Design and Simulation of DC-DC converters using open source tools

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Lecture – 11
Understanding Boost and Buck-Boost

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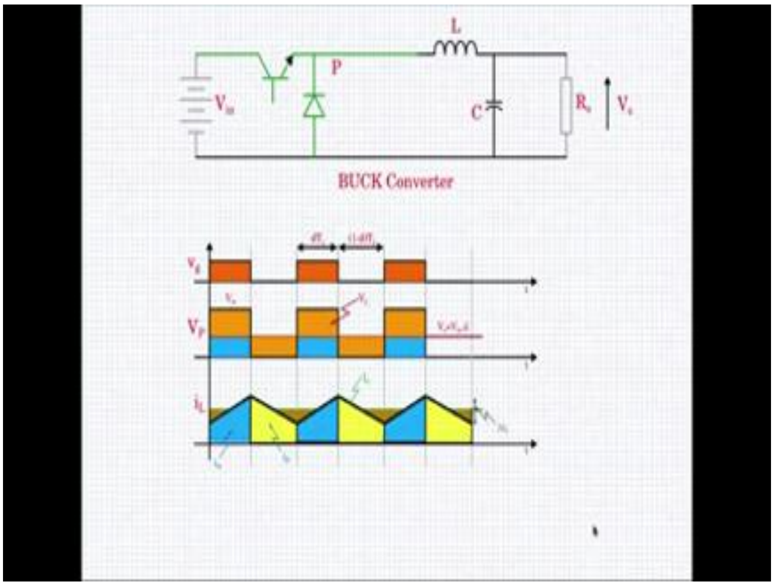

So, this is the BUCK converter. We are familiar with the circuit by now, we need to rate the components, the switch, the diode, the inductance and the capacitance. These are the four elements that we need to design this. To rate the components properly we need to have an understanding of the various waveforms that are that are pretty critical.

Now, the voltage V t is a very important waveform that you should understand because it will help in rating both voltage rating of both these diode and the transistor. The current waveform of the inductor is very critical because this is an important part in this component, in this particular topology see that is current through the inductor gives information about the current flow in the input and therefore, the current flow in the transistor, the current flow in the diode because the current also flows through the inductor, the current flowing through the inductor also divides into the capacitor current and the capacitor current through the load.

As we had discussed earlier, the current through the capacitor will have 0 average value in steady state and the current through the output load will be at o d c. So, keeping these things in mind, let us construct the waveforms and based on the waveforms we can just read off the rating values of the various components. Let us now start by placing the x and y-axis. Now, I have to here x-axis which is the time axis and on the y-axis, we have three important things V g; V g is nothing, but the gate signal which we will be applying at this point. I did not want to put it as V b because it may be confused with battery voltage. Therefore, I am calling this one as V g as we had indicated in the simulation and this is the signal to drive this on or off.

So, what is that signal and before that the other important variable voltage that we need to see is the pole voltage; pole voltage the voltage at this point with respect to the ground and then the current that is the inductor current. Now, the pole voltage will give information on this diode rating in terms of voltage and the rating of the transistor and also the voltage across the inductor to check for the volt second paths. The current of the inductor will give wrong information on the input current, the current through the diode the current through the capacitance current through.

So, let us look at them one by one for the voltage, let me install this here. So, this is the waveform, the voltage waveform that we would see at the base or the gate of these powers and conductor switch the time, when the pulse is high then the switch is on the time when the pulse is low, this switch is off and during that time the diode is. So, this time would be the d t s time and this time would be the 1 minus d t s time, this is the on-time and this is the off-time. So, we shall mark them accordingly. So, let me place the marks here. So, this is the d t s time and this is the 1 minus d t s time.

Now, such a waveform we will apply at the gate now. So, what happens, during the time when this is on V in comes to the pole. So, the pole voltage will be V in value and during the time when this is off the diode is freewheeling this path and the pole voltage is connected to the ground. So, it will be 0, let us mark that. So, I am going to place this waveform here. So, see here that the blue colored waveform is the pole voltage waveform that appears here during the time, when the q is on the pole voltage is high and it is V in value and the value there let me indicate by this symbol V n.

Now, this has an average value. So, let me indicate the average value by a line like this. So, this is the DC value that you would see at the output because this is the average of this, what is the average of this V in this area and this portion will get average down this will fill up here and then you will get a smooth and that is our V naught, V naught which is V in into d V in into d is the average of the waveform

Now, if I take the average at V naught whose amplitude I am indicating by the arrow will be V in minus V naught and this amplitude from the average value to 0 would be V naught. So, this portion in fact, would be the waveform that you would be seeing across the inductor. So, you see that the portion above the average and one below the average. So, that yellow portion is the one which will be appearing across the inductor and there should be volt second balance doing the top portion of the yellow and the bottom portion of the yellow portion of the waveform above and below the average value.

So, the yellow portion of the waveform is what is called the V L or the voltage across the inductor. So, this wave the voltage the pole voltage here has so much information in it. It gives you what is the average down the pole. It gives you the voltage across the inductor and the volt second balance that is happening and with this we can rate these two components Now, let us see during this period the d t s period, the transistor is on. If the transistor is on the pole voltage here is V in then what should be the peak inverse voltage of the diode. The peak inverse voltage of the diode should be V in or at least greater than V in because this diode has to withstand a value the potential equivalent to V.

Now, let us say this is off and this is freewheeling. So, when this is freewheeling this is pulled to the ground. So, then is pulled to the ground and this is at V in. So, the voltage withstanding capability of this b j t or any other power semiconductors switch which is placed here should be V in which is this value. So, you see that this by looking at the waveform and the pole voltage waveform, we have found two important ratings of these two devices, the voltage withstanding rating of the switch and the voltage withstanding rating of the peak inverse voltage of the diode.

Now, let us look at the inductor current, I have drawn a green line here, the green line here is not the inductor current, but it is the current that is flowing through the load assuming very negligible ripple across the output approximated it by a straight line and this is the current that is DC current flowing through the load, we will call that one as i naught. So, this is i naught, and now how will be the current through the inductor when the transistor q is on the voltage here is V in and the voltage here is V naught. So, in the steady state V in minus V naught is applied across the inductor.

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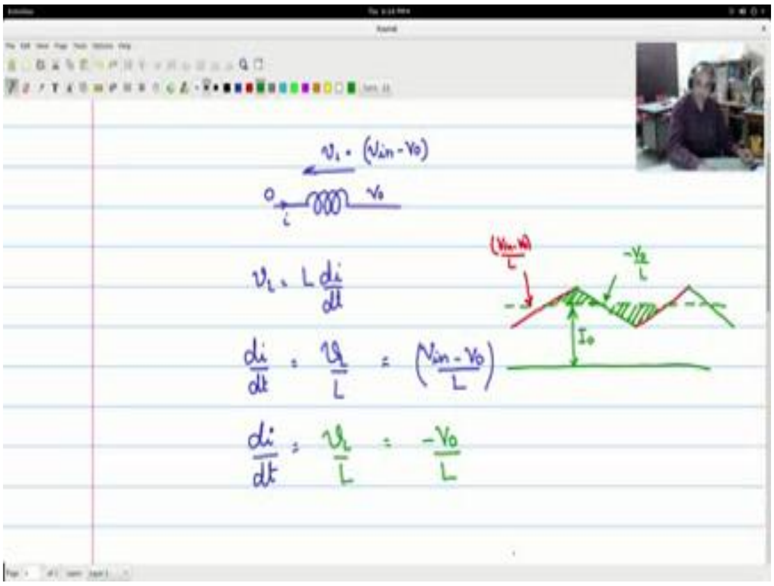

So, let me take the writing pad to give a view of what is happening. So, consider this inductor and it is receiving the voltage across this V L, which is equal to V in minus V naught at some index. So, we know that V L which is equal to L d i by d t and d i by d t where i is the current flowing through the inductor is given by V L by L ratio or it is V in minus V naught by L ratio.

So, this is the d i by d t or the slope of the current waveform. So, at this slope the current waveform should increase. So, if I draw this slope during the time when the voltage across the inductor is V in minus V naught it should increase like this because V in is a V naught is a constant, L is a known constant. So, the rate has to be a linear one and this is V in minus V naught by L and during the time when the switch is off. We saw earlier that this side of the inductor becomes 0 and here it is V naught and what is applied is minus V naught.

So, what is the rate d i under such conditions d i by d t would be a change in color. So, V L by l, but now V in become minus V naught by l. Now, minus V naught by L into k is negative slope. So, it should start falling at this state. So, this would be minus V naught by L and negative slope falling and then the subsequent cycle again should go in this fashion and start falling. So, this would be the shape of the current through the inductor

Now, what will be the average value? The average value flows the average value flows through the output and that is nothing, but i naught and the ripple value the one with that component with 0 average will flow through the capacitor. So, through the capacitor the one marked like this is what is going to flow. So, this is what we can expect and let us go back and have a look at that slide. So, the average value of the inductor current is i naught and that is what will go through the ripple component of the inductance will go through the capacitance and there would not be the ripple component here. So, let us place the ripple component here and see.

After placing the ripple component here, you see that the wave shape is just like as we had discussed during the time, when q is on and that was charging up and this charging up rate is V in minus V naught by L and then the inductor is discharging during the time when it is off when it is discharging it is freewheeling like this and it is falling down at the rate of minus V naught by L and it keeps on repeating under steady state condition like a triangle and the one that is filled up here the colored filled up portion is the 0 average portion and that is what will flow through the capacitance the filled up portion is the capacitance current the average value of that is current flowing through r naught and this entire wave shape is the inductor current.

So, you see that you get again here, log information in rating the components, if you look at the current flowing through the b j t; the b j t in the current flows only during this portion something like this. So, let me. So, only during this portion the current through the b j t flows. So, you can rate your b j t for this it has a peak current of i naught plus this ripple p. So, if I say that the ripple amplitude is like this delta i L, then the rating of the current for b j t will be i naught plus delta i L by 2, which would be this peak that will be the peak current.

The average current rating will be i naught into this cycle d and for the diode it will appear like this during this time, whenever the switch is off the diode is freewheeling and during this time. There will be current flowing through the diode and it is the same inductor current which has split into it therefore, the diode also has to have the same peak current value i naught plus delta i by 2 and the average value would be value of i naught one minus d.

So, this way you get the value of the current that would flow through the input and the value of the current that flows through the diode 2, now these are the critical waveforms that you have to be clear about and when you do the simulation, you should actually try to observe these effects in the simulation and see that this is what you are getting at this waveform is the waveform of the capacitor current, which flows through the capacitor this would actually be the 0 line in case the inductor current this line would be the i naught line.

Now, let us consider the current flowing through the capacitor. Assuming that this green line is 0, there is no average i naught component has flown to the load side, now what is important in the capacitor is that for charged balance and second balance this area should be equal to this area. So, the amount of charge put into the capacitor should be equal to the amount of charge taken out. So, this will be delta q

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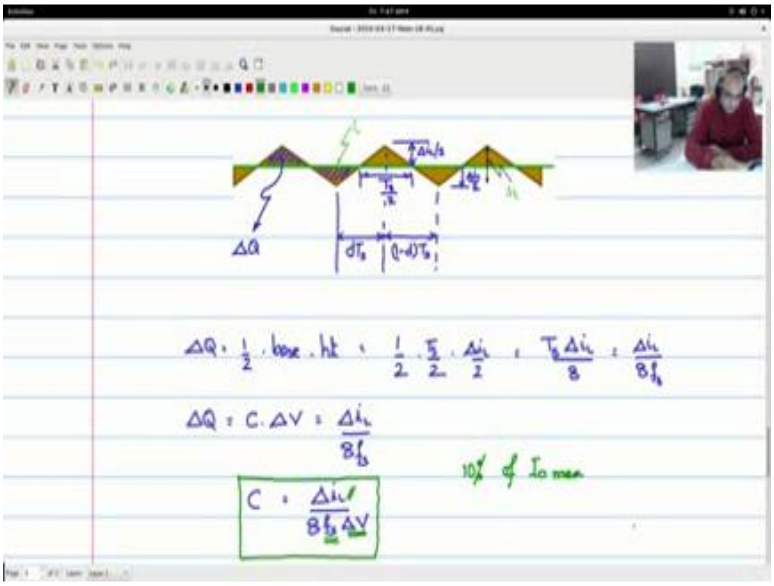

Now, looking at the capacitor waveforms we know that this is the time that inductor current has magnetically charged up. So, this is d t and this is the time when the inductor current is falling with a slope of minus V naught by L and therefore, this has to be the 1 minus d t t a; however, if you consider the triangle this upper triangle and the bottom inverted triangle are similar triangles because you see that the total height is delta i L therefore, the height of this triangle is delta i L by 2, the height of this part of the triangle is also delta i L by 2 and therefore, the bases are also equal because they are similar triangles the height is the same and you can easily say that the base is t s by 2.

So, going from minus delta i L by 2 to plus delta i L by 2 and this is a straight line the midpoint which is at 0 in the case of the capacitor will be half the distance likewise coming down the midpoint will be half the distance in time and therefore, this will be t s by 2, the other base will also be t s by 2.

So, now let us look at this triangle, the area of the triangle will give you the charge. So, the charge will be half base into height of the triangle, which is half the base is t s by 2 into height of the triangle delta i L by 2which is t s delta i L by 8 or further delta i L by 8 times, f s which is the switching frequency, t s is the switching period f s is the switching frequency.

Now, delta q are the change in the charge, in the capacitor is given by c delta V by V operation of the capacitor. Now, this we know is delta i L by 8 f s and therefore, we can find out c, c is equal to delta i L by 8 f s delta V now this is a important relationship which you can use for finding the value of the capacitance that you need to put for the buck converter.

Now, out of these things f s is a design step which is known delta V what is supposed to be the ripple across the capacitance is also obtained as an output ripple spec that the capacitor is also a design spec the capacitor should not have ripple beyond this particular value the value of delta i L is also a divine spec while designing the inductor because you see the delta i L value is assumed as around 10 percent of i naught max. So, this is I have a design, a starting designed value which people use or in some of the specification minimum value of i naught is specified. So, based on the minimum value of i naught delta i L value can be obtained.

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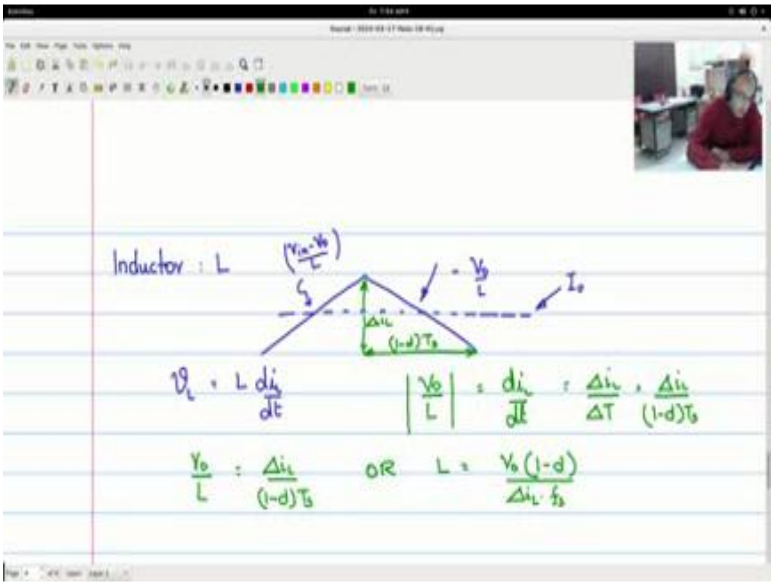

So, let us look at the inductor finding the value of the inductor also when the value of delta finding the value of delta i L becomes clear.

So, for now you can see that the capacitor value can be calculated knowing the value of delta i L delta V and f s; f s is known delta V coming from design spec delta i L also coming from design spec. So, let us now look at finding the value of the inductor L. So, we know that in the case of the current, it is rising at the rate of V in minus V naught by L at that rate and then it is falling at the rate of minus V naught by L this is. So, for the case of the buck converter, where the average value of the inductor current is i naught?

So, this we have seen just now, just for this the various waveform, when we are studying the various waveforms the inductor current goes by the Faraday's law V L, the voltage across the inductor is equal to L d i L by d t and V L by L is the. So, this is what we have here now you could use either of the slope there is one variable in the only single variable in the output in the falling slope.

So, therefore, we could use that. So, let us say that this rate i will just take the rate absolute value of the rate this slope finally, is the delta d i L by d t and because they are all linear straight lines people say delta i L by delta t now in this particular buck converter waveform case delta i L is this much. So, there is a change in delta i L from here to here in terms of time within this time.

So, this time was one minus d t for the buck converter case you could do the same in the upward slope also and you will get the same result. So, delta i L was is delta i L itself. So, this is nothing, but delta i L by 1 minus d t's. So, in this time period we have this rate V naught by l. So, we are writing here you will see that V naught by L will be delta i L by one minus d t s or L equals rearranging this equation you will see V naught one minus d by delta i L f s. So, I will replace it by f s because f s is another design spec which is normally given d is the due design. So, to get the maximum value of L we could use the minimum value of d that is d min.

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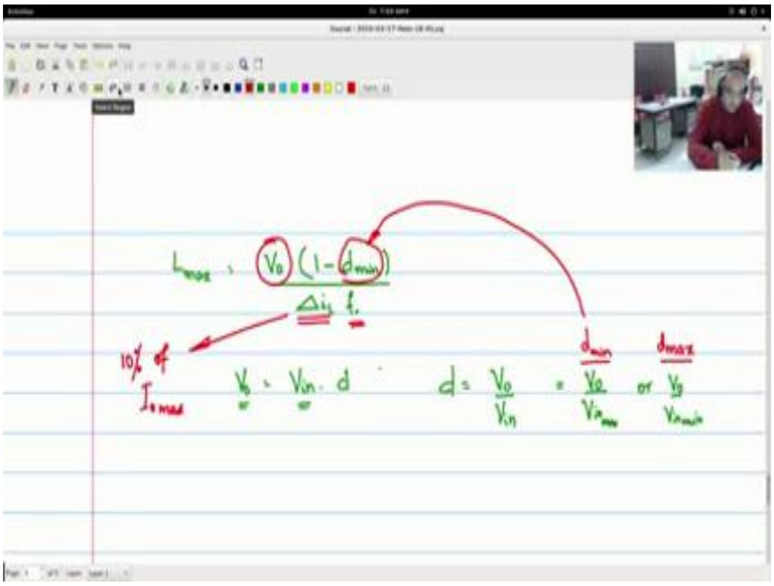

So, if you consider L max you would get V naught minus d min minimum value of d by delta i L f s. Now, how to get the value of d min, now we know how to get the value of V naught V naught is equal to V in into d. Now, in this V in is given and V naught is given normally V naught is the spec V in is also an input spec. So, d is actually calculatable. So, we calculate d which is equal to V naught by V in and normally you will see that V naught is supposed to be a regulator, it is supposed to be a constant value, it should be regulated in the phase of variation in V in.

So, you will see that d could be V naught by V in max or V naught by V in min and any value in between. So, this could be the limiting values where V naught by V in max will be d min value and V naught by V in value will be the d max value. So, this is how we calculate V in max and V in min are found from the input tolerance spec. So, you can find d min and d max and then use this d min value here to find out the value of n, sorry it was for minimum duty cycle. It will also for any other duty cycles the value of L will be large enough to take care of any other duty cycles.

Now, one other issue is here I mentioned that V naught is a spec f is also a spec f is f s is also a spec and V naught is also known d is known. So, everything can be used for calculating except i L and as a starting value you use 10 percent of i naught max load current use this and find some value of n.

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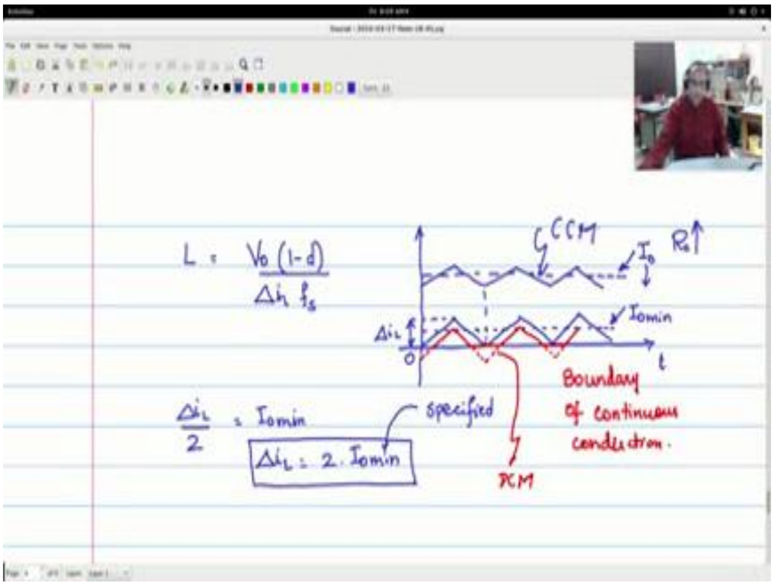

There is also another way, sometimes the following spec is also given sometimes, you will see that; let me write down this equation L is equal to V naught 1 minus d delta i L into f s. So, you see that in the case of the inductor this is t you see the inductor current going up and down in this fashion and here you have i naught this is i naught.

Now, what would happen when r naught value is increased, if r naught value the output load resistance value is increased you will see i naught decreasing. So, i naught will keep decreasing, but you see that their delta i L and the rate the slopes here will not change they will because they are determined by V minus V naught by L and V naught by L here and therefore, if they are independent of the load resistor value or the load current value.

So, the shape of this triangular ripple will still remain and the height of the ripple will also remain. So, in the limit you will see that it may just touch lines are not straight. So, it may just touch the 0 line like this. So, this would be considered as i naught min minimum value of i naught that value of i naught, where the inductor current ripple just touches the 0 line would be the i naught min because the average of that will be i naught min.

So, in this case, in this limiting case if this was supposed to be the delta i L. So, you will see that delta i L by two delta i L by two would be equal to i naught minimum or delta i L is equal to two times i naught minimum and this is a very important condition that you can use for choosing the value of delta i L; delta i L should be the two times i naught minimum where i naught minimum is specified. So, this is specified, if this is specified by the user then you can use this to find out the value of delta. If this is not specified then you use delta i L is 10 percent of i naught, this is how you try to find.

Now, here one more point is that this at i naught minimum, this is just touching the 0 line. So, this is at the boundary of continuous conduction, what it means is if you go any further we could have the triangle coming like this and I am putting this in dotted, if there is a bidirectional switch you will see the inductor current going negative, but the series, the switch if it blocks then you will see that the inductor current goes like that. So, this is a sudden change in the slope during this point.

So, the inductor current reaches 0, there is a change in the slope and then again change in the slope. So, that is why we say it is discontinuous or the conduction period itself is discontinuous. You have a period where the inductor current is present period where the inductor current is 0 not present again, it is present. So, this is discontinuous conduction zone or DCM for this one, this type of an inductor current waveform is called DCM and all waveforms above the 0 line, this type of waveform showed in blue or continuous conduction or CCM. So, you should ensure that the inductor current is operating in CCM and not in DCM because all the analysis that we have been talking about is for a continuous conduction mode.