Design of Power Electronic Converters
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Lecture 04
Design Example of Buck Converter

Welcome back to the course on Design of Power Electronic Converters. And we were in the module of analysis of power electronic converters. So, today's lecture will be on design example of buck converter. Previously, we had seen how to analyze the buck converter and how to also get equations which we can use for computing L and C. Today, I will take a simple example where I will show you how you can design the buck converter.

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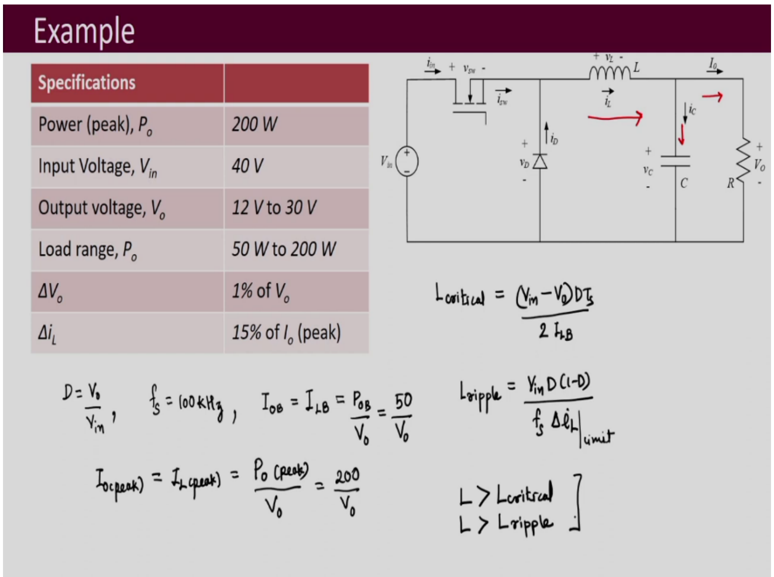

So, the example that is taken over here is that the specifications are like this that the output power the peak power is taken as 200 watt and input voltage is 40 volt, the output voltage range is taken from 12 volt to 30 volt. Now, here I have chosen it like that the output voltage is varying and the input voltage is almost fixed.

But note that there are many applications where the opposite may be true that the input voltage may be varying and the output voltage may be fixed in either case it is the duty ratio which is going to vary and then accordingly some other calculations may also change.

So, then the load range for whatever purpose we are designing let us say the load varies most of the time from 50 watt to 200 watt. Now, for this range then we would like to keep the control simple and so 50 watt can be taken as the boundary power at which the inductor current is at boundary. To do the design we can use that point of 50 watt.

Then, the delta Vo the ripple allowed in the output voltage is let us say equal to 1 percent of Vo and the inductor current ripple let us say there is a limit that is specified on it which is I have taken it as 15 percent of peak value of the output current. Now, know that this many times may not be specified in your particular application, sometimes it may be required sometimes it may not be.

But here I have taken it to demonstrate the example. So, now, to begin with what you will be doing is that of course, first of all you can calculate the duty ratio D. So, D you know that for buck converter it is very simple, which is

$$D = \frac{V_0}{V_{in}}$$

And since the output voltage is varying your D is also going to vary. Now, we have to choose the switching frequency. So, when you choose the switching frequency most of the time, we see the power level and the voltage levels.

So, power level is here 200-watt, voltage, input voltage is 40 volt, which are relatively lower voltages and we can use MOSFETs there which can switch very fast in the range of 100s of kilohertz. So, let us say we choose the switching frequency fs as equal to 100 kilohertz. Now, note that your choice of components depends on this choice of frequency, if you change the switching frequency many of the values in your circuit are going to change.

So, keep this in mind here we are doing it for the switching frequency of 100 kilohertz you may change it, you may let us say take 150 kilohertz, 200 kilohertz or below then that also 50 kilohertz or 75 kilohertz it depends on your choice, but values will change accordingly. Then, we can also calculate these boundary current which is your IOB which we had denoted with the which is actually equal to ILB the inductor boundary current.

Now for the case of buck converter here this inductor current is the sum of your Ic and Io which we had assumed to be constant, this load current. So, since the ripple in the average current through the capacitor is going to be 0, so that is why the average inductor current is equal to the average load current or we can say that the load current which we have assumed to be a constant.

So, that is why we are able to write this IOB is equal to ILB, but please be careful if you are doing the design for other DC to DC converters, that is not the case. So, you have to use the equations then accordingly. So, that will be equal to

$$I_{OB} = I_{LB} = \frac{P_{OB}}{V_0} = \frac{50}{V_0}$$

And here we have chosen POB as equal to 50. So, this will be 50 by Vo. Then, you can also compute this value of peak current, your Io peak, this over here will be

$$I_{0(peak)} = I_{L(peak)} = \frac{P_{0(peak)}}{V0} = \frac{200}{V0}$$

Now, for this example, this is taken as 200 by Vo. Then, we can compute this value of L critical previously we had derived these expressions. So, this is given as Vin minus Vo into DTs by 2 ILB. Now, you have chosen Ts. So, you know this, you know the duty ratio, you can compute Vin and Vo will be known to you and you have also computed ILB. So, you can calculate the value of L critical.

$$L_{critical} = \frac{\left(V_{in} - V_0\right)DT_S}{2I_{LB}}$$

Then, you can also calculate the value of L ripple

$$L_{ripple} = \frac{Vin\, D(1 - D)}{f_S\, \Delta i_L|_{limit}}$$

And this will be given by your Vin D 1 minus D into fs by delta i L. Now, this delta i L we have said that there is going to be a limit on it. So, that the limit, you can calculate using this you have calculated the Io peak, so 15 percent of that is going to be the delta i L limit. So, here I will write this as the limiting value which we can use for calculating L ripple.

Now, many times people do not calculate this L ripple they just calculate the L critical and then take the value of L which is much greater than that, but sometimes people also use that for choosing your value of L. So, whatever L you are going to choose that has to be greater than this L critical and you would also like it to be greater than L ripple, both of these you may like to satisfy.

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Choice of L and C

$L = 100\,\mu H$

$$C = \frac{V_{in} D(1-D)}{8 L f_s^2 \Delta v_o}$$

$C = 10\,\mu F$

$$\Delta i_L = \frac{(V_{in} - V_o) D T_s}{L}$$

$$\Delta v_c = \frac{(1-D) V_o}{8 L C f_s^2}$$

	V_o=12 V	V_o=24 V	V_o=30 V
D	0.3	0.6	0.75
I_o (peak)	16.67 A	8.33 A	6.67 A
R (peak)	0.72 Ω	2.88 Ω	4.5 Ω
I_{oB}	4.17 A	2.08 A	1.67 A
R_B	2.88 Ω	11.52 Ω	18 Ω
Δi_L (limit)	2.5 A	1.25 A	1 A
Δv_C (limit)	0.12 V	0.24 V	0.3 V
$L_{critical}$	10 μH	23 μH	22.5 μH
L_{ripple}	33.6 μH	76.8 μH	75 μH
C	8.75 μF	5 μF	3.13 μF
Δi_L	0.84 A	0.96 A	0.75 A
Δv_C	0.105 V	0.12 V	0.094 V

So, I have done the calculations. And here in this table it is shown this is done for Vo equal to 12 volt, Vo equal to 24 volt, and Vo equal to 30 volts the output varies from 12 volt to 30 volt, I have just used one of the mid voltages also 24 volt to show the computations of how values are going to change. So, we can calculate the duty ratios, then you can calculate the peak load current depending on the output voltage.

So, 200 divided by the voltage will give you the peak currents Io peak currents average currents, then you can also calculate the corresponding load resistor. And the boundary current 50 by your output voltage that will give you the boundary current values, average boundary current values. And you can also calculate the resistor corresponding load resistor, then delta i L limit corresponding to these Io peaks also are written here.

And delta vc limit because it is we have taken as 1 percent of the Vo, so that also is written over here. Then using all these values, I have calculated this L critical, you can calculate the values of L critical using these equations that I have just written over here. And you can also compute L ripple. So, now, what we observe here is that as this output voltage increases the peak current reduces because your power level we are keeping is fixed.

So, obviously, as your voltage is less your currents are going to be higher. So, then what we expect is this delta i L limit is going to be reducing as your output voltages are increasing. And your boundary currents what we see that also is reducing here. And then what we see as your boundary current levels are reducing. So, that means your current levels are higher at lower voltages.

So, obviously, your L critical is going to come out lesser for lower voltages. So, lower output voltages. So, we see L critical increases and the output voltage increases. Then what we see is L ripple that also increases as the output voltage increases and that also is obvious from this delta i L limit that we see here delta i L limit reduces, so if the limit reduces the L ripple accordingly will be increasing.

So, from all these things what we see is that if we choose a value of L which is bigger than all these values, so that means, it has to be greater than this 76.8 Micro Henry, if we choose value of which is greater than 76.8 Micro Henry, so that will satisfy all this L being greater than L critical and L ripple for all the range of output voltages and load currents that we have taken.

So, let us say that we choose L to be equal to 100 Micro Henry. And this is a choice you may choose something else as well you have to choose greater than 76.8 Micro Henry, you can just keep it exactly 76.8 Micro Henry also, but we can choose higher than that as well. So, let us say we choose it L equal to 100 Micro Henry. Then using this expression for C which is computed using your ripple in the output voltage which we have seen before, C can be written as

$$C = \frac{V_{in} D(1-D)}{8L f_s^2 \Delta v_0}$$

So, here also what we observe is this that your D is going to change and delta Vo accordingly also changes. We have chosen L and we have also chosen fs, so different values of C we can compute. And that is what we are computing here these different, different values of C we will be obtaining. And what we observe here is that as the output voltage reduces this capacitor value what is required is increasing.

And what is the relationship there, why this is happening? We can see that this delta i L limit has increased. So, your average current level increased. So, that also will have an impact on your delta i L limit. And then, so, if your capacitor has to handle more ripples, it has to have a higher value of capacitance to maintain delta Vc. And also, you can see that the delta Vc limit is also reducing.

So, that is another way of finding what is the cause of it that your delta Vc is reducing as output voltage is reducing and so your capacitance values are increasing. So, we need a value of C which is greater than this 8.75 micro farad. And so, let us say we choose C is equal to 10 micro farad. Now, one more thing that you should be knowing is that practically it may not be possible to design what theoretically values you are getting.

For example, here you are getting 76.8 Micro Henry, not necessarily you can make these inductance values. So, next what we see here is that this 8.75 micro farad that also is something which may not be possible for you to get exactly this value of capacitor. Also one more thing that you can see here is that you may say that here the values are slightly higher than this whatever 22.5 Micro Henry which is slightly higher than 23 Micro Henry, so those small little value changes may be there.

So, that you can do the calculation and then you can check that. And then this delta i L what you are going to get when you choose these value of L and C, that is what we can calculate, so that you can do using this expression of delta i L which is

$$\Delta i_L = \frac{\left(V_{in} - V_0\right) DT_S}{L}$$

And delta Vc you can compute using

$$\Delta v_C = \frac{(1 - D)V_0}{8LC f_s^2}$$

So, using that these are the computations for delta i L that you can see that what are the ripples that you are obtaining and what are the ripples of delta Vc that you are obtaining. And what we can see is that these are definitely lesser than what we expect here.

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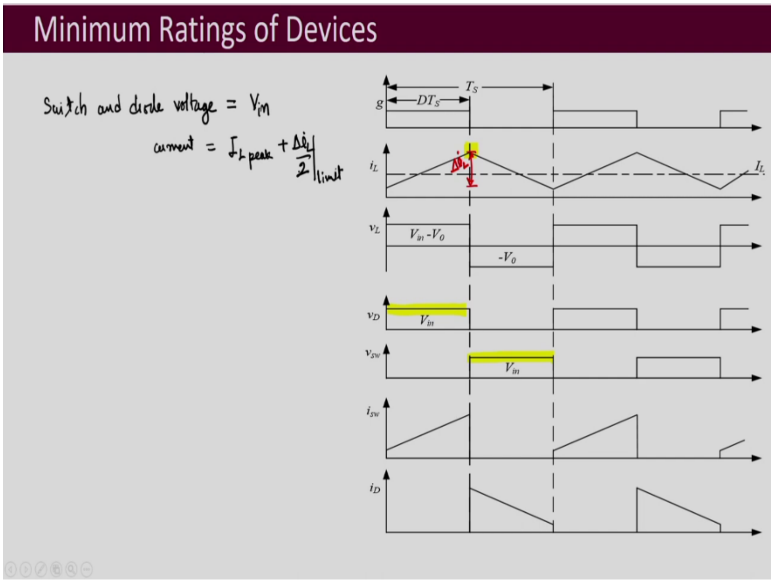

Next. You can choose the minimum ratings of the devices based on the waveforms. So, your switch voltage, switch and diode voltage rating will be equal to Vin that we can see here from these waveforms that your diode voltage and switch voltage this is equal to Vin. So, whatever device that you choose that has to have a rating higher than Vin. And usually, you have to keep a safety margin as well.

And then the current rating, so, what we can see this is the minimum current rating corresponding to the peak value of current has to be there. And what this is equal to? So, that this is equal to your this is the ripple delta i L. So, therefore, your current ratings that will be required, minimum current ratings will be

$$\text{current} = I_{L\,peak} + \frac{\Delta i_L}{2}\Big|_{limit}$$

So, you have to choose the current rating of the device which is higher than that and again the safety margin has to be kept. So, this is how we choose the device voltage and current ratings and also the inductor current rating that also is going to be the same

$$\text{current} = I_{L\,peak} + \frac{\Delta i_L}{2}\Big|_{limit}$$

So, you have to choose an inductor which can carry more current than that. And the capacitor voltage has to be equal to the output voltage and obviously, you will be choosing the capacitor voltage rating higher than that, keeping some safety margin because there may be some spikes also which are going to come those things we will be discussing later on in the course.

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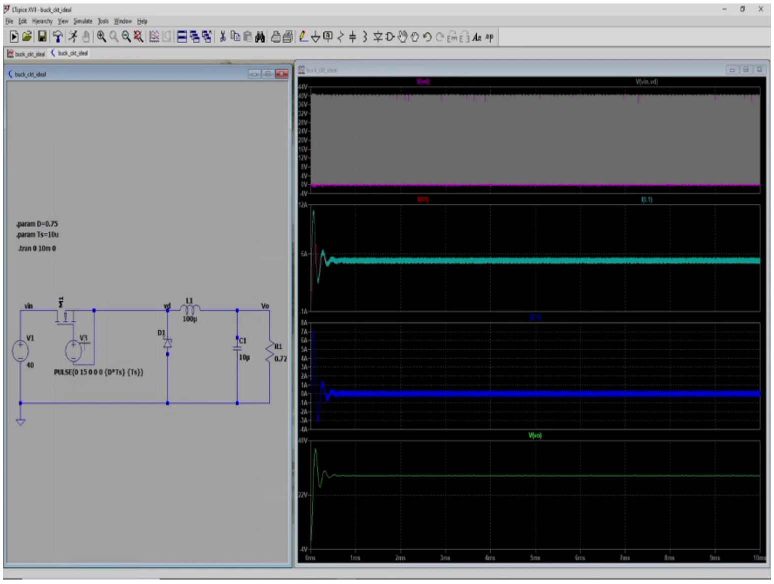

Now, let us look into the simulation. How you can verify your design using simulation? Simulation is a tool which helps the power electronic engineer to design the converter. Many times, it is not possible to do all calculations using equations sometimes the equations may be too complicated to be used, and moreover most of the analysis for power electronics that we do is assuming converters to be ideal, but in actual practice there will be several non-idealities.

So, in simulation you can see the effect of some of the non-idealities. So, we will be looking into the simulation of buck converter now. And the software that I am using in this course is LTspice, there are several other software which are available and you can use them as well, several powerful tools for simulating power electronic converters are there. LTspice is a free software, you can download it on internet, and then you can install it on your computers.

And you can also learn it by yourself because on Google there is a lot of help that is available for LTspice. So, this course we will be using this LTspice software for seeing the simulation for power electronic converters. So here I have simulated this buck converter.

Now, you can see that this duty ratio that is used is D equal to 0.75 and the input voltage chosen is 40 volt which is what the example that is taken and then the resistance value load resistance right now is kept as 0.72. So, then this 100 Micro Henry and 10 micro farad what we just chose in the example that is what is taken to see whether it works or not. And this is the pulse, this is the voltage source which is going to give the gate pulse and this time period is taken as 10 micro second which corresponds to 100 kilohertz.

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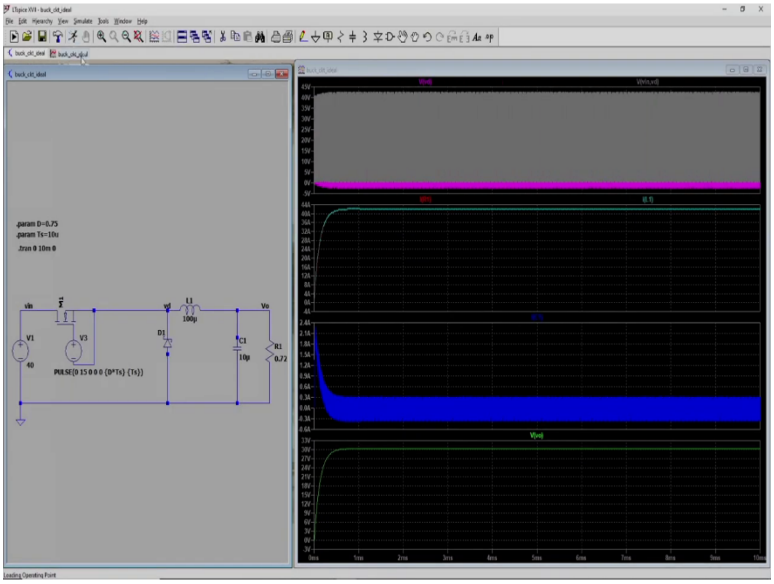

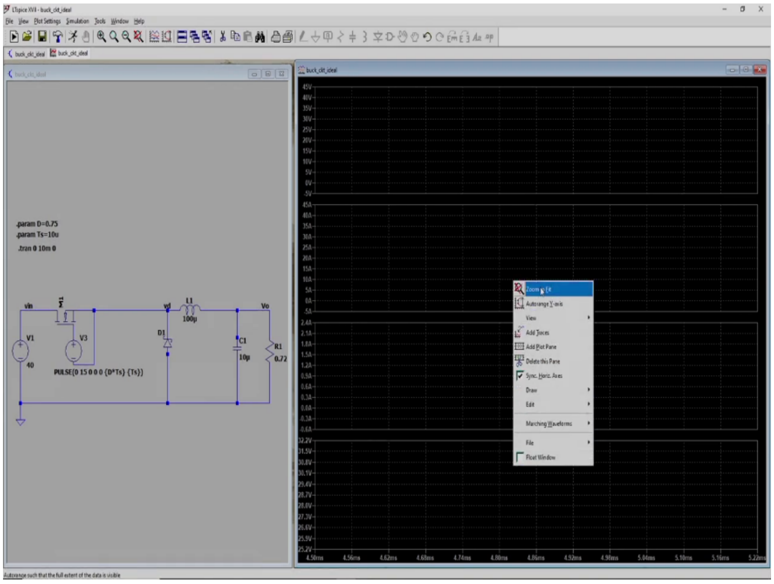

So, now, let me run the simulation for this. So, if we is zoom it. So, the simulation is done for 30 milliseconds.

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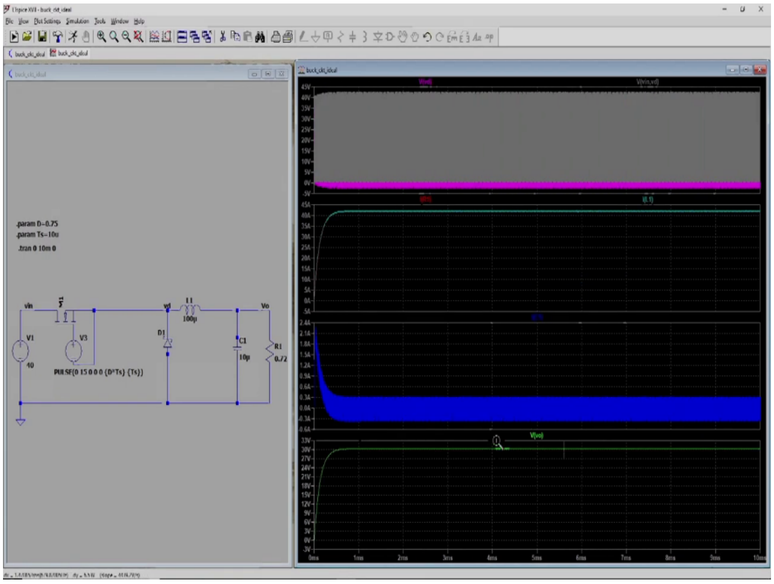

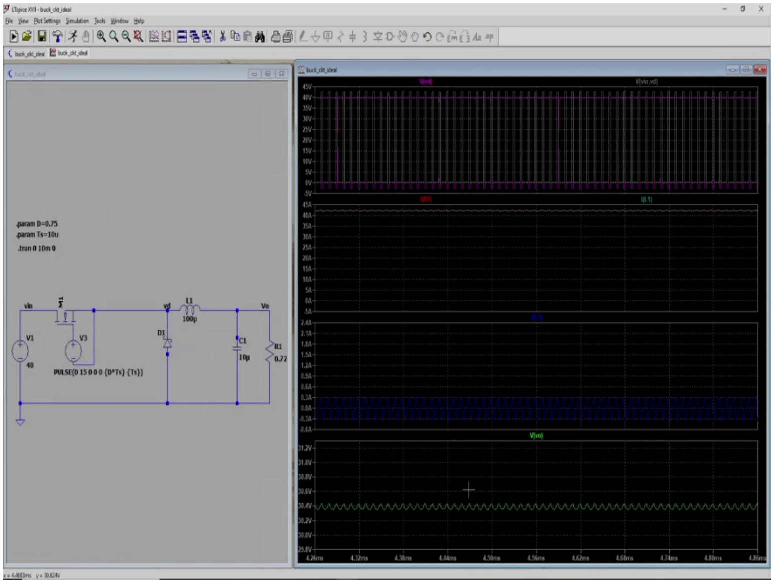

So, here you can see that you are not getting exactly 30.0. So, there is going to be some deviation because these diode voltage drops and MOSFET drops are going to be there. So, at least 1 or 2 non-idealities are included in this simulation. And moreover, what we had assumed that this load current to be constant, but that is not going to be so, because here you see that there is a ripple in the voltage in the output voltage and that ripple is also going to be coming in the load current. And then your capacitor current gets formed accordingly as you apply KCL over here is inductor current is the sum of capacitor current plus load current.

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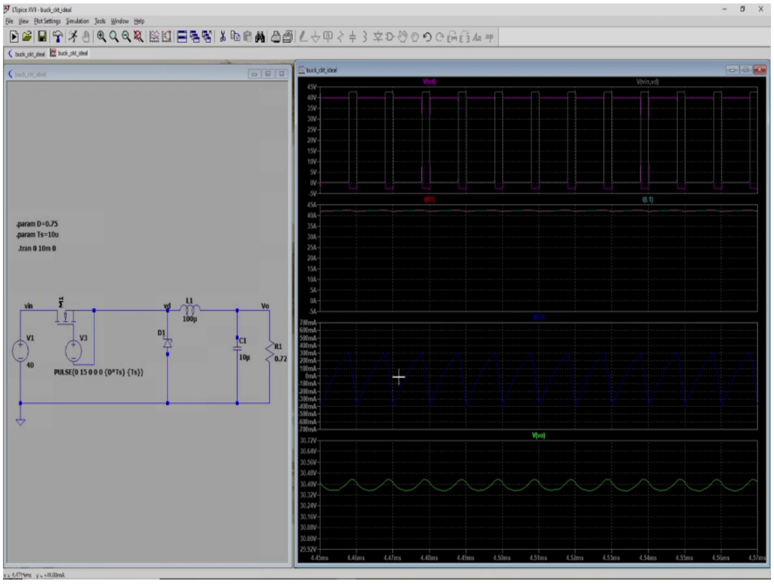

So, now, this is the capacitor current you can see this capacitor current how it goes from positive to negative and accordingly this ripple in the output voltage is forming whenever the capacitor current is negative over here it is discharging and whenever it is positive over here you can see that it is charging.

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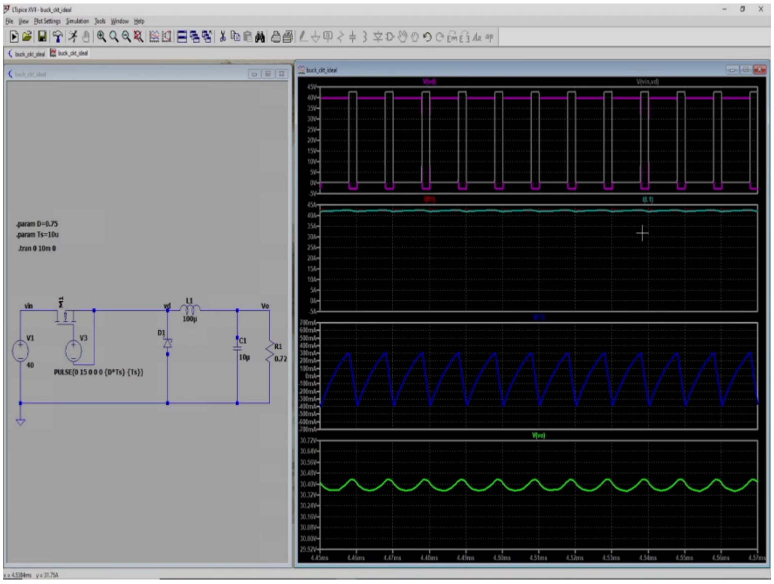

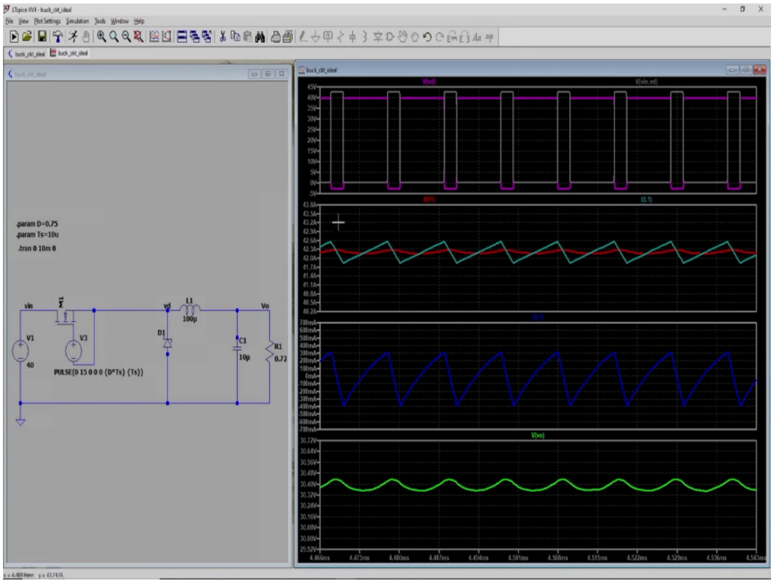

Then let us look into the inductor current ripple. So, this is your inductor current now, here this current seems to be much higher than what we had computed. Now, we have to see the reason for this, this current level we see is going to be something around greater than 40 amperes. But what we had computed we saw that it was coming around maximum current for the converter for output voltage 12 volts was coming around something, around 16.67 amperes. So, what is the reason behind it?

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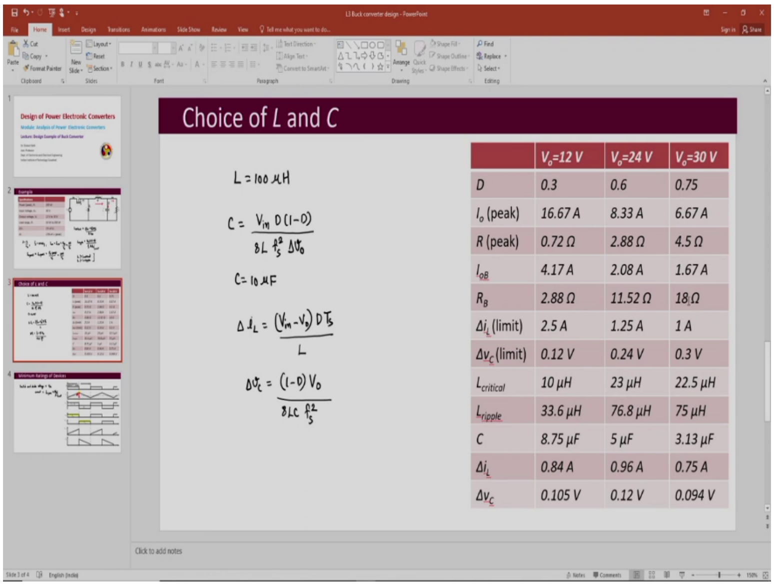

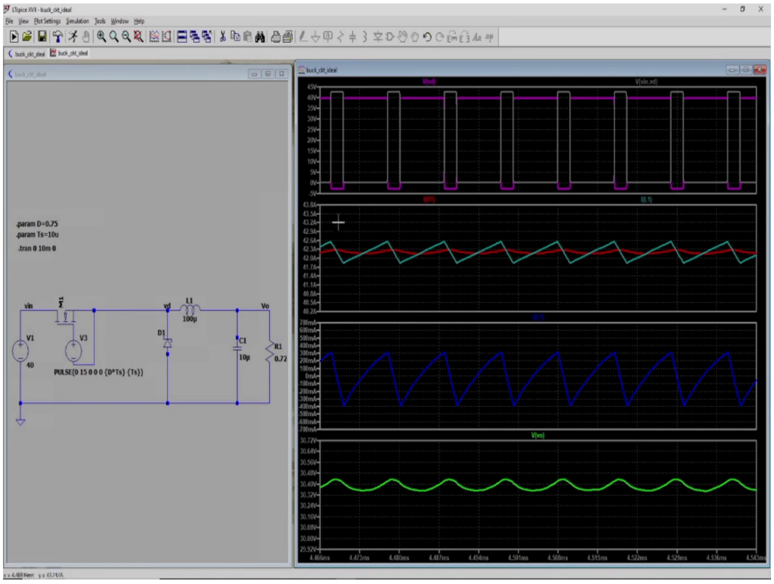

So, let us look into these values. So, when we see these values, what we see over here is that the resistance range that corresponds to 30 volts, 0.75 duty ratio is 4.5 to 18 ohms. And here the resistance that I have used is 0.72. So, that means we are exceeding the peak power level. So, we need to change it.

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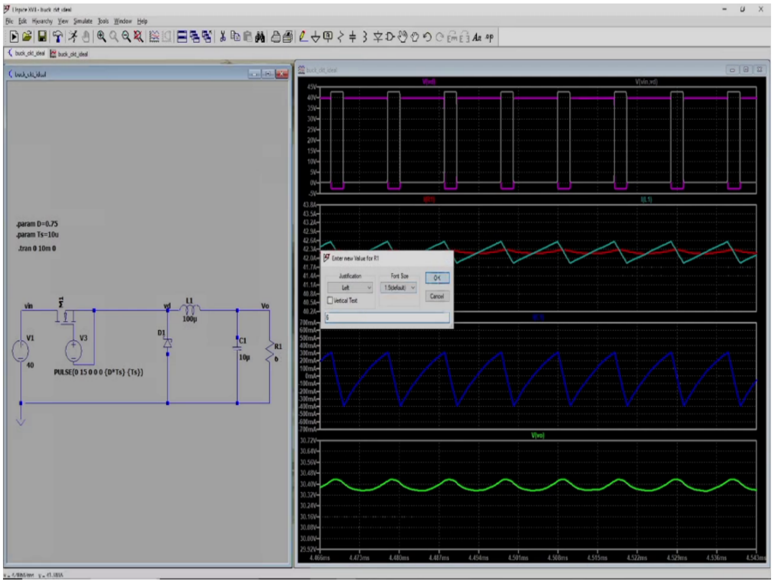

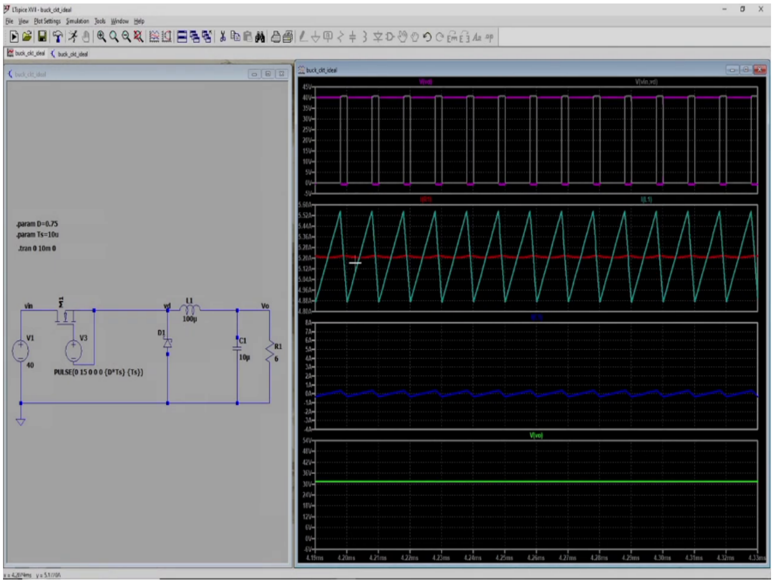

So, let us change it, let us make it 6 ohms and rerun the simulation so, now, let us again zoom it. So, now, you can see that, that the current levels are now within the range what we expect. You can verify it. It turns out to be as equal to 5.2. So, you can compute what is the power corresponding to 6 ohms here and then whether that is what you are approximately getting in the simulation.

Then, let us also look into the ripple in the current you can see that it goes from 4.88 amperes to about 5.52 ampere. So, that also ripple also you can compute that whether your current ripple is within the limits of what you wanted to design for.

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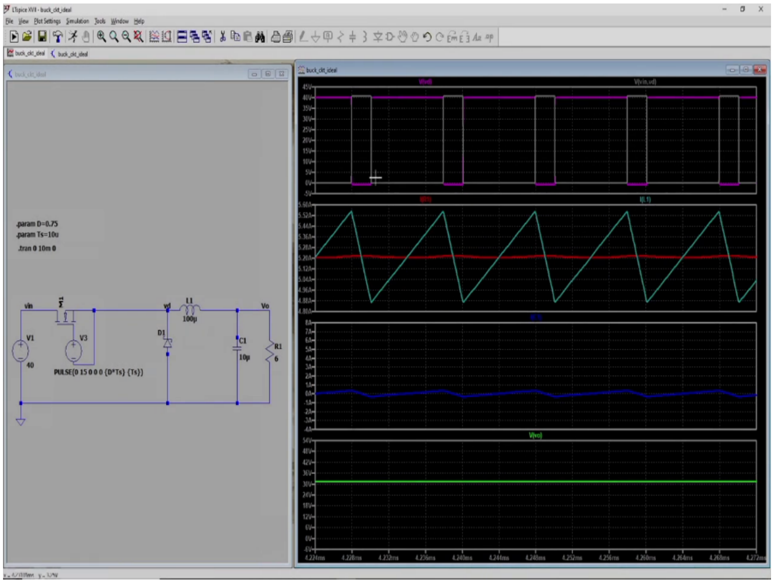

Then next, let us see the diode voltages and the voltage across the MOSFET. So, this grey waveform is the voltage across the MOSFET. You can see this is the time for which it is on and so it is close to 0 and then when it is off, so, it is 0.75 duty ratio. So, for most of the time it is on and that is when you see the current to be increasing and then here it is blocking the MOSFET is blocking and the voltage is close to 40 volts.

Now, you won't not be seeing exact 40 because when you now apply KVL here this diode voltage drop is also going to get added. So, you will see that something greater than 40 volt coming here. And then this is the diode this pink waveform is the diode voltage waveform, you can see that this is 40 which is blocking, close to 40 and then when it is conducting, you will see a small negative voltage here.

And why negative voltage is coming? Because we are measuring the polarity assuming this is positive with respect to here, but the current is actually flowing in the opposite direction and the drop is also in the opposite direction. So, close to 1 volt drop you will be able to observe here, you can see here that this is about minus 1 volt that is coming.

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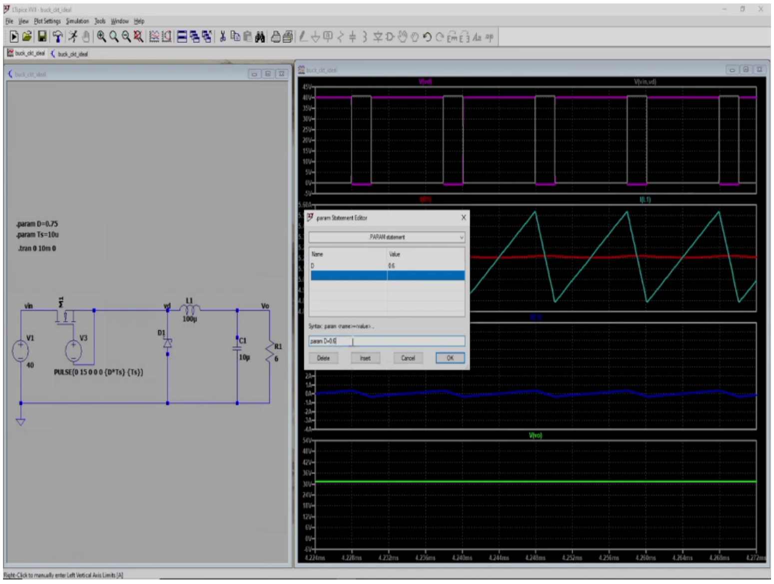

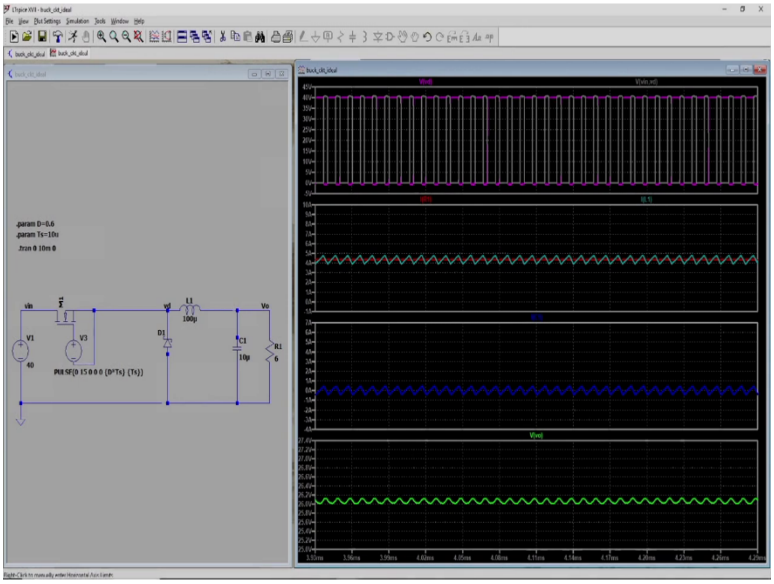

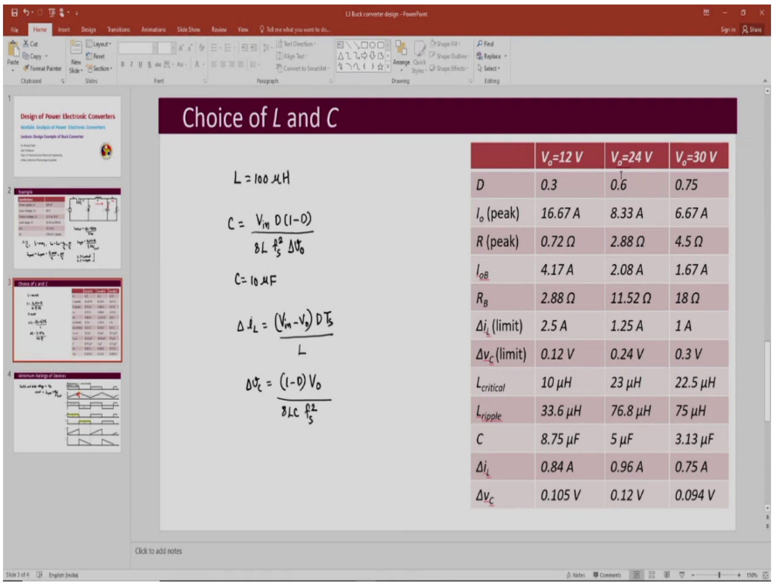

So, now, let us change this duty ratio let me make it a 0.6 and let us see what happens, whether the output voltage changes or not. So, now what you can see here that the output voltages has changed, but corresponding 0.6 what voltage you were assuming that we had seen that 0.6 should give us 24 volt.

Now, when you do this simulation, you do not see exact 24 volt coming there is a deviation from there 1 to 1.5 volt deviation may be there. So, the reasons I said there will be certain non-idealities that will be also coming into picture and that is why when we practically use these converters we always use it in closed loop.

Practically never these converters are used in open loop because this theoretical duty ratios that we are computing using the circuit to be ideal it does not hold true in practice. And so, all these deviations will be there 1 or 2 volt deviations here and there will be there and so accordingly the duty ratios have to be adjusted. So that means you have to sense the output voltage and then whatever is the division coming up that the controller has to take care of it and the duty ratio has to be adjusted accordingly.

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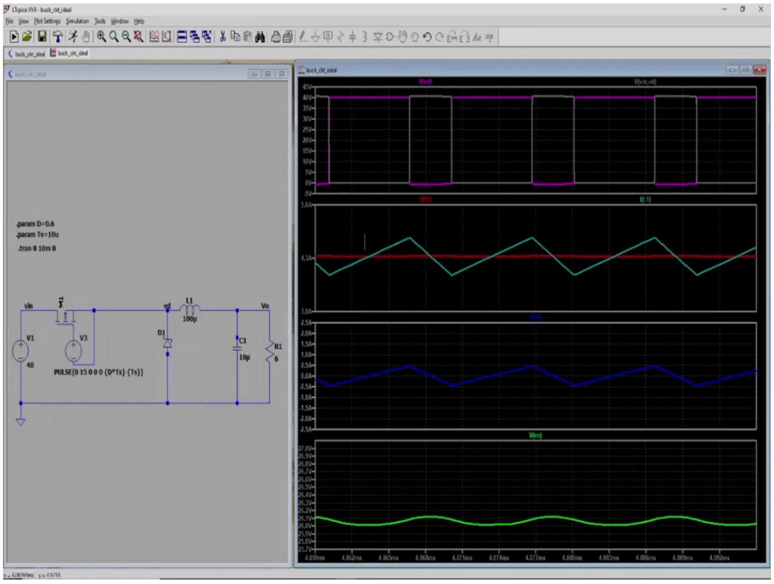

So, here also you can see that what is the ripple that you are getting whether the ripple is proper or not and then you can see the current ripple also what is the current ripple that you are getting. And this diode voltage waveform and MOSFET voltage waveform.

So, you can play with these simulations and then you can run the simulation for different, different values and that is how you can check whatever values of L and C that you are choosing and other ratings that you are choosing, whether they give a satisfactory result or not. So, always before doing the hardware, people do simulation and verify their design. Thank you.