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DAVID PERREAULT: OK, why don't we get started? So we've been talking about DC-to-DC converters and analyzing them and understanding what they'll do in steady state, and I'd like to today bring that maybe one step closer to things you have to think about to design one. OK, but just as a reminder, last class, we introduced what's known as the buck-boost converter, or the inverting buck-boost converter.

And one version of that looks like this. We have an input voltage that I'll call V1 for example, a switch, a diode. Here's my output. That'll be V2.

And then we have a filter capacitor-- in this example, I'm going to put the filter capacitor here, OK, because this is sort of the actual switching loop-- and then an inductor, where we have iL. And, right, and what we've said so far is let's think about the case where L and C are big, right, that they're approximately infinite, and that's not a bad place to start for analysis because you can learn a lot of things about that. And what that means is that iL is approximately equal to its DC value IL and vC is approximately equal to its DC value capital VC.

And we said, OK, if I had to think about this converter, right, I might think about the switch voltage, v switch, and the switch current, i switch, and the diode voltage vD and the diode current iD. Right, and what we discovered about this converter last time is that if I thought of, here I have, say, an input current that I'm going to call i1 and an output current that I'm going to call i2, and if I said, OK, suppose this thing filters perfectly and i1 is approximately equal to its DC value capital I1 and i2 is approximately equal to this DC value of capital I2-- and in order to really get that, you'd probably need a tiny bit of source impedance here, but let's assume that's the case-- what we saw for this converter is that IL, the DC current in the inductor, is equal to the magnitude of I1 plus the magnitude of I2, and the DC capacitor voltage VC is equal to the magnitude of V1 plus the magnitude of V2.

OK. And so, basically, the capacitor has to see the sum of the magnitudes of the input and output voltage, and the inductor current carries the sum of the input and output currents. OK. And then if I thought, well, OK, what is the switch voltage? OK, when the switch is off, what voltage does it block?

Well, that blocks VC, and the same thing, when the diode is off, it also blocks VC. So v switch max is equal to vD max is equal to VC, which is equal to the magnitude of V1 plus the magnitude of V2. And if I thought of i switch max and iD max, well, when they're on, they carry the inductor current, which is the magnitude of the input current and the output current, the DC input and output current.

OK. So at least now I have a sense of what the stresses are on the diodes and transistors and the inductor and capacitor, right. Why do I care about that? Because ultimately, I have to go buy switches that can carry-- diodes that can carry the current without blowing up and can block the voltage without blowing up, and I've got to go buy capacitors that can block the voltage and inductors that can carry the current, right. So we have to start going through this analysis to say, How much voltage and current do I need in the circuit?

OK. How does this circuit compare to, like, a buck converter or a boost converter? OK, well, if I took my buck converter-- OK, so here's my buck converter. In this case, I'm going to put the-- I'm going to think about the capacitor at the input, because that's where the switching current goes. OK, and here's my switch, here's my diode, and here's my inductor. I won't worry about-- I don't actually need a capacitor at the output. Although, I would typically put one. So here's v2. So I could again think of v switch and i switch and vD and iD.

All right. This would be vC, and this would be iL. And again, I'm going to think of L and C big, really, really big, so that basically the inductor current and the capacitor voltage here are basically constant. OK. In that case, what I get is v switch when it's off and vD when it's off are both equal to this capacitor voltage, which is equal to v1, right. And i switch equals iD when the switch and diode are gone. They carry the inductor current, which is also equal to I2, if the inductor current is really big and I just have a DC current, right. And this is the i1, and this is i2.

So that's for buck converter. What about a boost converter? Well, a boost converter looked like this. Here's v1. Here's iL. And in this case, I'm going to put the capacitor here because this pulsed current comes through the diode. OK. And here's v2.

OK. So again, I have sort of v switch, i switch, vD, and iD. OK. Now, in this case, il is again constant if L and C are big, OK, so that the switch current and the diode current when they're on is equal to iL, which also equal to I1, right, because whatever the current is coming out of I1 is now the current that's being switched to the diode and the transistor. v switch is equal to vD is equal to vC, which is equal to V2 in this case.

OK. So why am I going through this? Well, for either the buck or boost converter, keep in mind, in the boost converter, V2 is the big voltage, between the input and output voltage, and I1 is the bigger of the currents between the input and output current. Likewise, the switch voltage is V1. That's the bigger of the input and output voltage, right, and the current is I2, which is the bigger of the input and output current.

So for either of these converters, I might write the v switch is equal to v diode, which is equal to the maximum of magnitude of V1 and V2. And this is also equal to the capacitor voltage, and the inductor current is equal to the switch current is equal to the diode current is equal to a maximum of I1 and I2.

OK. So how do these two compare, right? The buck and the boost converter can only do a very specific function. One can step down, the other can step up, but they can't do both, right. But the stresses on them in either case, basically, the switch and the diode and the capacitor see the maximum of the input and output voltages, and the switch current and the diode current see the maximum of the input and output currents.

If I use a buck-boost converter, I can go up or down, at least in magnitude, but now I see higher stresses. Instead of seeing the maximum of the input and output voltage, I see the sum of the input and output voltage magnitudes and the sum of the input and output current magnitudes, right. That means, for a given conversion ratio, the buck-boost converter is going to have a higher stress on the switches and the diodes and the inductors and capacitors than a buck converter or a boost converter. And why is that?

In a buck-boost converter, remember, we said how it ran was basically I take energy from the input, I put it into the inductor in the first part of the cycle, and then the second part of the cycle, I take that energy out of the inductor and put it in the output. So all of the energy flowing through the circuit from the input to the output ultimately got stored in that inductor.

OK. With a buck converter or a boost converter, that's not quite true. In the first part of the cycle, we turn the switch on and we store up some energy in the inductor, but we also have direct current path from the input to the output through the inductor. And in the second part of the cycle, we take the energy out of the inductor and put it in the output. So in a buck converter, only part of the energy ends up stored in the inductor, and part of it flows straight through from the input to the output. And the same thing can be said for the boost converter.

The consequence of this is, is that to do a given conversion function, the buck-boost converter imposes much greater stresses on its components than the buck converter or the boost converter. All right, so we can get away with a lot of things in terms of reducing the stresses on the component by being in this sort of direct conversion approach, where I'm sort of not storing all the energy in intermediate form that I can with a buck-boost converter. Questions about that or about any of the prior material?

So one of the things we're going to want to think about as we kind move from theory to thinking about design is, boy, if I'm going to do things one way or another, how can I get away with smaller voltage in current switches and less energy storage in my passive components? And some ways of doing things are going to be much better than others, OK, and that's part of the art of design, is figuring out, Well, geez, what do I need to do, and how is that going to translate into the size and loss and weight of the thing I'm designing?

OK. And I want to take some initial steps today towards thinking about how we might do that, OK, and one of the things we're going to have to do in order to do that is we're going to have to throw out this assumption, right. For purposes of figuring out my conversion ratio and those kind of things, I can imagine that my inductors and capacitors are really big. That's a perfectly valid thing to do, and we do it all the time.

But if I'm going to go build this thing, first of all, I can't go out and buy a one-henry inductor very easily. And the bigger the inductance I buy, what we're going to see is the more energy it has to store and the bigger it is and the lossier it is, and everything else. So I need to start figuring out, Well, how big does L and C have to be in order to achieve my goals? And that's what I'd like to talk about today. And the first thing we've got to do is figure out, Well, what is the impact of finite component values on the converter?

OK. And what we're going to see is there's a few things that might-- one of the things I have to do is figure out, in any of these converters, what value of L do I pick, what value of C do I pick? How I figure those out depends upon a few things. OK. Things that might determine that, first of all, is ripple, how much voltage and current ripple are permissible in the circuit, and we're going to focus on ripple today.

There's also the question of transient dynamics. We'll look at that a little bit later in the term. And that can also impact the decisions you make, but it's sort of ripple first, transient dynamics second.

And the other thing that's is going to come into play is, How big and lossy and expensive are the components? And we'll touch on that today a little bit. We'll at least get sort of a rough measure of how that goes.

OK. So let's start to think about how we might start sizing components. In order to do that, we need to figure out a way to calculate ripple in the components. OK, so here's the game we're going to play. Let's think about the boost converter, for example.

OK. So here's my boost converter. And I'm going to worry about what the ripple, for example, on the capacitor voltage is, and I'm also going to worry about what the ripple in the inductor current is. OK. If I make an L and C really big, then the ripple goes to zero, but I can't afford to make them too big because the components will be too big and too lossy.

OK. So what does this look like? Let me plot for a second what iD would look like. And what do I mean by iD?

Let's look at this current. OK. Why? Because that's going to be a key to figuring out how much ripple I end up with on the capacitor voltage.

So what happens in this converter? In the first part of the cycle, q of T is high. And the switch is on, and iD is 0. And then the second part of the cycle-- so that goes on for some time DT. OK. And in the second part of the cycle, the output goes to v2. Right, so the-- I'm sorry. In the first part of the cycle, iD is 0 because iL is going through the switch, and the second part of the cycle, iD is equal to iL, right. So this, I'm just going to call IL, capital IL.

OK. Now, I'm kind of assuming that L is really, really big here. I'm going to ignore the ripple current in the inductor in order to calculate the ripple voltage on the capacitor. All right, and it turns out that you can do that freely and you'll still get the right answer, OK, and I'll show you that in a moment. OK. But this is what ID looks like. OK. So here's T, and this is ID.

OK. Well, what's ID's average value? Right, if I were to calculate the average value of the diode current ID, that would simply be the average of this pulsed waveform, which is basically 1 minus D times IL. OK. So maybe what I would do is say, OK, let me come up with a model for this converter, that I don't really care about what's going on over here, right.

In terms of figuring out the capacitor voltage ripple, all I care is about what current's coming through the diode and driving this output circuit. OK. So I might model this this way, model this as some ripple current iD, OK, that is then going into my capacitor vC and my load resistor. OK. Any questions about that?

Now, if I design this circuit, I'm interested in the ripple on the capacitor, and what I'm likely to do is put the switching frequency, T is equal to 1 over-- this is equal to 1 over the switching frequency, right. What I'm likely to do is to make this rC such that it filters that ripple current. I've got this pulsating current in, and what I really want is vC to be almost constant, and hence the v2 is almost constant, right. So that means that sort of the AC component of this pulsating waveform, we really want it to go through the capacitor, almost exclusively, and the DC component of this current, 1 minus D IL, is what goes to the output, right.

Well, what do I need to make that happen? What I need is 2 pi f switch ought to be much greater than 1 over RC, right, so that this rC network filters the pulsating component of this current, and so that gets the DC current going this way and the ripple current going this way. OK. Any questions about that?

AUDIENCE: How did you get that, that 1 over RC?

DAVID PERREAULT: OK, so the time constant of this is RC. That means its pole is at s is equal minus 1 over RC. And so I'm putting the switching frequency, the ripple frequency, far beyond that so that this becomes essentially a low-pass filter, so I'm putting it well beyond the cutoff.

OK, so suppose I do that. OK. Maybe what I should be thinking about is, if I can make the approximation that all the ripple current is going to the capacitor and all the DC current's going to the resistor, and I only want to focus on the ripple, why don't I think about, with the ripple current, let me make an AC model for this thing and just subtract off the DC component? OK, I know none of the ripple-- I know none of the DC current's going into the capacitor, right. We sort of know that from the fact of the periodic steady state.

OK. So maybe what I could do is make a new model, that I'm going to call iD tilde, which is exactly just the AC component of this waveform ID. OK. So I'm going to subtract off the DC value and just keep the AC value, and what's that going to be? Well, in the first part of the cycle, it's going to be 0 minus 1 minus D IL, so this will be minus 1 minus D IL, OK, in the first part of the cycle.

In the second part of the cycle, it would be ID minus 1 minus D IL, which would make it D IL, OK, like this. Right, and this is DT. This is T. OK. So this is the AC component of the ripple current coming through the diode.

So here we have iD tilde. OK. And where that's really going, it's all going into the capacitor. Right, that's my approximation.

All the ripple current goes into the capacitor. OK. If I make this approximation, then, I ought to be able to calculate the ripple voltage on the capacitor, vC tilde. Does that make sense?

So what should happen? Well, if I have-- in the first part of the cycle, right, here's vC tilde. OK. In the first part of the cycle, I've got a negative constant current through the capacitor, right, so basically, the capacitor voltage ought to be falling in the first part of the cycle linearly, OK, for DT, and then should be rising in the second part of the cycle for DT.

OK. This is what the ripple current-- this is what the ripple voltage vC tilde is going to look like, all right, under my approximation. All right. Well, what does that mean? Well, it turns out that if I have a triangle wave, its midpoint is halfway between the two extremes. So this, I might call delta vC peak-to-peak, and it turns out, what that means is this will be delta vC peak-to-peak over 2, and this will be delta vC peak-to-peak over 2.

OK. Well, what is this value? And I should have said this is DT and this is T, all right. iC is equal to C dvC dt. Right, delta vC peak-to-peak ought to be equal to 1 over C.

The integral, I could do it from here to here, for example, between DT and T of iC dt, which works out to be what? That's 1 over C. The current is constant at D IL.

And that happens for a time 1 minus D T. All right, so this is delta vC peak-to-peak. Does everybody buy that?

So what can I say, then? The capacitor ripple voltage under these approximations is inversely proportional to the capacitor value, right. So if I were to come up to you and say, you know what, I'm only going to allow a hundred millivolts of ripple in my output, or some value, other value of delta vC peak-to-peak, this equation tells me what that should be, right.

This just says, basically, C has to be greater than or equal to D times 1 minus D IL T over delta vC peak-to-peak. All right. So if you tell me, OK, what's my load current and my switching period and my duty ratio? this tells me, How big does the capacitor have to be in order to reduce the output ripple down to an acceptable value that I set? Any questions on that?

Now, it turns out that I could do the same kind of calculation for the inductor current ripple. All right, and I should say, by the way, that in a typical converter, I usually am not allowing very much capacitor voltage ripple. Right, if I want a DC-to-DC converter, this has to be small, and we'll come into what we mean by, How small is small?

OK. Inductor current ripple, maybe we can allow a bit more, but we can do the same trick to calculate it, right. So if I were to come up here and say, OK, let me go through the same really quick procedure, OK, so here we go. Here's my converter, and what I'm really going to think about now is, What is this voltage?

Suppose I define this voltage vX here, OK, I could come up with a model that looks like this. I have v1 and then an inductor and then a voltage that I'll call-- a pulsating voltage that I'm going to call vX.

And what does vX look like? vX looks like this. In the first part of the cycle, in the first part of the cycle, when the switch is on, vX is 0 until some time DT. In the second part of the cycle, the switch is off and the diode is on, and it's equal to vC which is the same as v2, right.

So here I go. Here's capital VC. OK, so the switch voltage-- I'm sorry, the switch voltage comes up here. OK. And I could then say, OK, this is vX of T in my ripple model, and the average voltage here, which is the same thing as the average value of v1 is 1 minus D times VC, right, is the average voltage of this pulsating waveform. OK.

I could then say, all right, this is what the circuit model looks like. Let me just consider its AC values. Right, let me consider the ripple current only in this thing. So, OK, what happens? What's the ripple in capital V1? It's nothing, right.

Then I have my inductor, and this is L with a current iL. All right. Here's iL. This will be iL tilde, the AC component only.

This thing, I may have a ripple voltage that looks like this. In the first part of the cycle, this is minus 1 minus D VC. And the second part of the cycle, it's VC minus 1 minus D VC, which is D VC.

OK, so this is what vX tilde looks like. OK, and here's vX tilde, my circuit. All right, and of course, v sub L is just minus vX tilde, right. So then I can figure out that, OK, basically, the negative of this voltage is the voltage on the inductor. Right, so v sub L is equal to L di dt. So delta iL peak-to-peak is simply going to be 1 over L the integral from 0 to dt of v sub L dt.

OK. And so what am I expecting? I'm putting vX is negative constant voltage, so that means vL is a positive constant voltage in the first part of the cycle. And I should get an inductor ripple current here that does this, and then in the second part of the cycle, it does this.

So again, the voltage ripple-- I'm sorry, the inductor current ripple iL tilde is going to be triangular. And this amount here Is going to be delta iL peak-to-peak, which I can calculate that as 1 over L-- this is going to be 1 minus D VC, which goes on for a time period DT.

OK. And what I get in the end is that L ought to be greater than or equal to 1 minus D times D times VC T over delta iL peak-to-peak. Right, so if I have a limitation on the allowable ripple current in the inductor, I can calculate, for a given operating condition, how big that inductor needs to be. And the only assumption I made was that I ignored the ripple in v2 when I calculated this. OK. Are there any questions about that?

Now, interesting, I made some approximations, right. When I calculated the capacitor voltage ripple, I ignored the inductor current ripple, and when I calculated the inductor current ripple, I ignored the capacitor voltage ripple. Does it matter that I did that? The answer is no.

Why? Because I pretended that IL was constant at a constant current when I calculated this waveform, right. Well, what does IL look like? IL has some ripple in it and so this triangular ripple falling. The only thing that would have happened had I included that is that I would have had a little ripple here.

OK. And if I included that and then I calculated the voltage characteristic from that, all that would have happened is instead of getting a slope or instead of getting a ripple waveform that looked like a perfect triangle wave like I drew here, all that would have happened is I would have gotten a different version with a slightly different curvature, and the peak to peak ripple would have been exactly the same thing. OK. So I can make these approximations. Ignore the inductor current ripple for calculating the capacitor voltage ripple, and vice versa, and I still get the right answer. And what those have given me is a means to get to, How big a capacitor do I need to get to a certain capacitor voltage ripple, and how big an inductor do I need to get to a certain inductor current ripple? Questions?

So I would say that if I was going to sit down and design a converter, I might start to think about, Hey, how much ripple is tolerable? Right, that's sort of an application thing, right? I'm building this boost converter to power some thing or other, and perhaps the specifications I'm giving you for the system is you're allowed a hundred millivolts of ripple on top of whatever your 50 volts of output is, or something. Somebody's going to tell you you're going to have this much voltage ripple or this much current ripple allowed into the input.

OK. Now, one way to get those is just to make these components bigger. We'll see other ways to reduce those by adding higher-order filters and that kind of thing. But this is a pretty good place to start to get L and C values. OK, and you notice, in either case, what I ended up with is triangular-shaped ripples, OK, because essentially we're assuming that the current's just-- the ripple current's just going into the corresponding passive component, the constant current's going to a passive component, and I get a triangular ripple waveform.

OK. Well, we can actually use that to our advantage. We can kind of say, OK, any such component-- suppose I have some waveform I'm going to call x of t, OK, and maybe it has some DC value X that I'll call capital X. This could be a capacitor voltage or an inductor current. And then maybe it has some triangular ripple on it like this.

OK. And so then I'll have some peak value. I'll call this x peak, and I'll call this x min. OK. And If this is delta x peak-to-peak, it turns out that for triangular ripple-- any triangle wave, like this, the average is exactly halfway between the peaks. That means that this is delta x peak-to-peak over 2 and this is delta x peak-to-peak over 2. All right, that's just a property of triangle waves.

OK. Why am I getting to that? Because we might define the ripple ratio. OK. And I'm going to call this script R sub x, and I'm going to define this to be equal to delta x peak-to-peak divided by 2. That's sort of the middle, the average to the peak, normalized to X, right.

So this is sort of-- you might think of this as being like a percentage ripple or a fraction ripple. OK. Why am I interested in that? I'm interested in that because a hundred millivolts of ripple on top of half a volt is a lot. A hundred millivolts of ripple on top of a hundred volts, maybe it's not so big, right? So we might want to normalize the ripple we consider to the average value of any waveform, inductor current or capacitor voltage.

OK. So people often talk about the ripple ratio of the waveforms, or it's sort of a version of the percentage ripple if you multiply by a hundred. OK. I will say that if you look in the literature, there's a skew in how people define things. Some people define the ripple ratio as being delta x peak-to-peak over X, and some people define it as delta x peak-to-peak over 2 over X. You've just got to be careful of what's being referred to when you read the literature.

I kind of like this definition, A, because it's what used in the text. But one of the nice things about it is you can then say x sub peak is just simply equal to the DC value times 1 plus the ripple ratio of x, all right, and so it's convenient to use this form of the definition of ripple ratio. Any questions about that?

OK, so how might I think about using this kind of definition? Well, I might talk about sort of-- I might talk about the ripple ratio and the capacitor voltage as being delta vC peak-to-peak over 2 divided by VC, and the ripple ratio and the inductor current as being delta iL peak-to-peak over 2 divided by the DC inductor current.

OK. And we can then use the ripple ratio that I'm talking about to relate sort of the average values to actual peak values because we know the ripple is triangular. OK. There's another way we can use this, too. There's a way to start thinking about, as I change the ripple ratio of my converter, How much ripple is allowed in my converter? How big does the converter get?

OK. I've come up with expressions. I need this big an inductor or this big a capacitor if I knew those factors, but it might be nice to be able to express that a little bit better. How does that relate to the size of the component?

That's a very complicated question in general, right, saying, How physically big is my inductor capacitor going to be? That's a hard question to answer because-- and we're going to see that when we start to design the components themselves, but it's reasonable to expect that to first order, the size of your component, the physical size of your component, ought to be related to the amount of energy it stores. Right, if I have to store twice as much energy and I get a certain energy density, if you imagine, of storage, then twice as much energy storage ought to be twice as much size, the first order, right?

So engineers often use energy storage of the components as a very crude stand-in for how physically big the components are going to be, and I want to emphasize that it's a very crude stand-in. It's not true, necessarily, that it's a-- it's exactly proportional relationship or something like that. It's not, but it's at least a rough measure that you can get your hands around.

OK. So let's think about what that might mean. OK. Well, let's think about the energy storage of the capacitor, right. I've got an expression here for the energy storage of the capacitor. OK. So we said that C has to be of this size, OK, and in my boost converter, IL is the same thing as I1, right.

So what I get is, for a boost converter, then, I get C is greater than or equal to D times 1 minus D-- IL is the same thing as capital I1. This is the switching period divided by delta vC peak-to-peak over 2-- I'm sorry, delta vC peak-to-peak. OK. Let me substitute this in. So that means C has got to be greater than or equal to D times 1 minus D I1 T divided by 2 VC, which is also equal to V2, RC, ripple ratio of the capacitor.

OK. So this is the same thing, just expressed in terms of input and output quantities and the ripple ratio on the capacitor. How much percentage ripple am I going to allow in the capacitor? Everybody buy that?

If I then came back and said, OK, how much energy is stored in the capacitor? energy in the capacitor is simply equal to 1/2 C vC peak squared, right. If I've got to go buy a capacitor and I want to know how much energy is stored, I care about the peak voltage I'm going to put on the capacitor because that's what the capacitor is rated for. And I care about the capacitance value I'm using, and that energy is 1/2 C vC squared. Everybody buy that?

So what is that going to be? Well, all that's going to be is vC is equal to 1/2-- C, I'm just going to substitute in this here, so it's going to be D times 1 minus D I1 T over 2 V2 RC. And v peak squared on the capacitor is simply equal to v2 times 1 plus the ripple ratio on the capacitor, quantity squared. All right, this is v peak. It's v2 times 1 plus the ripple ratio.

OK. If I were then to rewrite this, what I would get is D times-- if I look at this, by the way, D times 1 minus D I1 is I2-- right, this is the same thing as I2-- T over 2-- I'm sorry, over 4. 2 times 2 is over 4. And then this is going to be v2 squared divided by V2 is just v2, and then times 1 plus the ripple ratio squared over the ripple ratio.

OK. And I'll rewrite one more thing, V2 times I2 is just the output power, right. So this is going to be D times P out times T divided by 4 times 1 plus the ripple ratio squared over the ripple ratio. All right. I apologize for all the math. This is the energy stored in the capacitor.

OK. So why am I telling you this? This tells me, as a very broad function of ripple and operating power and everything, How much energy do I have to go put in that capacitor which I can use as a crude measure of how big and expensive that capacitor is going to be? OK. So what makes my capacitor requirement bigger?

Its proportion-- the energy storage, which I'm claiming ought to be proportional to size, it's proportional to the output power. That's sort of physically reasonable, right. If I double the power, maybe I need twice as much energy storage to do the same conversion function.

OK. It's proportional to D. Well, keep in mind, the bigger D is, the bigger the voltage conversion ratio is, right, because v2 is v1 over 1 minus D. So the more I'm stepping up voltage, the bigger D I need, so if I want to do a bigger step-up conversion, that means I need more energy storage in my capacitor. Also notice that this function over here is some function of the ripple ratio.

It turns out, for most ranges of ripple ratio which I care about, which are much less than 1, making ripple ratio smaller makes this fraction bigger. So if I tell you I need less ripple, smaller ripple ratio, suddenly my energy storage got bigger. All right. So that says, if I want really nice input and output waveforms, I'm going to need more energy storage.

OK. Lastly, notice that this is the switching period here, or 1 over the switching frequency. The energy storage I need is proportional to the switching period, or 1 over the switching frequency. That means if I switch slowly, I need very big capacitors.

And I showed you this for the capacitor in the lecture notes. I put the equivalent expression for the inductor. Basically, if you just substitute ripple ratio of the inductor for a capacitor, you get the same result.

OK. So what that says is either the inductor or capacitor are going to get bigger and bigger and bigger if I either reduce my switching frequency or reduce the amount of ripple, OK, and that's what gives me a means to start saying, geez, I'd better limit-- if I want to limit this physical size or the cost of this thing, I'm going to have to start making some decisions about how I pick my components. OK. And that just gives you a first-order place to be in terms of picking component values.

And this is only one thing. This is based on ripple. We're also going to talk about based on things like transient performance and that kind of thing, but this gives you at least a place to start for picking component values to get down to certain allowed levels of ripple. Any questions about that?

AUDIENCE: These results are all for the boost converter?

DAVID PERREAULT: These results are for the boost converter. You can derive exactly equivalent results for the buck converter or any other converter you want, and people often do. I will say that if I said, How much EC or EL is required for a boost converter to certain conversion ratio? and I went back and did it for the buck-boost converter that we started with, it would be significantly worse, much more energy storage.

And what that would mean is I'm going to end up with a bigger, more expensive converter,. And what this comes down to is you're competing, right. Like, the other guy's designing something and you're designing something, and yours is smaller and more efficient because you've used less energy storage to do the same conversion function. You know, you could win or lose based on those decisions.

But yes, you can derive similar results, and the typical thing is true. The more conversion transformation you're doing, you tend to require more energy storage. The lower the ripple you need, you require more energy storage. The slower you switch or the higher the power, you require more energy storage.

Any other questions? OK, next time, we'll start thinking a little bit more about conversion ripple and what can happen in extreme cases. Have a great day.