

# CHARGING INFRASTRUCTURE

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Lecture-39

## Lec 39: Small Signal Modelling of PSFB-I

Hello everyone welcome to the lecture number 39 of this NPTEL lecture series on charging infrastructure and in this lecture we will study about the small signal modeling of phase shifted full bridge converter in the last lecture we have studied about the phase shift full bridge operating modes of phase shift full bridge converters we saw that in total there are six operating mode zero one two three four five i mean there are six operating modes and which repeats itself when this will be the same I mean for the next set of diagonal switches here we were in this we have seen diagonal switches S1 and S4 and then we have seen the diagonal switches S2 and S3, how they actually turn on and off and we have also seen that how because of this presence of this output capacitances of the device And this L leakage, you know this transformer, how we can achieve using these two combinations or using these two parasitics, how we can ensure we have a ZVS turn on of all the leading leg switches. These are leading leg switches and lagging leg switches.

We have seen that. and we have derived the different aspects regarding to them the dead time requirements which ensures that the body diode of the MOSFET gets turned on first before the gate pulses are given to or before the gate pulses are given to form the channel in the device. Now because of that diode turns on the voltage across the device is actually zero and that's when we will achieve the zero voltage switching during turn on and since we are getting a zero voltage switching during the turn on that means the diode turns on that means the output capacitance is discharged by the output current which is coming out of the half bridge so because of that  $\frac{dv}{dt}$  at the output of that bridge is actually limited by the charging and discharging of the output capacitance of the devices in the particular leg. We have seen the primary current

which is nothing but the reflected part of the inductor current then in this part again we have this  $n i_L$  which is there in this part here again it is  $n i_L$  which was there and, in this period, it was actually the IP will be because of the resonating of this particular leakage and the lagging lag switch capacitances and then after that we have seen that the current will fall down and doing the zero crossing and then it will keep on going in that way here we have the slope which will be defined by  $\frac{-V_{in}}{L_{lk}}$  the slope is done in such a manner that till the point it reaches the point where the IP is equals to  $n i_L$  or the reflected current from the  $i_L$  so here it is again  $n i_L$  which is coming over here. So, till that point you know the output rectifier which is applied across I mean at one end of the output inductor the voltage is still 0 and after that only the voltage of  $n V_{in}$  will be applied across the one end of the inductor. And then we have seen that if we look very carefully these are the different modes in mode 0 my S1, S4 and DR1 is conducting in mode 1 the C1, C2 the output capacitances of the switches S1 and S2 in the leading leg it is conducting then we have the diode DR1 and S4 switch is conducting then, so here it is we are doing you know the the changeover of leading leg switches of leading leg switches changeover of.

Then in mode 2, we have seen the D2, S4 and DR1 is conducting. And then in after from the mode 2, since the D2 is conducted before the gate pulses of the S2 switch is been given. So, the S2 switch will achieve the ZVS turn on of S2 switch. So, to do that we must provide some sufficient dead time and that dead time was nothing

$$t_{deadtime} > \frac{2CV_{in}}{I_1}$$

where  $C \approx C_1 \approx C_2$ . Then in the mode 3 that which occur when you remove the gate pulses of the lagging leg. So, changeover of lagging leg switch. like switches is taking place. So during that time again my S2 and then C3 and C4 is actually discharging and C3 is charging and then because of that here the voltage across the A and B will be  $V_{AB} = -V_{C4}$  and since  $V_{C4}$  is discharging, so the voltage  $V_{AB}$  will be discharging as a result of is the  $i_p$  will be less and it falls short of the actual output inductor current and that's when both DR1 and DR2 gets conducting and as a result of which what will happen is that from the secondary side of the transformer is

completely short circuited that means primary side of the winding i mean primary side voltage is also you know zero and all the  $V_{AB}$  will be coming across the  $L_{lkg}$  and as a result of which  $L_{lkg}$  goes to resonance between here  $L_{lkg}$  is actually doing the resonance with resonates with C3 and C4 and that's when you will have you know because of the resonance that if we have to provide sufficient amount of time for that resonant in which this capacitor get fully charged or discharged so for that we have seen this particular scenario that we have to provide the dead time for the lagging lag which is we have obtained in this manner.

Now after this kick in what happens is that let's say we have given sufficient dead time such that the voltage of the  $V_{C4}$  goes to 0 and that's when the D3 will get conducted and then after some time since the D3 is conducted you can now give the gate pulse to S3 and that's when we can get the ZVS turn on of S3. So, we have moved from S1 and S4 switch to S2 and S3 switch and then after turning on S2 and S3 switch the IP or the primary current will keep on going in the negative direction such that until it reaches this point when  $i_p = ni_L$ , until the  $i_p = ni_L$  it will keep on going and during that time this, so DR1 and DR2 is still be on because output inductor has to find a pathway and then after mode 5 my  $i_p = ni_L$  and that's when my entire changes entire finally this thing will take place here. So if we went from S1 as for DR1 to S2 S3 DR2 and we see that from mode 2, we can say mode 5 till this point from mode 2 to mode 5 there is something duty loss which is taking place during that duration and so we can say  $t_{2-5}$  because this kicks in at  $t_0$  this kicks in at  $t_1$  this kicks in  $t_2$  this kicks in three  $t_3$   $t_4$   $t_5$  and if you see  $t_5$  we have the  $t_0$ , mode 1  $t_0$  mode 2  $t_1$  mode 3  $t_2$ , mode 4  $t_3$  mode 5  $t_4$  and this is mode 6  $t_5$  to the point i mean the time period and because of that what we will see is that from  $t_{2-5}$  which is we can say mode 3 to mode 5. So we have the duty loss from mode 3 to mode 5 that means time  $t_{2-5}$  this duty loss will be there similarly we have also seen what is the necessary condition for the ZVS to happen for the lagging leg switches and the leading leg switches and that too during turn on period. We have seen that for the leading leg it is the output inductance which is a very large in value that is actually coming in series with the  $L_{lkg}$  and we can say that  $I_1$  which is actually the current reflected from the output inductor which is coming into picture and that energy is actually being used utilized to discharge the C2 and charge the C1 capacitance to

either  $V_{in}$  voltage and or zero voltage. and that is where we will we can say that this particular condition is true even if this  $I_1$  is small also it is true so we can get 100 ZVS for most of the load range. However, for ZVS turn on of the lagging leg switches since the energies or form the capacitance of lagging leg switches has been getting taken out by you know current which is flowing through the  $L_{lkg}$  and only  $L_{lkg}$  is coming into picture so this this value becomes very critical because you know at less load condition less loading condition when the  $i_p$  is very small this energy is actually very small and that is when which is not sufficient to actually discharge the C3 capacitor and charge the C4 capacitor. So, that is why you know these are the conditions and this may or may not happen this you know this particular turn on of this may not happen at the light load conditions or when generally when you have smaller leakages and when you have good amount of larger value of C3 and C4 and larger input voltages are there. then we have seen the duty loss as we know that from  $t_{2-5}$  there is some amount of duty loss which is happening. Now we have finally derived the duty loss expression and which is you know this duty loss is actually

$$D_{loss} = \frac{4L_{lkg} n I_o f_{sw}}{V_{in}}$$

$$V_o = nV_{in}(D - D_{loss})$$

$$\delta = \frac{t_z - t_0}{\frac{T_s}{2}} \times 180^\circ$$

And this,

$$(1 - D)\frac{T_s}{2} \approx \frac{\delta}{180^\circ} \times \frac{T_s}{2}$$

That means if you increase the  $\delta$  value, you will actually reduce the you know, reduce the output voltage. So, since it is a derived topology, if you look at the output part of this circuit, it is nothing but same as the buck converter LNC and then RRL. So, what we can say that it is a buck derived topology. That's why our  $V_o = nV_{in}D$ . However, because of achieving this, you know, ZVS operation, what happens is that we are actually losing some of the duty ratio and because of the presence of this capacitance and the inductor, we are losing some of the duty

and we can say  $D_{eff} = (D - D_{loss})$ . So, what we are trying to do, we can say that if we write down this thing, let me write down this thing,

$$D_{loss} = \frac{4L_{lkg} n I_{o'_{sw}}}{V_{in}}$$

So, we can say that my  $V_o$  is nothing but

$$V_o = n V_{in} D_{eff}$$

and my D effective is nothing but equal to actual D which you are applying which is corresponding to you know phase shift which you are giving  $- D_{loss}$ , which you are actually losing out. So, this is what we were seeing this  $D_{eff}$  and this  $D_{eff}$ . If you look very carefully this  $D_{eff}$  is actually related to Related to  $L_{lkg}$ , we can say.

$$\text{And this, you know, we can also write this } D_{loss} = \frac{4L_{lkg} n I_{o'_{sw}}}{V_{in}}$$

We can write in that way, because we assume that the average value of inductor current is nothing but equal to the you know which is going into the load. So, we can say the average value of inductor current is nothing but the output current. So, we can just write an  $i_L$ .

Now, we can say that the  $D_{eff}$  is dependent upon the  $L_{lkg}$ . It dependent upon the  $f_{sw}$  the switching frequency the  $V_{in}$  voltage and we can say that the current through the  $i_L$ . Whatever the current which we have which is flowing through the  $i_L$  which has some average value which is coming over here. So, the  $D_{eff}$  is effectively dependent upon or related to  $L_{lkg}$ ,  $f_{sw}$ ,  $V_{in}$ ,  $i_L$ . That means when we are changing these four values our  $D_{loss}$  changes and that is when our  $D_{eff}$  also changes.

Now, if we have, you know, a circuit or if we have the actual hardware circuit, the  $L_{lkg}$ , in  $f_{sw}$  is not going to change. Since the  $L_{lkg}$ , and  $f_{sw}$  are not going to change, we can say that the  $D_{eff}$  is kind of independent of, you know, there is no change which may occur due to the  $L_{lkg}$

and  $f_{sw}$ . However, during the circuit operation or during the operation of this converter, we will see that this  $V_{in}$  may change and  $i_L$  may change. Because suddenly there could be a transient which changes the  $V_{in}$  voltage and the average current which is going through the inductor. You can imagine, let us say, suddenly the load changes. So, your  $i_L$  value also changes.

Now, if those things change, so if  $V_{in}$  changes and there is some  $i_L$ , which is actually a small change in the  $i_L$  that takes place. So, what you will see is that you have the  $D_{eff}$ . We can just write  $D_{eff}$  in a small, this one we have, a  $D_{eff}$  will also change. Change. So, in this phase-shift full-bridge converter, what are the control objectives now? The control objective is, you know, if you recall, if you see the control objective, the control objective is only one, which is to regulate the output voltage as per the reference. So, it is to regulate the output voltage. Now, in this converter, if you see the converter, so in this particular circuit, what we have here, we have the output voltage  $V_o$  and we have  $i_L$  current going in.

Now, if you look very carefully, this output part of the circuit, this output part of the circuit, which comprises this L, C, and  $R_L$ . This particular part of the circuit, the output part of the circuit, is similar to that of the buck converter. If you recall the buck converter, we have the buck converter, we have one switch, we have the diode, and at the output, we have this RLC, L, diode D, and switch S. This is the buck converter. If you look very carefully, the output. Filter stage of both the converters are nearly the same, and that is why we can say that this is the buck-derived topology. And if we see the output voltage, we know that our output voltage is

$$\text{nothing but } V_o = nV_{in} D_{eff}$$

It is  $D_{eff} = (D - D_{loss})$ .. And if we see, if we wanted to regulate the  $V_o$  as per the set value of reference, what can we change?

We can only change this duty ratio D. The moment we change our duty ratio D, the  $V_r$  voltage will change. And if there is a  $V_r$  voltage change taking place, what happens is that the current through the inductor changes. And because the current through the inductor changes, the capacitance voltage also changes, which determines the output voltage. So here, if we see, the moment you change the duty ratio to regulate the output voltage, the moment you change the

duty ratio  $D$ , what happens is that your  $i_L$  changes, and since your  $i_L$  changes, your  $V_0$  also changes. And if we see very carefully, the moment my  $i_L$  changes, my  $D$  loss will also change.

Or, let me say in a small-signal manner, if there is a change in the duty ratio, this in there, and my  $D_{loss}$  will change. And since there is a  $D_{loss}$  change in there, there is some change, an effective change due to the current change in the  $i_L$ , which is taking place and which is actually getting added up over here. So, what we can say is that my  $D_{eff}$  will be nothing but the change which has to occur to make sure the output voltage is controlled. This duty ratio has changed, along with this, there is another term which is  $di$ , which has occurred, this extra change in the duty ratio which has occurred because our  $D_{loss}$  is changing, and this  $D_{loss}$  is actually leading to the change in the  $D_{eff}$ . We know that our  $D_{eff} = (D - D_{loss})$ , so the  $D_{eff}$  actually changes with the  $D$ , and along with this, our  $i_L$  changes, and because the  $i_L$  changes, there is a change in the  $D_{loss}$ , and that  $D_{loss}$  will also come along with this  $D$ . And if there is a change in the  $V_{in}$  voltage, in order to make sure the output voltage is regulated even if there is a change in the  $V_{in}$  voltage, the  $D$  changes, and again, if the  $D$  changes, my  $i_L$  changes, and along with  $i_L$ , my  $V_{in}$  voltage is also there, so we can say there is also the  $dv$ , which is coming into the picture, where we can say that  $di$  is the change in the duty ratio due to the change in inductor current.

In the duty ratio due to the change in inductor current. And how does this change in the inductor current take place? It is because you are actually changing the duty ratio, or you can say the  $V_r$  voltage which is coming over here. I mean, the time for which the  $V_r$  is non-zero. So that has changed, and similarly, we have  $dv$ , which is the change in the duty ratio due to the change in input voltage.

And because of this change in this thing, our  $D_{eff}$  changes because  $D_{eff}$  is obviously because of change of a duty ratio, this is changes. And along with this, we have  $di$  change and  $dv$  change as well. So, what we are trying to do in order to ensure my output voltage is constant, we are changing the duty ratio. Since we are changing the duty ratio, our effective changes and since our duty ratio is changed, the duty ratio, what we can say duty ratio is the time during

which the  $V_r$  in the fraction of the time during the  $\frac{T_s}{2}$  period when my  $V_r$  is non-zero value. So, during that time my  $i_L$  changes and because of the  $i_L$  changes there is a change in the  $V_0$  and because of the  $i_L$  change there is a change in the duty loss and that is actually corresponds to the  $di$  and that  $di$  will now get added up to this  $D$  to have defined the effective duty ratio  $D$ . So, now let us see let us see how we can this to extra term what we have how this will impact the response see you try to understand this when duty ratio  $D$  changes  $V_r$  voltage changes and then the inductor current will respond to the change in  $V_r$  with some dynamics which will then get reflected in capacitor voltage with some dynamics as capacitor takes some time to respond to this change further with  $i_L$  change there is change in  $D_{loss}$  value which will further change the effective duty ratio which corresponds to the  $\tilde{di}$  term and thus  $\tilde{di}$  term has to be added in the effective duty ratio to see the effective dynamics further when input voltage changes the  $D_{loss}$  changes which impacts the duty ratio so the  $\tilde{dv}$  tilde term also need to be added to see the effective change in the duty ratio which is defined in  $D_{eff}$ . so the dynamics in the  $D_{eff}$  is the combined dynamics of  $\tilde{di}$  and  $\tilde{dv}$ . So we can say that the dynamics in  $D_{eff}$  is is the combined dynamics of due to change in  $D$  and along with that  $D$  the you know  $di$  and  $d$ . Now let us try to see or let us try to find out how my  $di$  will look like now let us see how we can say how our  $di$  changes, so effect of  $di$  small change of  $di$  let me try to draw the  $di$  effect of  $di$  okay, so let us first see  $i_p$  and then we will also see bab here. So  $i_p$  was rising nothing but with  $ni_L$  whatever the output inductor current is that got reflected here then from here to it goes down like this from  $t_0$  to  $t_1$  then from  $t_1$  to  $t_2$  it falls down again and at the same time my  $V_{AB}$  was at  $V_{in}$  and from  $V_{in}$  it goes after this point it goes to actually 0 with slanting this thing and from there it goes to 0 here goes to zero here and at  $t = t_2$  my S4 switches turns off because of that there is no oscillation is there during this time my  $V_{AB}$  will rising like this and it goes to  $-V_{in}$  it goes to  $-V_{in}$  at last and after this what happens is that if you see here my  $V_{in}$  is actually goes to  $-V_{in}$  over here and at that point we will see our current is actually linearly rising up till goes to 0 and then finally it goes to  $t_5$  where again it is  $V_0$  it is there and then it continues its operation similarly we can also draw you know our one more thing which is our  $V_r$  if we try to draw a  $V_r$ . So, it was here it was  $nV_{in}$  here again it was following the  $V_{AB}$  and after this it goes to 0 here it goes to 0 here T0, T1, T2, T3, T4 it is 0 here and it again goes to 0 here and at that point and that's when it goes to here  $ni_L$  it has moved.

If we look very carefully on this side, what happens is that the moment at this point when the DR2 turns on, the  $V_r$  voltage is nothing but again goes to  $nV_{in}$ , and this is again minus  $V_{in}$ ,

which was there from the  $V_{AB}$ . Now, if you see, there is a fixed change in the  $i_L$ . Assume that fixed change in the  $i_L$ . If we just take this one here, we can just write  $ni_L$  is here, and here, let me write here it is  $ni_L$ . Here, here also, it is  $ni_L$ . The reflected part of  $ni_L$  here also is the reflected part of  $ni_L$ . However, in this part, it is not the reflected part of, you know,  $ni_L$ , what we have. So now, what we can see is that if we see there is a fixed change in the inductor current, what happens is that we will have the fixed, you know, let us say this is a fixed change,  $ni_L$  change we have, we have incorporated here. Then we can have something like this here. On this side, we have the same thing coming over here, the same thing coming over here. And what we see is that beyond this point, we will see that our this part goes like this, and from here, it actually follows, follows, follows, and it goes here, and then it follows like this here. You know, this part goes over here, and then it follows from here. Now, because of that, what happens if I try to draw the things  $V_{AB}$  over here? So it will follow the same line, same thing, same goes over here, same thing over here. However,

The moment this point reaches  $ni_L$ , at that point only, my, you know, this  $V_r$  changes. Now, because of that, this is this time, which is defined as the  $\Delta t$ , which actually leads to an effective change in the duty ratio. So, this  $\Delta t$  corresponds to a change in the effective due to a change in  $i_L$ . So, we have given the change in the  $i_L$ , and because of that, we have a change in the effective duty ratio.

Now, if you look very carefully in this period of time, it changes from this period to this period. This is the time. So, the slope goes from this point to this point. So, let us try to write the equation corresponding to that. If we are trying to write the equation. Now, if you look very carefully, this particular slope is actually coming across the  $L_{lkg}$ .

And if we recall our expressions for that, we know that it is nothing but our, if we try to, because here it is  $t_4$  and here it is  $t_5$ . So, during  $t_{45}$ , if we write  $t_{45}$ , if we write  $t_{45}$  if you recall our  $t_{45}$  is nothing but

$$t_{45} = \frac{L_{lkg} n i_L(t_5)}{V_{in}}$$

is the value we got between  $t_{4-5}$  and if there is a change here if we see over here the changes is there if there is a change here. So, we can write down see this change is happening from this point going from this point to this point you know during from this point to this point so we can say during the unchanged time it was at this value and during this change happens twice the value so we can say that this the  $t_{45,new}$  will be nothing but

$$t_{45,new} = \frac{L_{lkg} (n i_L + n \tilde{\Delta} i_L)}{V_{in}}$$

$$t_{45,old} = \frac{L_{lkg} (n i_L)}{V_{in}}$$

And if we think, if we take the old using this particular thing, we can just write L leakage. Because from this point to this point, we can just write  $n i_L$ . Because here we have given the change to  $- n i_L / V_{in}$ , And then we can write  $\Delta t$  to be.

$$\Delta t = \frac{L_{lkg} (2n \tilde{\Delta} i_L)}{V_{in}}$$

$$\tilde{d}i = \frac{-\Delta t}{\frac{T_s}{2}} = \frac{-L_{lkg} (2n \tilde{\Delta} i_L)}{V_{in} T_s} \times 2 = \frac{-4n L_{lkg} f_{sw} i_L}{V_{in}}$$

$$\tilde{d}i = \frac{-4n L_{lkg} f_{sw} i_L}{V_{in}} \quad ; \quad T_s = \frac{1}{f_{sw}}$$

Now this is the  $\tilde{d}i$ . So we can write finally  $\tilde{d}i$  change in the  $\tilde{d}i$  is nothing but

$$\tilde{d}i = \frac{-4n L_{lkg} f_{sw} i_L}{V_{in}}$$

Now if you look very carefully, you will be wondering why we have taken the negative sign. The negative sign is taken because if your  $i_L$  increases, let us see your  $i_L$  increases.

If this  $i_L$  increases, so what happens? This distance will also increase. Because of this distance increase, what happens is that you will see more, you know, at that point it is coming. Now, because of that, your  $\Delta t$  is actually reduced because the effect is opposite to of  $\cos$  in this case because of that since here my delta since me with change with when  $i_L$  increases my  $\Delta t$  reduces that's why the negative sign is used.

And now if you look very carefully, so finally we got that whenever there is a change in the  $i_L$ , how that particular impact because of the change in the  $i_L$  is been captured and this  $D$  will be added with the effect captured due to the actual change in the duty ratio and this is in the actual change in the defective. So this is the additional term which will be seen additional dynamics which we will see whenever we are changing our duty ratio because when we are changing our actual duty ratio  $D$  our  $V_r$  voltage changes and because of  $V_r$  voltage our  $i_L$  changes because our  $i_L$  changes there is another addition in the inductor current which takes place and because of that there is more loss in the duty ratio and because of that the  $D_{eff}$  will have further changes.

So, let us see our effect of  $d\tilde{v}$  that means whenever there is a change in the input voltage that means due to change in input voltage. So, during that time how our thing changes let us see how our thing changes assume at this point our input value changes like this this value changes. So as a result of which what happens is that this value what we have seen is there will. Now be slightly changed so we will see how things will go so now if you look very carefully this particular slope if we see this particular slope is nothing but  $\frac{V_{in}}{L_{lkg}}$ . So this slope is actually going to change and that we can write down.

Since my  $V_{in}$  voltage has increased, so our slope will actually be increased. So, what we will see is that our change in the slope changes and actually it reaches to this  $i_L$  value faster. The moment it reaches to  $i_L$  value faster, after this, this will be going like this. Now because of that what happens is that since our slope has increased the slope which is actually falling down which you know this is  $-V_{in}$  with the  $-\frac{V_{in}}{L_{lkg}}$  slope it is falling and since my  $V_{in}$  voltage has increased. So that's why my slope has increased and that's why you will see it will fall down faster and reach to this ip where which is equal to the reflected value of il faster and as a result of which we

will see in our this period so this will be the same like this however during this point when this thing happens so this will actually be going over here and it is with slightly increased  $V_{in}$  we can just write you know so if we see so if we say this is  $nV_{in}$ . So our new will be this will be our this new will be  $nV_{in} + n\tilde{V}_{in}$  and this small change is nothing but your  $n\tilde{V}_{in}$  which is the small change in the  $V_{in}$  voltage we have given because of that now if you look very carefully this is the additional time which is which has actually reduced since our  $V_{in}$  will have gone through that. So this value is nothing but equal to  $\Delta t$ . Now from this term if we see very carefully this particular term and you know how it will look like so in this particular thing We can write down this  $\Delta t$ , this  $\Delta t$  period, you know, if you recall during this point, from this point to this point, we have seen that it is nothing but, if we assume  $t_{23}$  to be very, very small. be small then we can just write now if we assume  $t_{23}$  to be very small then we can say that this point and this point is very much near to each other. So, if this point is  $ni_L$  which is coming over here the same  $ni_L$  will also be coming over here as well, so we can say that if this is small. So, we can say that our  $\Delta t$  to be equal to you know we can just use the term  $V = L \frac{di}{dt}$  we can take it up.

So, which is nothing but your  $\frac{V_{in}}{L} * di$ . So, to write down this particular expression the delta t expression. So, before the  $\Delta t$  at during this time we can just write this is the assumptions we have taken. because of that we can write it is nothing but

$$\Delta t = \left[ ni_L - (-ni_L) + \frac{V_o}{L} \frac{(1-D)T_s}{2} \right] \left[ \frac{L_{lkg}}{V_{in}} - \frac{L_{lkg}}{V_{in} + \tilde{V}_{in}} \right]$$

$ni_L$  we can write  $ni_L$  which was there previously and at that point it reaches to this point we can just write  $-ni_L$  because this point you have again this to  $-ni_L$  value so this is also  $-ni_L$ . So  $-ni_L$  and plus there is this ripple which gets ended up and then again it is going up.

This value what we have taken this  $\frac{V_o}{L} \frac{(1-D)T_s}{2}$  is due to ripple in the output current. This will also be multiplied by N because you know we have this is the reflected part on the primary side. So, this is a ripple in the is due to the ripple in the output inductor current to be more precise inductor current. Now

$$\Delta t = \left[ 2ni_o - \frac{nV_o}{L} \frac{(1-D)T_s}{2} \right] \left[ \frac{L_{lkg} \tilde{V}_{in}}{V_{in}(V_{in} + \tilde{V}_{in})} \right]$$

$$\Delta t = n \left[ 2I_0 - \frac{V_o}{L} \frac{(1-D)T_s}{2} \right] \left[ \frac{L_{lkg} \tilde{V}_{in}}{V_{in}(V_{in} + \tilde{V}_{in})} \right]$$

$$(V_{in} + \tilde{V}_{in}) = V_{in}$$

$$\Delta t = n \left[ 2I_0 - \frac{V_o}{L} \frac{(1-D)T_s}{2} \right] \left[ \frac{L_{lkg} \tilde{V}_{in}}{V_{in}^2} \right] \quad (1)$$

$$\tilde{d}i = \frac{-\Delta t}{\frac{T_s}{2}} = n \left[ 2I_0 - \frac{V_o}{L} \frac{(1-D)T_s}{2} \right] \left( \frac{L_{lkg}}{V_{in}^2} \right) V_{in}^2$$

So, we can write that in this particular thing, we can say that our total change in the effective duty ratio is the summation of the change in the small change in the duty ratio, and because of the small change in the duty ratio, there will be a change in the inductor current, and because of that, there is again a change in the  $D_{loss}$  term, and because of  $D_{loss}$ , there is a change in the  $D_{eff}$ . However, this change was in the opposite direction because whenever the il value increases, the  $D_{loss}$  actually increases, and that's when my  $D_{eff}$  will actually reduce. So that's why, while deriving my di, we have taken the negative sign. However, in the case of dv, if you look very carefully, in the case of dv, whenever my voltage increases, this  $\Delta t$  is actually in the reverse direction because my  $D_{loss}$  term has reduced. Since my  $D_{loss}$  term has reduced, my  $D_{eff}$  term has improved, so that's why we have taken the positive sign here, and that's when we have addition which is coming over here. So, we can see that here the positive sign is due to the fact that whenever there is an increase in the voltage, there is a positive effect or there is a positive change in the defective.

$$\tilde{D}_{eff} = \tilde{d} + \tilde{d}i + \tilde{d}v$$

And thus, the overall change in the  $D_{eff}$  will be equal to the actual change in the duty ratio which we have introduced, and because of that interaction, there is a change in the inductor current which has also changed the  $D_{loss}$  and which actually inherently changes the d effective. Similarly,

whenever there is a change in the input voltage, there will be a change in the  $D_{loss}$ . And because of the change in the  $D_{loss}$ , there is a change in the  $d$  effective, which is captured in this  $dv$  term, and that is when we can see our overall  $D_{eff}$  will be the summation of these three quantities.

So, by using this information, we will try to derive our small signal model of the PSFB. So, whenever there is a change in the duty ratio, how the plant will respond to that change, that transfer function we will derive by defining the small signal model. That we will do in the coming lectures. So, thank you very much for patiently listening to this lecture, and we will see you in the next lecture where we will be deriving the complete small signal model of the PSFB converter. Thank you.