[SQUEAKING]

[RUSTLING]

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DAVID PERREAULT: Moving on to the class material, so last class, we were talking about the AC grid and AC to DC interface. And we'll come back to that kind of topic.

But what I'd like to do today is return to some topics about power converter analysis and, particularly, as related to DC to DC power conversion. Because we're going to see that that underpins a lot of kinds of power conversion, not only DC to DC but DC to AC and AC to DC.

And I'd like to return to the notion of analyzing power converter circuits, particularly, in periodic steady state. And I was subtly using what I'm going to talk about right now in the first couple lectures, but I'm going to return to it. And the real question is, What tools do we use to take an arbitrary power converter and understand what kind of conversion function it can do?

And let's just think about what we do for circuit analysis. Generally, one of the main things we might use is Kirchhoff's current law, which basically says, if I have a bunch of currents-- i1, i2, up to some iN-- coming into a node, the KCL just, basically, says that the summation over the j currents of i sub j has to add up to 0. And that's, basically, conservation of charge, assuming no charge builds up at any node.

Well, I could take this equation and take the average of each side. So let me take the time average of this side of the equation. And doing an average-- 1 over t, the integral over t-- that's, basically, an integral. And I can interchange the order of the integral in the sum. So I could equally write the following-- the summation over j of the average values of i sub j is equal to 0.

So this is average KCL. What it says is-- and it makes sense. If, instantaneously, all the currents add to 0, then the sum of the averages of the currents also have to add to 0. That's sort of-- what would I say, intuitively obvious that that's true? But it's mathematically true.

And you could do the same thing for KVL, adding voltages around the loop, So I could have an average version of KVL which says that the summation of the average voltages around terminals in a loop adds to 0. So we could put these two together as two new analysis techniques that we could do when we're talking about doing circuit analysis, where we're thinking about the averages of currents going into a node or the average voltages around a loop.

And just to remind you what other tools do we have at our disposal, well, we said-- previously, we said, OK, in periodic steady state, we know that if I have a capacitor and I have some current iC, the average value of iC has to be equal to 0 because iC is C dv/dt, and the average dv/dt is 0 in periodic steady state.

Likewise, for an inductor, I have some voltage across the inductor, v sub L. And what I can say is the average of the inductor voltage is equal to 0 in periodic steady state. So those are four things I can use as circuit rules to help me analyze something.

One more thing I might say is, if I have a power converter and I have some input power here and some output power here-- input power is coming in this way, P in, and output power is coming out this way, P out-- if I assume that the efficiency is 100%-- so if there's no loss-- then I need to have P in equals P out where we're talking about the average power flowing in and out. So that's just conservation of energy, which I often use because, even though real power converters aren't lossless, I might make an assumption for a first-order analysis that assumes they are lossless.

So let's go back and think about how we might use that. And let's come back to our really simple first switching regulator example. So we said, OK, maybe I have some voltage v1. And here, I'm going to put a capacitor in parallel with v1 just to illustrate that maybe there's-- some local source of charge is holding this voltage. And I will go have some single-pole double-throw switch like this, an inductor, another capacitor that I'll call c2 here, and a resistor. And I'll call this v2.

In principle, I don't need capacitor c1 if I have a perfect voltage source here. But I'll draw it in because we often, for filtering purposes, practically put a capacitor there, too. And we said, we can define operation of this circuit by the switch state here.

So maybe when the switch is in the up position, I'll say my switching function q of t is equal to 1. And when the switch is in the down position, I'll say my switching function q of t is equal to 0. And we'll see later that that's useful to mathematically model things. So this is, basically, the notion of this converter we were considering last time.

In practice, how do we build this thing What I would really do is I would come back and say, OK, we'll have some voltage v1, c1. And I will have two switches like this. And I'll operate these two switches in a complementary fashion. And that serves the same function as the single-pole double-throw switch. So this switch closes when q of t is equal to 1. And this switch closes when q of t is equal to 0.

Now, what would we look at in this system? Well, we can consider the voltage here that I'll call vx. Or here, it's vx. I also have vL and a current iL.

And how are we going to analyze this thing? Well, let's consider periodic steady-state operation. So what I'm going to do is I'm going to switch the switches like so. Here's q of t. When the top switch is on, it's on. And I'll do that for time DT. And then I'll hold the top switch off for a time 1 minus DT and operate like this-- T plus DT and so forth.

So I've got my periodic switching with some period T. So what happens in this circuit? If I were to look at this voltage vx, when I've closed this switch, vx is equal to v1. When I open this switch and close this switch, vx is equal to 0. So vx here looks just like q of t, except that it's scaled by v1 and so forth. And this is value v1. This is DT. This is T.

So how would I go about analyzing this circuit? Well, I can write KVL for this circuit. And maybe what I'll do is I'll think about average KVL. So I could write, for example, vx minus vL minus v2 is equal to 0. And could take the average of this, which would give me the average value of vx minus the average value of vL minus the average value of v2 is equal to 0.

If I think about that, though, the average value of vL is 0 in periodic steady state. So if I look at this equation, this equation is just average KVL. I'm taking the average voltage around a loop.

So I'm using what's on the board behind the top board here. And then I'm saying the average value across the inductor is 0. And that gives me that the average value of v2 is equal to the average value of vx. And we might write the average value of v2 of t is just capital V2.

Well, what is the average value of vx? It's this average value. And it's v1 for DT of the time and 0 for 1 minus DT of the time. So that's just going to be equal to D times V1. And this is the same result that we got when we analyzed the circuit before.

The only thing that's any different is I've explicitly used average KVL, and I've explicitly used the fact that the average voltage across the inductor is 0. And I'm showing it to you in this very basic circuit because it gets a little trickier in much more complicated circuits. So are there any questions about this result?

What that means is, then, my output voltage in this circuit, if I'm switching these functions with some period and some duty ratio, v2 will settle to DV1. D is a duty ratio that's between 0 and 1. So I can control v2 to be anything less than v1. And as we said before, ideally, everything's lossless.

So let's think about a different aspect of this circuit, just to illustrate these analysis techniques. Let's take a look at, for example, this current. I'm going to call this current i sub y. So it's the current through this switch.

And the thing I'm going to do is let me assume-- and we often do this when we're analyzing DC to DC converters, PWM DC [INAUDIBLE] converters. Let me assume that my inductors and my capacitors are really big.

Well, what do I mean by really big? If you let it go to infinity, then it's really big. But what I'm really saying is let me assume that iL of t is approximately equal to its DC value. And v1 of t is approximately equal to the DC input. And v2 of t is approximately equal to V2.

So I'm basically assuming that the capacitors are so big that there's no voltage ripple on them, and the inductor is so big that its current ripple is 0. Any questions about that?

So what does that mean? What would iy look like? Well, let's plot it. When q of t is 1, this switch is closed, so iy ought to exactly equal iL. So here's iy. It's going to be equal to IL when the switch is on. And then, when the switch is off, obviously, iy goes to 0. So I have this pulsating waveform here.

Now, what's the value of iy? I'm sorry. What's the value of iL here? Well, I could call this current i2. And I'm assuming, since this capacitor voltage is really, really big, I can assume the capacitor is really, really big. This capacitor ripple voltage is really small, so the ripple current through the resistor is really small. So this is approximately equal to I2.

And what do I know about-- let me call this capacitor c2, and let me call this current ic2. What do I know about the average value of ic2?

AUDIENCE: 0

DAVID PERREAULT: 0. So that means that the average value of current I2 must equal the average value of current iL. Or, put another way, iL also has to equal I2. There's no average current coming down here. So whatever the average is going through the inductor just can go to the resistor. Does that make sense to everybody?

So what can I say about the average value of i sub y? Well, the average value of i sub y is whatever the average value of this waveform is. And I'll call that capital Iy.

And that's going to be the average value of this PWM waveform. Well, it's I2 for a fraction D of the time and 0 for 1 minus D of the time. So this must exactly be equal to D I2, which is the same thing as DIL. Any questions about that?

OK. So now I know the average current coming this way. What's the average current going through this capacitor in periodic steady state?

AUDIENCE: 0.

DAVID PERREAULT: 0. So if I introduced this as my node, there's no average current coming here. So that must mean if this is current i1, the average of i1 must equal the average of iy. Because no average current through the capacitor. So then I could say that, OK, this also, by average case cL, also has to be equal to I1. So what I can say then is that I1 is equal to D times I2.

So what I've really figured out is the current conversion ratio. I could have written I2, the output current, the average output current, is equal to 1 over D times the average input current. So I have this as a result, which I got by basically looking at averages of currents and knowing that the currents through the capacitors were 0.

There's another way I could have gotten to that. I said that V1 is equal to what? Or V2 is equal to what? V2 is equal to DV1. So I could have said V2 is equal to DV1.

So if I multiplied each side by-- so suppose I multiplied this side by I2, I could have the output power, P out, is equal to V2 times I2. Well, if I substitute this in, V2 is equal to DV1. And I2 is equal to 1 over D times I1. So that has to be, if these two cancel, has to be equal to V1I1.

So another way I could have gotten at this result is, by knowing the voltage conversion ratio and the fact that power is conserved, I could have gotten to this current conversion ratio. Or the current conversion ratio is the exact inverse of the voltage conversion ratio because there's no power loss in the converter.

So these tools that we have-- average KVL, average KCL, conservation of energy, periodic steady-state relations-- can let me go through a given power converter and figure out the relationships between the DC input and the DC output quantities in periodic steady state. And we'll often do that as a first step when we're looking at some power converter in order to know, What is it doing? What can it do?

In this case, this converter can step down voltage. This converter can create a v2 that's smaller than v1. But it couldn't, for example, create a voltage that was bigger than v1 because the average analysis tells me so. Any questions about that?

One thing I should say about doing this kind of analysis-- because I'm doing the world's simplest case here. And you'll need to use these techniques on all kinds of converters. The thing that often messes people up, the thing that will make you make a mistake and get the wrong answer in your analysis, the number-one thing, is the following-- these statements are all about average currents and voltages. Do not mistake the average for the instantaneous.

So, in other words, I can say that the average value of iy, which is equal to the average value of I1, which we calculated over here, is D times I2. But that's true of the average value. But here's iy. It's almost never equal to its average value, except at these instantaneous points.

So if you take and say, oh, I know the average value, but then you substitute it for the instantaneous value, you're going to get strange results. So just keep in mind, separate out in your mind, when you're talking about averages and when you're talking about instantaneous waveforms. And the waveforms in the circuit that, obviously, the average is equal to the instantaneous is if you have an inductor current or capacitor voltage, and the ripple is small.

What would I do-- how would I implement this converter? And we're going to talk a lot about switch implementation. What I might typically do in this kind of design is the following.

I might get a MOSFET for a switch, a power MOSFET for a switch, and make my other switch a diode. And then I can turn on this switch by controlling its gate voltage. So I can modulate this switch on and off. And when I turn this switch off, the diode will carry the positive inductor current, and I can convert energy.

And this is a converter that will let me clearly take energy from this side and put it to this side. I've got a resistor over here. And this, by the way, is known as a buck converter, if I haven't mentioned that, because it bucks the input voltage down, or it steps the input voltage down.

Let's talk about what else I could do as another example of using these tools. Suppose I was to take this kind of converter. And let's forget about the switch implementation for a moment. But suppose I was to come over here and say, OK, I have a source over here and a load over here. What happens if I just switch those two things? I'll switch the two ports. I'll switch where the source is and where the load is.

So let's draw that case. And I'll keep making the-- I'll make the left side v2 and the right side v1. So here we go. Here's c2. I put my resistor over here now-- v2. And I'll go back to my single-pole double-throw switch notation, like this, just for simplicity. Here's c1 one. And here's v1.

And I'm going to make the same kind of assumption. Let me assume that the inductor is really big, the capacitors are really big, and the ripple current in the inductor and the ripple capacitor voltage are both small. The capacitor voltage ripple is small.

I will, again, redefine this voltage vx here. But maybe just for fun, I'll redefine my switching function. You could have done it either way. In this case, I'm going to say q of t is equal to 1 when the switch is in the down position. And q of t is equal to 0 when the switch is in the up position.

Now, why am I choosing to define that way? I could do it either way I wanted. It doesn't matter. I happened to define it this way because in the kind of converter we're doing, that's the way you usually define it.

So let's think about what happens here. I'm going to do the same thing I did before. So here's q of t. It's going to be 1 for some fraction of the time DT and 0 for the remainder of the cycle T and so forth.

What's going to happen to vx in this case? vx is going to do the following. When the switch is in the one position, vx is 0. When q of t is 0 and the switch is in the up position, vx is V2. So it's going to switch oppositely this time. And this is V2.

And again, I'm assuming c2 is really big so that V2 has no ripple, and I can write it as a capital letter-- that is, as a DC quantity. So what can I say here? What do I know about the average voltage vx?

AUDIENCE: It's v1.

DAVID PERREAULT: It has to be v1. Why? Let me define-- this time, I'll define the inductor voltage this way. Here's v sub L. So if I have v1 minus v sub L minus v sub x is 0, the average value, capital V1, minus the average value of vL minus the average value of vx is 0. The average value of vL is 0. So hence, v1 must equal vx, on average.

So that means that if I was to plot the-- I'm sorry, this is vx-- if I was to find the average value of vx, the average value of vx is equal to-- if this is DT and this is T, it must be equal to 1 minus D V2. And it's exactly what's said. This also ends up having to equal-- the average value of vx, which we know is 1 minus D V2 also has to be equal to v1.

Or I could rewrite this as V2 is equal to V1 over 1 minus D. And remember, D is some duty ratio. It's a fraction of time. So I have 0 is less than D is less than 1. Does that make sense to everybody?

So what does this converter do? Well, that means that if 0 is less than D is less than 1, that means that if D was equal to 0, V2 would be in V1. And as I make D bigger and bigger and bigger, this denominator gets smaller and smaller and smaller. And V2 gets bigger, bigger and bigger and bigger.

So what I get is v1 is less than v2 is less than infinity. What this says is this version of the circuit, I can make v2 anything bigger than v1 that I want in periodic steady state.

That's kind of interesting. This is no longer-- before, I picture this circuit over here as something where I synthesize an average value, and I just filter it. That's not quite what's happening over here. Or maybe it's not as simple to think about it that way. But I can get this conversion result.

I could also figure out what it's doing about the currents. So if I said, OK, I have i1 over here. And, on average, this would be i1 approximately equal to capital I1. And I have i2 over here capital I2, what should I have?

Well, I think what I'm going to end up with, it has to be that I2 ought to equal I1 times 1 minus D. Because that means that V2 times I2 ought to equal V1 times I1. So I can infer this current conversion ratio.

So the output voltage, V2, has to be bigger than the input voltage. And the output current, I2, has to be smaller than the input current to get 100% efficiency. Any questions about that?

What makes this work? Well, I'm going to make an assumption here. And I've kind of been assuming this, that v1 is greater than 0, and v2 is greater than 0, and so forth. If we looked at building this converter just the way I looked at implementing this other converter, the way you would typically implement this thing is like this. You would perhaps come and say, OK, here is v2.

And what I would usually do is I'd build my switch pair like this. I'd make the bottom switch a MOSFET and the top switch a diode. And I put v1 over here. And basically, the reason I made the switching function q of t that way is because this switch is now the, quote unquote, "active" switch, or in the simplest implementation, this is the active switch.

And I switch these two switches, so when the switch turns on, the diode turns off, and vice versa. And v2 will grow to be bigger than v1. So if I need a big voltage, that's the way-- or I have a small battery, and I need a much higher voltage to run my stuff, this is a great converter to do it. For that reason, it's called a boost converter because it can take a small input voltage and boost it to a bigger output voltage.

In this case, my source is on the right, and my load resistor is on the left. So you can infer that power is going to flow from right to left. Very often, people like to draw these things with power flowing left to right, maybe because that's the way people read or I don't know.

There's nothing fundamental about it. You can do it any way you want. But it might look a little bit more familiar to some people if you drew it the other way, like this. And we have a boost converter.

Let's think about what this converter is really doing. How is this thing working, really? What's going on with its operation? We can look at it from a couple of perspectives.

One way to look at it is this. I'm showing you the voltage vx here. Why don't I look at the current iL. And I'm going to draw the current iL this way in this example.

So when the switch is in the down position, what happens? v1 is, basically, applied across the inductor. So if v1's is applied across the inductor, what happens to the inductor current? We've said the ripple is small, but let's just now not think this inductor's infinitely big. What's going to happen to the inductor current during that time?

Well, if I'm applying a positive voltage across the inductor, I gotta have a constant di/dt. So in that first part of the cycle, if I were to plot i sub L-- and this is, I should say i sub L of t. I'm looking at its ripple now. I'm including its ripple. In the first part of the cycle, when the switch is in the down position, I'm applying a voltage across the inductor. The inductor current is ramping up.

What does that mean? I'm storing energy in the inductor. I'm taking energy out of the input. I have a positive current coming out of the input. And it's basically going into this inductor. So power is being drawn from v1. I'm charging up the inductor. I had 1/2 Li small squared here. Now I have 1/2 Li slightly bigger squared here. So I put energy into this inductor.

What happens in the second half of the cycle? In the second half of the cycle, I reconnect the other end of the inductor to the v2. Now, is v2 bigger or smaller than v1? Bigger, right? Because we said this is a boost converter. It makes a big v2.

That means, in the second part of the cycle, when I have the switch in the up position, the voltage across the inductor ought to be negative. And so that means I ought to have a negative constant voltage across the inductor, and the current ought to ramp down.

So in the second part of the cycle, the current's going to ramp down like this. And so what does that mean? If the current in the inductor is decreasing, is energy going into the inductor or out of the inductor?

AUDIENCE: Out.

DAVID PERREAULT: Energy is coming out of the inductor. So that's true. So we're taking it-- in the first part of the cycle, we put energy into the inductor. The second part of the cycle, we're taking energy out of the inductor. Well, where is that energy going? Well, it's got to be going to the output. I have current flowing this way into the output.

The other thing that's true is, even in the second part of the cycle, there's still current coming from the input through the inductor to the output. So I also have power flowing from the input to the output. So in the first half of the cycle, I'm taking energy out of the input and putting it in the inductor. In the second part of the cycle, I'm taking energy out of the inductor, plus more energy out of the input, and putting it to the output.

And it just works out that when I do this periodic steady-state analysis thing, what this thing has to do when it settles down such that the end of the cycle is just like the beginning of the cycle and the next cycle looks exactly the same-- does the same thing-- that the output voltage has to be bigger than the input voltage.

Now, I don't know about you, but when I first saw that, I thought it was kind of cool. It's very easy to make a voltage divider. This is kind of like a voltage undivider. It makes bigger voltages.

Well, let's take a look at this in practice. Montsy set us up a nice demo of an actual boost converter. And we'll get to see--

[HUMS]

--a converter running. By the way, this particular converter was designed by an undergraduate at MIT who is now a famous power electronics designer, as well as a high school student, so pretty early design for the high school student. So let's see if we can get waveforms up here.

So what do we see on the screen up here? My orange, which is the inductor current, is actually the deep blue waveform on the right. The yellow is exactly what you're seeing. It's the voltage across the bottom switch. And the input voltage is the light blue. And the output voltage is the purple.

So what you can see is that we are-- and we don't have all the waveforms quite lined up here in terms of the magnitudes and where the voltages are. But we can do that. All right.

But the point is, in the first part of the cycle, I grab energy from the input, and I put it in the inductor. Inductor current ramps up. Second part of the cycle, that energy, and more energy from the input's, being thrown to the output. And I rinse and repeat that.

And the thing that lets me get the voltage higher at the output than the input, outside of the fact that the math says so, is that when I turn the bottom switch off, when I turn the switch from here to here, or if I turn the bottom switch off, this inductor current doesn't want to go to 0. And v is equal to L di/dt. The inductor will generate whatever voltage it has to to keep the current flowing. And so what it does is it generates enough voltage to deliver energy to the top of the device.

I could-- let's see, do I have-- if I looked at this waveform, if I turn this switch off and I have a positive current going this way, even if the diode's off, this inductor is going to generate a big negative voltage to try to keep current flowing. And it's going to generate voltage until it turns this diode on.

So current can then keep flowing from this lower input voltage to the higher output voltage via this negative voltage across the inductor. So this ability of the inductor to force current flow is what lets me generate the output voltage that's higher than the input voltage. Yeah?

AUDIENCE: When you first turn on the [INAUDIBLE] why does the current ramp linearly when you touch it?

DAVID PERREAULT: Ah. Because if I have this bottom switch on-- that's an excellent question. Why does the current ramp up linearly in the inductor? If this switch is on, I've imposed 0 voltage here.

I've got v1 across the inductor. So I got v is equal to L di/dt. That means that di/dt is equal to 1 over L times v, which, in this case, is v1. So the slope of that current is simply the input voltage divided by the inductance.

If the inductance is big, that slope is small, but I'm nonetheless putting energy in the inductor. Yeah?

AUDIENCE: I have a follow-up question. How do the slopes know to change with the duty cycle? It seems like magic that it stays in the periodic steady state.

DAVID PERREAULT: First of all, not all converters that you could conceive of will reach steady state. And this kind of average analysis we're doing is one of the things you use to do that. So I've seen converters where people had some conversion idea, but it turns out that, no matter what you do in the converter, it has a positive average voltage across the inductor, which means the inductor current ramps up until something blows up.

What happens, in this case, is suppose the output voltage was too small. Well, in that case, then, the inductor current would ramp up with v1 over L slope. It would ramp down but not with as great a slope, and the inductor current would keep increasing. And it would start to pump more and more charge to the output until the output voltage comes up.

So what happens is there's a feedback loop that's driving the inductor current to keep increasing. And that drives the output voltage up further, for a given resistance, until you hit some equilibrium. And that equilibrium is the output voltage is now big enough that the negative volt seconds on the inductor is the same as the positive volt seconds.

So will all converters that you could think of, all combinations of switches, inductors, and capacitors do this? No. Some will just blow up on you. Others will come to a nice, happy periodic steady-state operation. And that's usually the kind of converters we aim for. Excellent question. Other questions?

AUDIENCE: Theoretically, does the frequency at which you switch make a difference if your duty cycle's the same.

DAVID PERREAULT: That's an excellent question. The question is, does the frequency make a difference as long as you're doing the right duty cycle? And the answer is, on the one hand, no. Nothing about this said what the period capital T is in this mode of operation.

What does change is, however, this ripple. So if I made T bigger, I'd get more current ripple. And I started off the analysis saying, oh, I'm going to assume all my ripples are small. Well, how big L has to be in order for my ripple to be, quote unquote, "small" depends upon the period.

So we'll talk a lot about, how do I pick my period, how do I pick my inductors, all those things. So it matters in the practical sense but, if I had big enough components, not in the theoretical sense. Any other questions?

Let me just note a couple of other things. And what I'm about to tell you is completely unimportant from a practical perspective. But it's an interesting thing to observe. Let me come back to this buck converter here. This is a stepping down converter.

If I asked, What is the actual thing that this switch is doing-- this has some v switch and i switch-- it turns out that if you go analyze this-- and I put it in the lecture notes, even though I'm not going to go through it in detail-- if you turn around and ask, What is this switch physically doing, it's absorbing power in DC and voltage and current components on the switch. So the current through the switch has a DC term and a bunch of AC terms. And so does the voltage.

It turns out if I look to the DC voltage times the DC current, the switch is absorbing power from the DC waveforms. And it's generating AC waveforms and the AC components of those waveforms. So in some sense, this switch, what it's really doing is it's taking power in DC waveforms and turning it into power to AC waveforms.

If I ask what this switch was doing down here, this guy down here, he's actually doing the opposite. So I can think of this as, quote unquote, an "inverting switch." It takes DC and turns it into-- power in DC waveforms and turns it into power in AC waveforms.

And this switch does the exact opposite and turns it back into DC waveforms. And between the two of them, they give you the voltage conversion. So the switch in our power converter could also be thought of as a funny kind of "change where the energy is in the waveforms it's processing" kind of device.

Now, that's not necessarily important or helpful for analyzing power converters, but it's just an interesting fact to understand the function of what the switch is doing. It's moving energy around in frequency without losing any of it.

The last thing I'll note is just that we can view-- and, again, you don't have to view things this way-- but we might view both the buck converter and the boost converter as two connections of one structure. All I did was, really, flip it around.

But I could block this off and just think of this structure from here, here, and here-- I'm sorry, here, here, and here-- as being this cell that has one capacitor, one inductor, and one single-pole double-throw switch. And that's also buried into this circuit-- one inductor, one capacitor, and one single-pole double-throw switch.

And the only reason I mention that is because you can build other kinds of converters that have different connections to this that will give you different power converter functions. And we will introduce one of those next class.

So what I wanted you to take away from this class was, first of all, what are the kind of techniques that we can use to analyze power converters. There's average voltage, average current, average KVL, average KCL, inductor and capacitor constraints.

And we can use that to say, How does power flow through the converters? And I wanted to start talking about some of the functions we can do. So we've seen now a buck converter and a boost converter. And next time, we'll move on and look at some other approaches. Have a great day.