Design and Simulation of DC-DC converters using open source tools
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Lecture - 10
Understanding Buck Converter

Now, let us look at the BOOST Converter waveforms.

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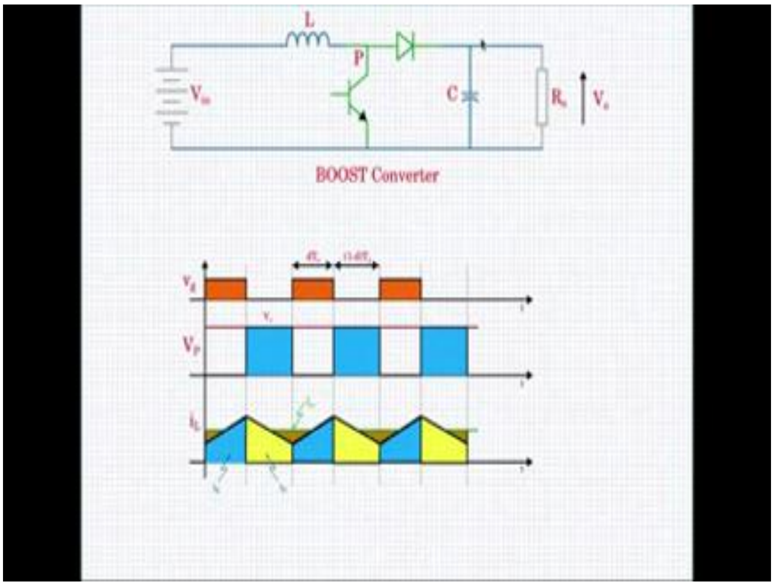

BOOST Converter

This is the BOOST converter, I hope you recognize this topology the inductor is on the input side and when this (Refer Time: 00:31) is formed using electro current flowing in this direction charging the inductor when this is on you will see the inductor current pumping through current into the output capacitor in the output flow. So, the base drive or the gate drive for this power semi conductor switch which is given here to turn it on and off is shown in here in the g, like the code as in the BOOST converter.

So, when the signal is high the transistor is on, when it is low the transistor is off. So, that is what we use convention. During the time when the transistor is on it is on the period d t s, and during the time when the transistor is off it is called period one minus dts. Now take the pole voltage where also two critical things are; pole voltage we have to see and the current through the inductor. This flow will give the information to rate your devices and components. As before the pole voltage here is easy to detect. So, when the device is on the pole voltage here will be 0. Whenever the gate drive is given the pole voltage will be 0. And whenever this is off the diode is conducting the inductor which I have sent the charge to the output. So, when the diode is conducting output is connected to the board so it will be V naught 1. So, it will be 0 goes to V naught then goes to 0 and goes to V naught so on and so forth.

So, let us put that waveform here. This is the wave form that you would expect to see in an ideal case at PV at the pole voltage. And we know that this is V naught value because when the transistor is off diode is conducting and V naught point and the (Refer Time: 02:42) point out same, so which means that in the case of BOOST converter the V naught is the actually the maximum value of the pole voltage. Looking at this pole voltage you can rate the transistor and the time. During the time d Ts transistor is conducting diode is off. So, what should be the diode with standing capability, point is connected to 0, this is 0 and this is V naught.

So, the entire V naught value is coming as reverse voltage of the diode and the (Refer Time: 03:26) voltage diode should be V naught that is one rating which you can have of diode. And likewise for the B J T when the B J T is off diode is conducting V naught value comes in here and the B J T should withstand and the V naught during it is off condition as in waveform. So, voltage ratings for the devices can be got from the pole voltage. Now for the inductor current; so inductor current here also go in with a triangular ripple kind of a wave shape as we discussed in the buck converter, but only the values the amplitude the significance will be different.

So, let us say that we have an inductor current wave form something like this it is raising with one slope and falling with one slope and so on. Now the raising slope is during the time when the transistor is on which is (Refer Time: 04:40) to 0. So, the raising slope is V in the voltage across the inductor by l, so this will be V in by L slope. And this falling slope is when this is off and the diode is conducting and this point is at V naught V P is v naught, so the falling slope is V in minus V naught this is V in minus V naught divided by L that will be the falling slope. Why do we say it is falling? Because the output voltage is greater than input voltage, so V in minus V naught negative. And therefore, you have a negative slope, so it keeps continuing.

The average value of the inductor current is naught I naught as it was in the case of buck converter. In the case of buck converter the inductor was on output side and therefore the average value directly indicated I naught here the average value is indicating the source current or the input current I in. Here also we can define a delta i L the peak to peak ripple amplitude of the current.

Next let us see the components of the inductor current. During the time when the transistor B J T is on the inductor current flows through like this you have the inductor current charging up the inductor and therefore it has to linearly increase. So, let us put that current wave shape, so this is the component of the inductor current which is flowing through the inductor and the switch B J T q. So, this is i q. And during the time when the switch is off you will see that the current i q is 0 and during the time when it is on we just follows the inductor current. And during the time when the switch is off the current through the diode should be the blank portion, the other portion let me fill that in, so it would be like this.

So, the yellow regions are the part of the current that flows through the diode, so that is also the current that is flowing through the capacitor or not combination. Let me remove out the blue region so that we have some clarity in the current flowing through the diode and which will again split up in to c and I naught current. Now this yellow wave shape is the one which is flowing through here and this is having two components; one is the average component and the AC component. The average component will flow through R naught that is i naught. And the AC component which is having 0 averages should flow through the capacitors.

Now, let us say the average value of this current is placed somewhere here and that would be i naught. The average power component placed here that would be i naught. So, you will see the capacitor this triangular portion of charging the capacitor and this bottom white portion here I am indicating is capacitor discharging into the load. And there should be this area should be same as this area. This triangular upper area and this area should be same to have charge balance we will look at that shortly.

So, this is how the current wave shapes coming to picture and about the rating. If you take the current rating for the B J T you will see that the average of the inductor current will be I in. And I in and I naught are related if you use the (Refer Time: 08:54) balance you will see that I in into d is I naught or I in will be I naught by d, and therefore you know the average value for the B J T here.

So, B J T has to be rated for this weak current here which is I in plus delta i by 2. Likewise, the diode and the output average current I naught it is a spec given to you and it is actually the average value of the yellow portion of the waveform.

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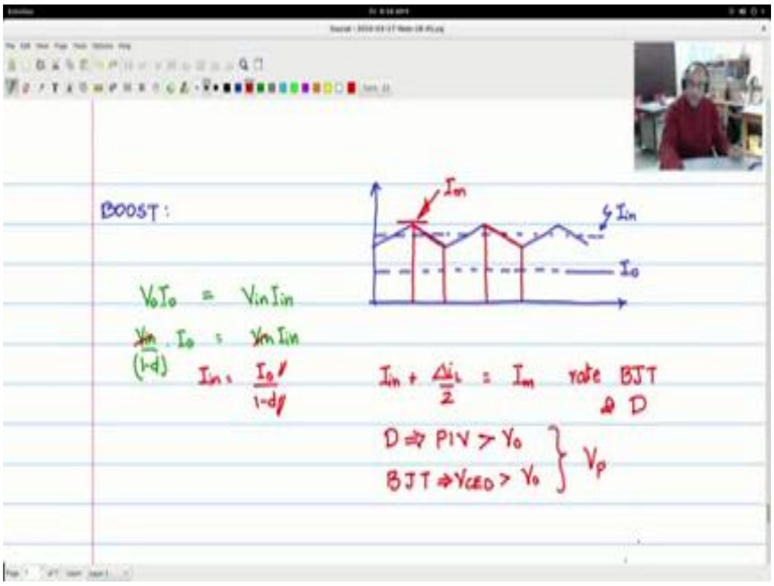

BOOST:

$V_o I_o = V_{in} I_{in}$

$\frac{\cancel{V_{in}}}{(1-d)} \cdot I_o = \cancel{V_{in}} I_{in}$

$I_{in} = \frac{I_o}{1-d}$

$I_{in} + \frac{\Delta i_L}{2} = I_m$ rate BJT & D

$$\left.\begin{array}{l} D \Rightarrow PIV > V_o \\ BJT \Rightarrow V_{CEO} > V_o \end{array}\right\} V_p$$

Now, let us look at bit close at the current wave form, so that we can calculate the values of C and L. In case of the BOOST converter we saw the inductor current waveform is something like this. Then draw the inductor current waveform here and we have seen that there is a kind of a triangle (Refer Time: 10:05). Now what you are interested is this average value which we call I in, and I naught where you be somewhere here and that is actually coming as the average of this part of currents we saw that just now is not it. Now, how I naught and I in interrelated? If V naught I naught is the output power and V in I in are input power, we say that there is in a ideal senses there is no loss within the converter because they are either using switch components or we have other components which are LLC’s both are non designative.

So, the input power should be equal to the output power, so these two should be equal. Now you know the relationship between V naught and V in the case of the BOOST converter. This is valid for any converter V naught I naught is equal to V in I in. Now in the case of the BOOST converter we say that V naught is V in by 1 minus d into I naught is equal to V in I in, so we can remove this and we will say that I in is equal to I naught by 1 minus d. We get the current relationship. We can do it this way or you can use the

(Refer Time: 12:01) balance in the capacitor to get the same relationship. So, I in can be found out because I naught is a spec V is obtainable by the voltage relationship I in value is known.

So, knowing the value of I in you can say that I in plus delta i L by 2 will be the peak value here, I max value and that will be I max value you have to rate both the B J T and the diode the current rating for the devices. The average value of the those will be the average current rating of the device and for the diode, diode peak inverse rating will be should be greater than V naught and even for the B J T be V CEO should be greater than V naught as we saw from the pole voltage wave form (Refer Time: 13:15) form.

So, this way you find the relationship of the input current and the output current in the case of the BOOST converter.

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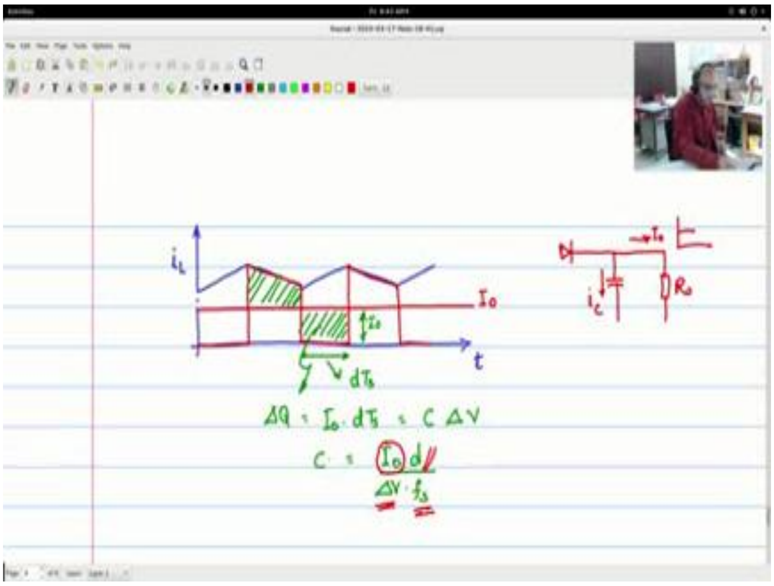

$$\Delta Q = I_0 \cdot dT_s = C \Delta V$$

$$C = \frac{\boxed{I_0}\, d}{\Delta V \cdot f_s}$$

Now, if you look again at the BOOST converter inductor waveform you will have the clue defined c. I will tell you how to move about you can probably use it for practice and then this is the inductor current wave form and this is i L (Refer Time: 14:00) I. And the portion that supposed to flow through the diode is this. This is portion that is supposed to flow through the diode. So, I said this is the diode current. Now this diode current splits into the capacitance and also into the load R naught. So, what flows here will be i c and what flows here is I naught and this I naught is d c and what flows here should be 0 average. And we know that I naught has it is specified this will be I naught value, that is it and what it will be. And what most of the capacitors should be actually this little portion, this is a (Refer Time: 15:11) portion.

So, these two areas should match, this is for the capacitor. Now I naught value goes on to the R naught and by (Refer Time: 15:22) current flow here the remaining portion is the diode current value minus I naught goes into I c. So, minus I naught with been for the capacitor this I naught line is the 0 line, so which would you mean this area as shown this area should match this area for (Refer Time: 15:43) balance.

Now, if I find the delta Q for this I know that this I is I naught and this width is d Ts when the inductor current is raising you know the area that is the charge I naught into d Ts and this is equal to C delta V. So, you have a way of calculating C, rearranging this, you have I naught d divided by delta V into fs we will see I naught is specified I naught is more, I naught is specified from the input d is calculated from the input output relationship fs is specified given delta V is the designed spec this should be a design spec you will allow some amount of ripple on the capacitor, so based on that the value of c will again calculate.

So, normally 10 percent of V naught is used for delta V and calculated the value of C. So, this is how you will calculate the value of C, likewise you can calculate the value of inductor L 2.

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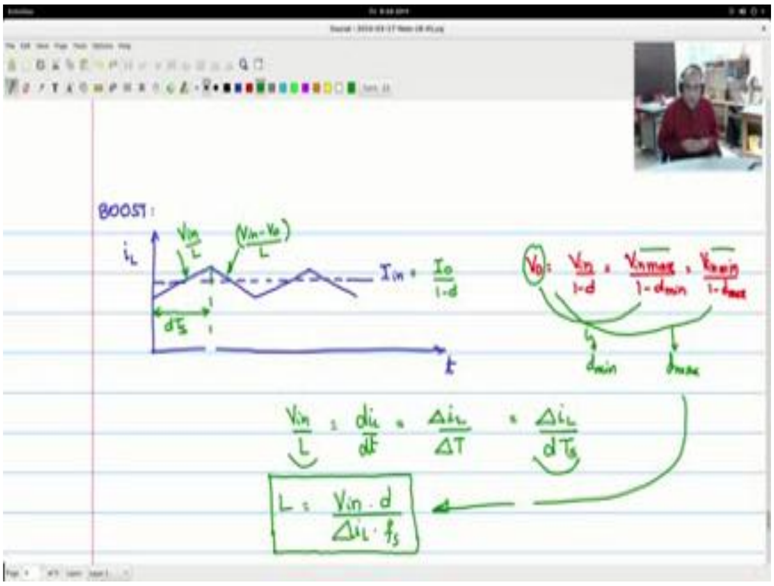

$$V_0 = \frac{V_{in}}{1-d} = \frac{\overline{V_{in\,max}}}{1-d_{min}} = \frac{\overline{V_{in\,min}}}{1-d_{max}}$$

$$\frac{V_{in}}{L} = \frac{di_L}{dt} = \frac{\Delta i_L}{\Delta T} = \frac{\Delta i_L}{dT_s}$$

$$\boxed{L = \frac{V_{in} \cdot d}{\Delta i_L \cdot f_s}}$$

So, again looking at the BOOST converter we see that this is the inductor current waveform, the average value I in and we know that I in is equal to I naught by 1 minus d for the BOOST converter case knowing the value of I naught and v we know the value of I in. And what are these slopes? This slope for inductor to charge on the pole voltage is 0 during the time and the switch is on and therefore this charger current in V in by L rate. So, the charger b i L by d t is mean by when this goes down this will be V in minus V naught by L. As we naught is greater V in this will be n negative slope in the falling slope. So, you could use either of the slopes to evaluate the value of L V in by L the raising slope here is having one variable we could use that, so you will say V in by L is nothing but d i L by d t and as the rates are linear they are straight lines they will approximately by delta i L by delta T. Now delta T in this case for this period is d Ts is the delta C. So, you will say delta i L by d Ts.

Now, this two parts we can combine together and we have L which is V in into d divided by delta i L fs t s as put as 1 by s. This would be the value of the inductors. And you can calculate the L max using maximum value of d, d max. How to find d max use the relationship? So V naught is suppose to be kept constant, V naught is equal to V in by 1 minus d. V naught is supposed to be regulated. So, if V in goes max you would like to make the duty cycle min to get the same V naught value or if V in goes min you would like to increase the duty cycle to get the value of v naught.

So, V in max and v sorry here it is V in min; V in max and V in min are mode from the input spec input spec tolerances and you saying these two V naught is known it is also a spec you can find out d min. Using these two equations you can find out v max. So, you can use d max here to find out the max value of L if to (Refer Time: 21:18) when you are doing the calculation for the value of L. Now, that would give you the deign equation for the inductance. Keep in mind now that we have only found the value of L, but we have not yet made the L where you need to have a magnetic code and you will have to calculate the number of windings and the air gap to be introduced to actually the manufacture the inductor with the physical inductor needs to be manufactured to obtain a value as you see on the screen here. So, how to go about manufacturing the inductance using the magnetic and the magnetic code and how to wind it how that I will discuss in the next weeks lectures.

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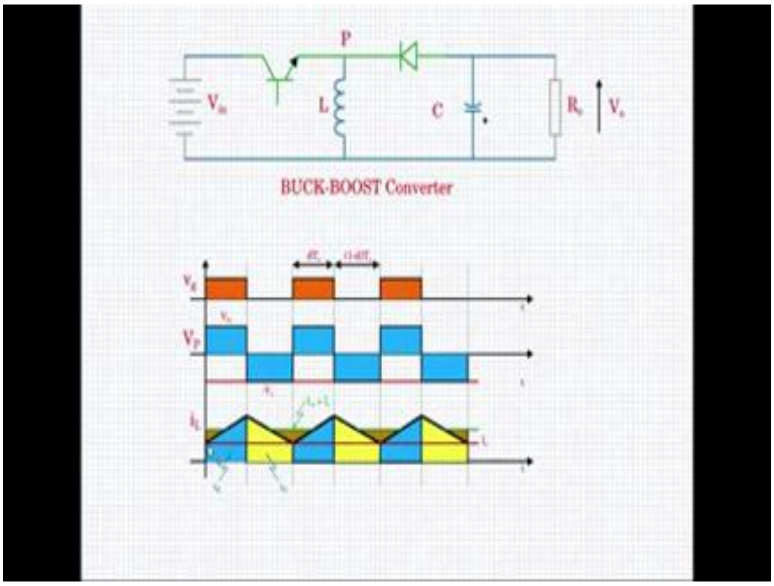

BUCK-BOOST Converter

Now consider the buck BOOST converter the third of the primary converter. You recognize the topology I suppose here, you see that the inductor is in between neither it is on input side nor on the output side you see that when the trans B J T q is on the inductor gets charged up by a current flowing from the input supply in this fraction and when the B J T is off the inductor current cannot be stopped and therefore it will start flowing in this fraction, such that the inductor current is in the same direction into the inductor. And as a result the capacitor will be charged with the polarity where the plus is here and therefore you get a negative voltage of the output.

So, this is the operation of the buck BOOST converter which we studied before. Now let us see the wave form and the critical point that is at the pole voltage and also the inductor current V g is the gate drive that you are giving to the B J T or any power semi conductor switch when V g is high the B J T is on, when V g is low B J T is off. The definition of time period is as shown here D Ts is the duty cycle t on time of the B J T 1 minus D Ts t is the off of B J T. So, for this kind of a gate drive when you look at the V P of the pole voltage when the B J T is on V in is appearing at the pole, and when the B J T is off drive is conducting minus V naught is appearing at the pole. So, let us draw the waveform for that and the position it here, so this would be the wave form that you would expect to see at V P in the port.

Now, when the B J T is on we expect to see this amplitude to be V in amplitude coming directly here and when this is off diode is conducting negative of V naught will come in here, because V naught is positive at this point. So, you can expect to see minus V naught at this point. The V naught measuring at V naught itself you will see V naught negative and it will have a negative value of d c as shown. This pole voltage give the information for rating the voltage rating of devices when the B J T is on this diode is off the voltage across that is V in. V in at this point and this is minus v naught, so the diode has to withstand the entire voltage which appears across this rule; so this whole height of this waveform from here to here V in plus v naught.

So, you have a V naught and you have a V in this gives us voltage loop equation if you apply that is the amount of voltage potential that the diode has to withstand or look at the pole voltage the height from this point to this point the diode as to withstand, which is V in plus V naught value. V plus V naught is this peak inverse voltage which will be greater than that and when the diode is conducting this device is off when this device is off this is at minus V naught and this is at V in, so V in minus of minus V naught again V in plus V naught there the device as to handle. You see that here the device ratings will be much higher than in the buck converter or in the BOOST converter.

So, the buck converter has a the least voltage rating, the BOOST converter will have higher rating and in case of the buck BOOST converter you have V in plus V naught as the rating for the devices. And coming to the current; the current wave shape for the inductor will be similar except that the notation will change this average value will be I in plus I naught you see that average value of the current which is flowing the time it is on this is I in, flowing the time this is off the time would be flowing here I naught. So, average of I in an average of I naught both are combining and flowing through L.

The average value here will be I in plus I naught and that is what we get it here. And likewise we have a positive slope, negative slope. When the B J T is on V in by L is the positive slope and when the B J T is off minus V naught is appearing for us L, and the down slope the negative minus V naught by L.

Now, let us now look at the components of the inductor. First let us look at the component that flows through the B J T. So, this part of the inductor current, the blue part flows through the B J T. The average value of this blue part is I in and that the peak value is the average value of the inductor current is I in plus I naught plus delta L, so I in plus I naught plus delta L will be the value. And for the current that flows through the diode you will see let us position it like this the yellow part is the current that flows through the diode, and average of the diode current is I naught value. Like in earlier case probably I showed that the average of the diode current value is the I naught just like in the case of the BOOST converter and let me remove the this wave form, so that it becomes clear to close see that this is the diode current wave shape as you would see on a (Refer Time: 28:51).

The rating for the diode you can take from this particular wave shape. So, the inductor current peak value I in plus I naught plus delta i L by 2 will be the peak current value. Average value will be I naught value. So, this would be the ratings for the diode. In exactly the same manner you can calculate the value of C. As we did for the BOOST converter you see take this wave shape, the area under this will be the delta Q, area under this will be the delta Q, I naught into D Ts during this time would give you the delta Q. And exactly like the BOOST connector converter value would get the value of C. And the for the rating of the transistor here we saw this blue way form just now would also be like the diode current ratings. The peak rating will be I in plus I naught plus delta L by 2 and the average will be I in not I naught, but I in. That will be the rating for this. I in you can find out knowing the V value and I naught and I naught is a spec given, so I can be calculated.

So, I will leave it as an exercise for you to find out the value of L and the value of C on exactly the same manner that we did for the buck and the buck BOOST converter. If you are not able to get it then leave it up in the forum then I will discuss that once again. So, I will also put the simulation circuits for practice so that you can practice the simulations and see the wave forms. Do the simulations for all the three converters and look at the pole voltage waveform and the inductor current waveform not only for the buck converter which we did in the class even for the BOOST and the buck BOOST converter.