t_1 = \frac{\delta^* T_s}{2} - t_1$$

$$t_1 = \frac{\delta^* T_s}{2} - \frac{LI_1}{V_{in} + \frac{V_0}{n}} \ (from\ eq\ (2))$$

(Substitute I_1 from (6))

$$t_1 = \frac{T_s}{4\left(V_{in} + \frac{V_0}{n}\right)}\left[2\frac{V_0}{n}\delta^* + V_{in} - \frac{V_0}{n}\right] \qquad (7)$$

By solving this correction which we get

$$t_2 = \frac{T_s}{4\left(V_{in} + \frac{v_0}{n}\right)}\left[2V_{in}\delta^* - V_{in} + \frac{V_0}{n}\right] \qquad (8)$$

Now, after knowing these T_1 and T_2 time instances—this time instance and this time instance—what we have to find out is that what we will see is that this particular part, from this point to this point, if we see, this is nothing but my $\frac{T_s}{2}$ period. Now, if you see my $\frac{T_s}{2}$ period, what we are going to see is that in $\frac{T_s}{2}$ period, we have the current going from I_0 to I_1, then then I_1 to I_2, and what we will see is that this variation of this i_L current repeats itself after the $\frac{T_s}{2}$. That means when it is going from I_2 to I_3 and then $I_3$to I_4, so we can say that this i_L is repeating itself after $\frac{T_s}{2}$ period. So, if we have to find out the IL average, we can find out by doing the averaging over the $\frac{T_s}{2}$ period. Now, if we see in our circuit—this circuit—if we see, whatever the average value of i_L current which we are getting over here will be the same current which we are actually drawing from the input source, and that we can define as $< I_{in,avg} >$ average. So, that much current is being drawn from this input, so that the same amount of average current will be drawn from the input, because this average current will be nothing but the average current of this i_L. So, what we can then write down is that our $< I_{in,avg} >$ is nothing but we can write down $< i_{L,avg} >$ over the $\frac{T_s}{2}$ period as the $i_L$repeat itself after $\frac{T_s}{2}$ period and then if we have to calculate the $< i_{L,avg} >$ over this $\frac{T_s}{2}$ period what we can do is we can then do simple you know we can then calculate this area under this curve that means this particular part this particular part and this particular part we can just take the area of these three portions and we can obtain our required you know expression or our required i_L average.

So what we can do is it is nothing but since we have to calculate in $\frac{T_s}{2}$ period. So we have taken the mean on that and let us take in this triangle which is nothing but

$$I_{in,\,avg} = \langle i_L \rangle_{\frac{T_s}{2}} = \frac{2}{T_s}[-\frac{1}{2}I_2 t_1 + \frac{1}{2}I_1 t_2 + \frac{1}{2}\left(I_1 + I_2\right)t\left(1 - \delta^*\right)\frac{T_s}{2}]$$

And this is nothing but is our entire area under this curve which is shown in the shaded red portion. So now let us try to put the t_1 ,t_2 .I_1, I_2 values from our previous derived equation. So, we can then obtain from 7 we can obtain t_1 from 8 we can obtain t_2 from equation 5 we can obtain I_1 and from equation 6 we can obtain I_2 so you can obtain all those scenarios and then

From 5 we can obtain I_2 and from 6 we can obtain our I_1. Now this, when we put this particular expression of t_1 ,t_2 , I_2 and I_1 in this particular big expression, what we gonna get is $I_{in,avg}$ is nothing but

$$I_{in,avg} = \frac{(1-\delta^*)\delta^* V_o}{2nLf_{sw}} = \frac{\left(1-\frac{\delta}{180^\circ}\right)\frac{\delta}{180} v_0}{2nLf_{sw}}$$

$$\left(f_{sw} = \frac{1}{T_s}\right)$$

Here the δ has to be in degrees.

So then we can then write our

$$P_{in,avg} = V_{in} I_{in,avg}$$

$$P_{in,avg} = \frac{(1-\delta^*)\delta^* V_O V_{in}}{2nLf_{sw}}$$

Now from the power balance what we can write is from the power balance what we can write down is that my $P_{o,avg}$ that means the power average power at the output is nothing but equal to average power at the input ($P_{in,avg}$) and then we can define that term to be P_{av} or the average amount of power which is the transfer.

$$P_{o,avg} = P_{in,avg} = P_{av}$$

So, we can write down the average power transfer is nothing but

$$P_{av} = \frac{(1-\delta^*)\delta^* V_O V_{in}}{2nLf_{sw}} \quad (9)$$

Now this is let us define this as equation number 9.

So we can see that the average power transferred from input side to output side can be obtained by this particular formula. Now let us try to understand this is the average power which can be obtained at the output. Now let us also see what is the maximum power which can be sent. So for that what we can do is we can then divide this P_{av} by with respect to δ^*.

$$\frac{dP_{av}}{d\delta^*} = 0$$

$$1 - 2\delta^* = 0$$

$$\delta^{*} = \frac{1}{2} \quad , (\delta = 90^{\circ})$$

$$P_{av,max} = \frac{V_0 V_{in} \cdot 1/2.1/2}{2nLf_{sw}}$$

$$P_{av,max} = \frac{V_0 V_{in}}{8nLf_{sw}}$$

So, this indicates if we put delta star in equation number 9. what we will get is our $P_{av,max}$ is nothing but

$$P_{av,max} = \frac{V_0 V_{in}}{8nLf_{sw}}$$

Now this is the expression you know which will define however you know what is the maximum power we can have we can transfer it from input to output side.

Now the same thing we can get when we are doing from power transfer from V_0 to V_{in} the same expression we will get. So, we will now see how our average power varies you know, with the δ^{*} and we can then also write parallelly how our power varies with δ, average power varies with δ.

So, what we will see is that this expression will become 0 whenever the delta star becomes 1 and this expression will also become 0 whenever δ^{*} is equals to 0. So, we can then define two points 1, 0 and zero and let's say one and we know that our maximum value of power reaches at half the point. So we can then define our value half here and what we will get is we will get a curve a parabolic curve which looks like define this at that midpoint which is nothing but goes like this and then comes back and then comes back like this so and this point is nothing but your $P_{av,max}$ value which is nothing but

$$P_{av,max} = \frac{V_0 V_{in}}{8nLf_{sw}}$$

Similarly in terms of delta we can say we have 180° whenever the δ^{*} is equal to 1 we have 0° whenever δ^{*} is equal to 0 and then we have a 90° whenever the delta becomes equal to delta star becomes equal to 1 by 2. So what we will get is we will again get the same variation parabolic variation having a maximum value at delta equal to 90° and going there so this point is nothing but my $P_{av,max}$ which is $P_{av,max} = \frac{V_0 V_{in}}{8nLf_{sw}}$

Now after obtaining this maximum average power which can be obtained at the output or which can be delivered at the output what we have to find out is what is the maximum limit of inductance L which we can or what is the range of inductance L which we can put in. So let us try to see the values of L that means we can now define some conditions that that means for the Minimum value of V_{in} because generally and the minimum value of V_O that generally because you know you have variation in the input and output voltages you have some repulse which, so that means the V_{in} and V_O goes somewhere between minimum value and the maximum value. So let us define that minimum value of V_{in} and V_O, so we can then able to transfer with the minimum value of input and output voltage is transfer maximum power so we can able to transfer P average maximum with minimum value of V_{in} and V_O only when our L value is

$$L \leq \frac{V_{in(min)} V_{o(min)}}{8nf_{sw} P_{av,\, max}}$$

less than equal to Vin min Vinot min divided by 8 and FSW and P average maximum now if you see this particular part this particular part is generally given in the specification this and this is also given in the specification of the converter whenever we are starting designing the converter f switching is the designer's choice depending upon depending upon the switching loss in the converter one can decide what could be the maximum switching frequency and depending upon the size of the transformer one can decide what could be the switching frequency limit we can go. So that's the designer's choice similarly number of turns is also designer's choice you know depending upon the various you know circuit parameters like different RMS currents at the transformer at the switches on both sides of the full bridges designer can choose what will be the best possible number of turns one can have and that will give you nothing but maximum value of L So this is the maximum value of L you will get.

Now the designer can do the iterations and can able to predict what could be the best possible value of inductor such that you will have the minimal losses as well as the maximum power density. That means you can then define your number of turns, your switching frequencies and then can optimally select this inductance value. similarly we can also define the constraints on the delta star because you know the delta star corresponds to the phase angle what what can be the maximum phase angle so this delta star because it is a generally these control schemes are developed in the microcontroller so this delta star cannot go go maximum or cannot go beyond a certain minimum value generally it is been clamped up to 0.5 and maximum side it goes up to 0.95 so this particular range can also be taken and depending upon the required amount of power to be transferred from input to output side and with this range of delta one can also decide what could be the minimum value of L one need to have to allow the required amount of power transfer to be done from input to output side. So, this is how one can select the inductance which is being used to actually facilitate the required amount of power transfer from input to output side or from one side to the another side.

However, as we have discussed in this DAB, we have several other modulations which are possible, like dual phase shift or triple phase shift, triple phase shift with variable frequency. So, for different modulation schemes, one can then define these different inductance values which can be used. One can either reach to the closed-form solution or one can do the optimization such that we can achieve the inductance value to be smaller, while at the same time, the RMS ratings of the switches as well as the inductor are also smaller. So one can do that optimization and can arrive at what will be my number of terms, what will be my inductance. So here, if you look very carefully, this waveform is there whenever we have $V_{in} > \frac{V_o}{n}$. Now let us also see how the inductor current varies when we have $V_{in} > \frac{V_o}{n}$. So, let us see how the waveforms look like.

Now let us take the condition when our $V_{in} < \frac{V_o}{n}$. So if you look very carefully, I am now drawing only VA1B1 because we already know how V_{A1B2} can be obtained. So, if this is for $\frac{T_s}{2}$, if it is like this, for another $\frac{T_s}{2}$ if it is like this. Similarly, for V_{A2B2}, assume at this point, this $A2B2$ is going like this and then again it goes like this. So, this is $-\frac{V_o}{n}$, $\frac{V_o}{n}$, and then again minus $\frac{V_o}{n}$. Here, this is referred to the primary side.

So, if we see our inductor waveform i_L, this is my Vin voltage. So at this point, my thing will be going sharply like this with a slope $\frac{V_{in}+V_o}{nL}$. With that slope, it is going here. If we look, it is Vin minus $\frac{V_{in}}{n} - \frac{V_o}{n}$, and since Vin is less than $\frac{V_o}{n}$, we have a negative slope which goes like this. So it will become divided by L.

$$\frac{V_{in}+V_o}{nL}$$

With that slope, it is falling since my $V_{in} < \frac{V_o}{n}$, so I have a falling slope here, and this continues. This continues not up till here. Let us This continues up to this point, and beyond that point, this voltage is minus Vin coming over here, $- V_{in}$ and I have $- \frac{V_{in}}{L}$. So, it is again falling to this one sharply, which is falling down. This will be, or you can say it is further sharply going down, this slope is nothing but $\frac{-V_{in} - V_0}{nL}$ slope we are having and finally from this point To this point, what we have is, we have the slope which is going in this way and this slope is nothing but my minus $\frac{-V_{in} - V_0}{nL}$. Since my $\frac{V_o}{n} > V_{in}$, so this slope is positive slope and if we look very carefully, this one and this one is I_0. Again, here we can say I_4. This is I_3. this is i1 and this is my $I_2$and we can say that my I_2 is nothing but minus I_0 is nothing but i4 and here we can say that my $i_L =$ is nothing but equal to minus I_3 you know we can also draw much simplest manner in

we have this one we have sharp slope like this and this one is minus v plus v naught by n by l this slope and this slope is the nearly the same when it is falling it is rising so we can then see our current waveform, current shape, if we see $\frac{V_o}{n} > V_{in}$, we have shape going rising up, then again rising, then falling, then falling. However, in this case, our shape of the waveform will be rising, then falling, then falling and then rising. So, our shape of the waveform changes and then one can easily find the RMS current of this particular waveform and can able to understand what could be the impact of Vin greater than Vin by N or Vin less than Vin by N and then can able to understand for the smallest value of RMS current of the inductor one can choose the number of turns N number of turns because here my Vin and Vin is fixed if I change the N value I can make either Vin greater than Vin by N or Vin smaller than Vin by N so that iteration the designer has to do here if you look very carefully

is nothing but delta star $\frac{T_s}{2}$period here we are giving the switch S1 and S4 is on here my S2 and S3 is on here if you look very carefully here my S5 and if you see S5 and S8 is on and here my S7 and S6 is on and here my S7 and S6 is on So, the phase shift between S1 and S5 is given by delta Ts by 2 and S4 and S8 is given by delta Ts by 2. Similarly, the phase shift between S2 and S6 and S3 and S7 is giving the phase shift of delta $\frac{T_s}{2}$accordingly. Similarly, one can also see how we can obtain the backward power flow. Backward power flow, how we can obtain?

There we have provided the, if you look very carefully here also, we have provided the lagging phase shift of VA2B2 with respect to A1B1. That's when the power is transferred from A1B1 terminal to A2B2 terminal. However, if we wanted to reverse this thing, we have to provide leading phase shift in the A2B2 as compared to A1B1. So that we can just quickly let us draw and see how the waveform look like VA1B1. and this is $v_{\pi 2} = k_2$referred to primary and we can then also see how my il changes that so here we assume the same thing we have ts by 2 period it is on and ts by 2 period it is off

so this is my s1 s4 and sorry this is off means we are applying minus vin here it is vin so here my s2 and s3 is on now if you look a2 b2 since we have given the link phase shift so at this point at this point my phase shift changes from from this value to this value then goes from this value to this value so here i am now applying v naught by n and here minus v naught by n and here my s5 and s8 is on and here my s6 and s7 is on and if you look very carefully similarly in this also we can define our this period is nothing but 1 minus delta star ts by 2 and this period is nothing but delta star ts by 2 so this is what we have given and let us see our waveform how our waveform changes in this particular thing in this particular thing since my voltage at this place is having something like you know this waveform which is again here we have considered my v in is greater than v naught by n so here the slope is v in minus v naught by n by l positive slope we are getting here if we look very carefully it is v in minus minus of minus v naught by n so we have positive slope which is you know v in plus v naught by n by l we got here here minus Vin is applied and minus of minus Vo by N so it is again we have a negative slope which we have here like this so we will have something like this waveform where it is nothing but minus Vin plus Vinot by N

this divided by L and finally at this place we have minus V and plus V naught by you know minus of minus V naught by N so we have you know this going like this this is I naught this is same as this one i4 and this is i1 this is i2 this is I3 here also we have the same thing i naught is equals to i4 is equals to minus i1 and i2 so minus i2 and it is i1 is equals to minus I3 and if we look during this point we have minus v in minus v naught by n by l so we are having So, here when we do the averaging we can get the pin average to be nothing but minus V0 Vin delta star 1 minus delta star divided by 2 and L fsw that one can get from by just following the same step what we have done for the forward power flow. Sorry, here it is plus sign. here we have given the phase shift in the a2 b2 in the leading direction because power always flow from leading phase shift to the lagging phase shift so accordingly one can calculate the backward power flow similarly one can also see how my inductor current changes with triple phase shift as well where when we have the triple phase shift we will be introducing zero state in the a1 b1 and a2 b2 so similarly one can also

Do it for triple phase shift modulation. And again we are now here drawing Vin greater than V0 by N. So let us see how our waveforms look like. If you look very carefully, first let us draw VA1B1 and then let us draw VA2B2 referred to primary side. and then finally let us draw my IELTS so if you look very carefully since we are having triple phase shift that means we are having delta theta 1 theta 2 theta 1 indicates the there is the there is a phase shift between the turning of period of the diagonal switches that's when we are now seeing the zero state applied from the a1 b1 side and similarly the zero state from the a2 b2 side so let us see how our zero state look like so let us first draw our first it goes here for some time it goes to zero

then it goes zero for some time and after that we have minus you know here v in voltage applied minus v in voltage here zero voltage so till this point it stays by two and then again it is zero applied and then finally it goes till this finally it goes up to this point and this point we say this is Ts by 2 this is again Ts by 2 so for some period we are now applying zero voltage from the A1 B1 in A2 B2 along with the zero voltage we are also applying some phase shift so let us define this phase shift to be delta and this was previously it was zero it is zero then it is delta is 0 applied then it zeros continues and then again it applies as v naught then goes like this so here it is v naught by n minus v naught by n this value is nothing but delta star T is by 2 and then from here to here it is 1 minus delta T is by 2 so then if we look very carefully we have several other you know time period we have got something like this there will be several steps in the il waveform now if you look very carefully during this time it is zero so here if you see it is v in voltage upper let us say it starts from zero so it goes here so we will have v in by l with slope with that it is rising then at this point it is v v in

minus V0 by N by L slope it is rising here it is minus V0 by N it is falling so assume assume we have reached to you know assume we have reached to this point so it is you know minus v naught by n by l slope it is falling from here to here it is zero exactly zero it is having and then from here to here it is minus v in voltage is applied so it again goes down so it again goes down so let us say it goes down like this it is nothing but minus Vin by L voltage it is falling down here it is with zero slope it is there from here to here it is minus Vin plus V0 by N so it is falling but it is falling with this one minus Vin plus V0 by N L it is there And from here to here, it is having some positive slope. Assume it goes something like this.

This is V0 by NL. It is rising. And then from here to here, it is zero slope. So with this kind of thing you see there are several segregations or several parts of this inductor current and then one can find out the RMS current of this and then able to understand which modulation schemes will give the reduced RMS current of the inductor current because the RMS current of inductor current RMS current of inductor current is actually tells you the RMS current of of transformer windings because the same current is going through the transformer windings and it will actually determine the currents of switches as well.

because the same amount of current will be drawing from these switches so it is important to see for the same amount of power transfer from b1 b1 terminal to a2 b2 terminal or a2 b2 terminal to a1 b1 terminal one can do either sps modulation or dps modulation or tps modulation or TPS modulation with variable frequency or DPS with variable frequency any kind of modulation one can do so anyone can apply different modulation scheme and can then calculate the RMS currents which is flowing through the inductor and then select that modulation scheme which has the minimum rms current and that's when one can ensure that they have the minimum conduction losses in their converters because this rms current of the inductor will indirectly determine the rms current of the transformer windings as well as the rms current of the switches Because in this period some switches are on, in this period some other switches are on, in this period some other switches are on. So, one can then find once they have the RMS rating of this IL, one can then calculate depending upon for how much time it is being conducted, one can calculate the conduction loss of those switches as well.

Which we have discussed in AC-DC converter, the same concepts can be applied over here as well. Now, if you look very carefully, this is the DAB converter. Similarly, there are other derivatives of DAB converter one can have. One can have, you know, resonant DAB converters. Resonant DAB converters where instead of just using the square voltages at the terminals of transformer or terminals of series connection of inductor and transformer, one can apply the sinusoidal voltages by just giving the resonant network

By putting the resonant impedance something like this, one can apply Mean B0, one can put C and L, and then you can do the resonance between C and L. That's when, instead of applying directly the square pulses at this A1 B1 terminal, because of the resonance, one can nullify the other harmonics and can then allow only the switching frequency harmonics to be applied from the transformer primary winding. That means one can now apply the sinusoidal voltage from A1 B1. Similarly, one can also apply the capacitor on the other side as well and can also do the resonance between this thing. That's when you can get, similarly, one can also get the multi-level DABs. You know, multi-level DABs—instead of putting this half-bridge compressors of two switches, which can apply only two levels of voltages, which is with respect to N, one can apply only VIN. From this point A1, between A1 and N, Vin or zero. Instead of that, one can also use multi-level half-bridges, like three-level half-bridges or five-level half-bridges, in all the four half-bridges or in one of the half-bridges. Various combinations are possible, and one can then make sure the RMS current flowing through the primary side and secondary side are minimal. That's when one can reduce the overall conduction loss in the converter. Similarly, there are also You know, multi-level DABs are there, and they are also modular multi-level DABs. However, we are not covering this in this lecture, but this can be looked upon for further higher power rating design of the power converters. One can look for this kind of derivative of DAB converters.

So, these are some of the isolated DC-DC converters we have discussed. You know, in the entire power conversion unit, we have discussed in detail about AC-DC converters—different kinds of AC-DC converters, single-phase, three-phase. Then we have revisited some of the isolated DC-DC converters, and in isolated DC-DC converters, we have discussed in detail phase-shifted full-bridge converter and the Dual active bridge converter. There are also other topologies which are there, which are the resonant-based converters called LLC converters, which are also used very frequently in applications where you want to have step-down operation. So, one can look for LLC-based resonant converters as well, which have transformer isolation. However, we will keep our discussion up to DAB converters only because a lot of literature is available where they discuss in detail about LLC resonant design of LLC resonant converters and all. So, these are the different isolated DC-DC converters which are being used in the power conversion unit of your EV chargers. The most commonly used are

PSFB and DAB, which we have discussed in detail. Also, for step-down operation, one sometimes uses LLC resonant converter as well.

So, we will restrict our discussions up to these topics, and from the next class onwards, we will discuss the concepts related to—in most of the isolated DC-DC converters, we have this transformer. So, we will see in brief how one can design the transformer—isolated transformer—for this kind of converters, and then we will proceed further, discussing the different communication aspects of the EV charging system. Thank you very much for patiently listening to this lecture, and we will see you in the next lecture.