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DAVID PERREAULT: So today, I wanted to continue our discussion of resonant power converters, which are power converters, either inverters or rectifiers or DC converters, where the power is modulated through high-frequency sinusoidal wave forms. And this is again, KPVS chapter 10.

And last time, we looked at the characteristics of an example resonant network, in particular, a series resonant network, where we said, OK, if we had some network that we were going to drive with a sinusoid VS cosine of omega t.

And maybe this would be a series resonant network. So I'd have IL, VC and R, where we are going to deliver energy from this source into the resistor. And we said we could look at the admittance, looking into the network.

And we said, that looks something like this. If I plotted the magnitude of the admittance on a log scale versus frequency on a log scale, we said, OK, at low frequencies, the impedance is dominated by the-- the admittance is dominated by the capacitor. So we get omega C.

At high frequencies, it's dominated by the inductor. So I get 1 over omega L. And at some frequency, the inductance and capacitive impedances cancel each other. And that's at omega 0 is equal to 1 over the square root of LC. And that asymptote happens at 1 over Z0, which is equal to the square root of C/L.

And right where these impedances cancel, the admittance goes to being 1/R. So maybe it looks like something like this. I have 1/R, where it peaks up to. So maybe my admittance characteristic looks something like this. It rises. I'll have some region about which it peaks up. And then it falls.

And we said, OK, we have-- if we have a high Q network, a high-quality factor network, which we said, the quality factor Q of the network evaluated at omega equals omega 0, which we might call Q0, is equal to Z0 over R, or the square root of L/C over R.

And we said that was exactly the amount by which this admittance characteristic peaks up above the intersection point of the low- and high-frequency asymptotes. So it peaks up by an amount. Q0 is equal to the square root of L/C over R.

And then the other thing we said was, how broad band is that peaking? And if we took the half power point, the point-- the bandwidth over which we deliver half the power to the resistor as we would at exactly at resonance where the inductance and capacitance of impedances cancel each other, then we said, OK, that bandwidth, if I took the bandwidth divided by omega 0, the center frequency-- so the percent bandwidth is exactly equal to 1 over Q0, which is R over the square root of L/C.

Now, this was all done for the series network. But we have these nice relationships which tell us how frequency selective this network is. So that's just a quick review of what we talked about last time.

How are we going to use this in a power converter? Especially, if it's a high Q network, this high sensitivity to frequency means that by modulating the frequency of some drive wave form, I can very easily modulate the power going into the resistor. So using frequency modulation isn't always the way you operate a resonant converter. But it's a very common way to operate a resonant converter.

So if we were to think about making an inverter, then by controlling frequency either above or below resonance, we can turn down the power. And when we're right at resonance, VS appears across the resistor. So that's the maximum voltage I can generate in the resistor because that's where the inductor and capacitive impedances are canceling. And at any other frequency, I'm going to have either a net effective inductive reactance or capacitive reactance in series. So I get a voltage divider. My admittance goes down, and I deliver less power. Any questions about that?

So let's think about a basic design. Here's what we might do. How am I going to get this drive? Well, it doesn't have to be a sinusoidal drive, in part because this network is very, very frequency selective. So I could drive with some other voltage wave form and extract out the fundamental component going to the resistor.

So maybe what I would do-- and this could either be called a half bridge inverter, resonant inverter, series resonant inverter. Somebody in the RF field might call it a class D power amplifier. That's another term that gets used. But it could look like this.

Maybe I'll have some voltage VDC, a pair of switches. And let's assume they're MOSFETs for a second. So internally, they have these body diodes that I'll just draw for fun here. And we can say, OK, I have L. And I have some current I sub L. I have V sub C, which is going to block any DC component. And then I have my output voltage, V sub R, which I'm-- to which I'm going to deliver energy.

And I might call this voltage here V sub X. So what is V sub X going to look like? If I just operate these two switches at 50% duty ratio, maybe V sub X looks something like this. It modulates between VDC and 0.

At some switching frequency, that maybe varies. So this may be 2 pi over f switch. And this is in time. And this is pi over fS. So I'm going to run this, for example, at 50% duty ratio.

So if I did that and I looked-- thought about-- this is my wave form VX-- what's important about VX in here? Well, I'm going to run this. I'm going to apply this to this very frequency-selective network. And let me assume that I'm going to be somewhere near resonance such that the current is going to be the voltage times the admittance here.

So if I thought about this, maybe I would say, well, what does VX look like in frequency? In the frequency domain, I could think of VX of j omega, which would look like what?

Well, I would have a DC term, which is basically related to the average value of the wave form. And then I would have-- at 2 pi fS, I would have some frequency content. And at minus 2 pi over fS, I'd have the same frequency content.

And then there's no second harmonic, because this is half-wave symmetric, or at least the AC component's half-wave symmetric. And so then the next thing would be the third harmonic out here. And if I think about this, and if you wanted to use the exponential series, the height of this is 2 pi times VDC over pi. And here would be 2 pi VDC over 3 pi.

So the third harmonic is one third of the fundamental. And it falls off as 1/n with n-odd harmonics. But what's important about this wave form is if I believe that this network is going to be doing a good job of filtering this square wave, in terms of what's important for driving current in this network, as long as this looks like a high impedance or a low admittance-- I'm looking in here. This is Y in.

As long as the admittance low with 0 at DC, because of the capacitor-- so I don't really care about the DC component-- and as long as this looks like a high impedance or a low admittance at the third harmonic, the only element I really care about is the fundamental. So I could then just say, let me just think about the fundamental component driving the network.

And so maybe I would mentally approximate this as the following. I call this VX1, the fundamental component, which would be VX1 of t would be equal to 2 over pi VDC. In this case, I've drawn it as a sine. So I guess it would be sine omega t, if I only thought about the fundamental component.

Or I could model it exactly as VX over here and think about the square wave component. And then I run this into my network. And if I look at this then, what am I going to get? I'm going to get a current.

Let me call this IL, which is also the resistor current. IL of j omega S is simply going is simply going to be equal to VX of j omega S times Y in of j omega S.

In fact, if I'm going to do it, let me just be careful. If I'm just going to do this in the Laplace domain and not worry about specific frequency content, maybe I would just say this is going to be IL of S is VX of S times Y in of S. And then I can evaluate that in the frequency domain on S equals j omega.

But here's the point. If everything gets filtered except for the fundamental, then I would expect IL of t will be only a sinusoid at the fundamental switching frequency. So that's what we call the fundamental harmonic approximation.

What I'm assuming is this resonant tank is sufficiently frequency selective that I can ignore all the nonfundamental components. I can ignore DC perfectly, because there's no DC component. But whatever third harmonic shows up, I just assume the admittance down to the third harmonic is really low.

For example, if my fundamental were here, maybe my second harmonic is here. My third harmonic is way down here. You started off at a third of the height. And then it's got this much bigger attenuation. Maybe I just ignore the higher harmonic content of the current and just pretend this perfect sinusoid. Any questions about that?

AUDIENCE: You're saying we can make this approximation because we're close to that resonant frequency?

DAVID PERREAULT: That's right. And there are times when that approximation breaks down. And we'll talk about that. But to first order, for basic analysis of resonant converters, we often make the assumption that at least as far as the current I'm going to get is concerned, I can just focus on the fundamental and just think of that current as being a sine wave with a magnitude that's determined by the magnitude of the voltage I'm driving with times whatever the amplitude is here, in terms of the admittance. Any questions about that?

And then, of course, the power is then I squared R. So we get a lot of attenuation. We get a very steep characteristic of that very frequency. All right. So we get an approximate sinusoid.

So I could say-- I could write then here that the component at the fundamental-- I have IL of t here. But I could relate that back and forth with IL of j omega S, which is equal to VX1, the amplitude of the fundamental, times Y in of j omega S. And it's the fact that this-- the admittance is so frequency selective that lets me modulate power.

All right. Let's think about how we could do that. We could modulate power, actually, by going in either direction off of resonance. I would get maximum-- according to this, if I put my switching frequency right here, I'd get maximum power for a given voltage. If I go in either direction, the admittance goes down, and I get less power. And the maximum voltage I can apply with this particular network is the voltage across the resistor is equal to the input voltage, or the-- I should say, the fundamental of the input voltage.

All right. Well, what would I choose to do? Very often, what we're going to do is we're going to run this above resonance, at least for modern devices. And when I talk about resonant converters, they don't have to be soft switched. But frequently, you choose this kind of approach because you can make it soft switched.

And if we operate above resonance, is the input admittance look inductive or capacitive? Or the input impedance, does it look inductive or capacitive? It looks inductive.

As I go to higher and higher frequency, the magnitude of the impedance of the inductor keeps getting bigger. And the capacitor keeps getting smaller. So it starts to look inductive once I get above resonance.

What that means is that relative to the phase of the voltage, the phase of the current is going to be phase shifted with a lagging current. So let's just think about what this would look like. Here's my half bridge again.

And again, I'm going to-- let me just draw in the body diode of these FETs just for clarity. And I'm going to draw-- and here's L, C, and R. And when I'm talking about I sub L, I can think of the same thing as being the same as I sub R. And here is the voltage that I'm synthesizing. I'll call this V sub X. So V sub X looks like this.

Just let me do this. V sub X looks like this, where I'm controlling this switching period. That should be-- supposed to be 50% duty ratio. So here's 2 pi over fS. And this is t.

So if I'm above resonance, so if 2 pi fS is greater than omega 0, what I expect is this net admittance to look inductive, which means that I sub L should lag the fundamental of this voltage. Well, what does the fundamental of this voltage look like?

This is VDC. So this is V sub X. And-- of t. What his fundamental looks like is something like this. V sub X1 is in phase with V sub X. And it looks like this.

So the fundamental of V sub X has an amplitude. If the amplitude of-- if the peak value of VX is VDC, this value is going to be 2 over pi times VDC. It's just a square wave. That's what you get for a square wave.

And what I've said is that the inductor current should lag the fundamental of the voltage. So this is VX1. The fundamentals should lag. So what I should see then is a current that does something like this.

So here is IL of t for under this condition. Any questions about that? Now, why am I interested in this case? Because let's think about the switching transitions on this inverter. Let's think about what's happening here.

If I call this S1 and this S2, in this time period, S1 is on. And in this time period, S2 is on. Make sense, everybody? Let's focus in right on this switching transition right here, right when I'm going to go from S1 to S2. And let me zoom in on that. So here I am. I have S1 on.

At some point, I'm going to turn S1 off. And I'm going to initiate-- I'm going to turn S1 off. And then I'm going to turn S2 on. But I need some dead time between them, because otherwise, I could accidentally short out my DC bus.

And in that time period, what is the sign of the current IL? It's greater than 0. So if I were to think about this switching transition-- and let me just think about this particular time. What I'm going to do at that particular time-- here's VDC.

If I were to think about this, what I'm doing is at that time, I'm opening this switch. And then this switch is already open. But there's a diode here. And then there's an output current that's IL that's greater than 0.

Now, the thing I haven't drawn in this picture is the fact that these devices actually have some capacitance. And I could go add additional capacitance. So that's either the device capacitance itself or maybe I'm adding external capacitance.

Now, if I put capacitors across the device, what kind of switching do you think I'm going to get? Zero-voltage switching or zero current switching? Zero-voltage switching, right? So because when I turn this switch off, when I pop the switch off, when I go to turn the switch off, there's a capacitor here. And there's a capacitor here, which are going to keep the voltage across the turning off switch low while he's turning off.

So I can turn off the top switch at very low loss. What's going to happen during this time period? So imagine I turn this switch off, and this switch is off. So now I have neither switch is on. Well, I have a positive current here. The total voltage VDC across these two capacitors is going to be constant. And if these two capacitors are equal, that means actually the current has to split between this capacitor and this capacitor.

And so that means the voltage on the top capacitor is going to charge up. And the voltage across the bottom capacitor is going to charge down. So then if I were to look at this voltage, I'm going to zoom in right at this time period, when I have both S1 and S2 off. What I'm going to see is a transition that's going to do something like this.

And then when this voltage hits 0-- and this is voltage VX-- when this voltage hits 0, the diode has got to turn on. So if this was S1 on, even if I don't turn-- even if I don't turn this bottom switch on yet, when this hits 0, I'm going to get S2/D2 is on. The diode will turn on naturally. And then I can turn on the switch with 0 voltage.

So if I were to zoom in on this switching transition, if I put some capacitance here and I put some dead time between S1 and S2, I can turn off this switch at 0 voltage. And I can turn on this switch at 0 voltage because the diode will catch it. Does that make sense to everybody?

Now, here's the cool thing about a resonant converter. What's the other transition-- or in a series resonant converter-- what's the other transition? I want to go from bottom to top. When I want to go from bottom to top, the inductor current is now negative. That means the inductor current's coming this way. When I turn off the bottom switch, this capacitor will charge. This capacitor will discharge until the top diode turns on. And I'll reverse the process. And I'll also switch the bottom device with 0 voltage turn off. And the top device with 0 voltage turn on. Does that make sense, everybody?

So it's a long way of saying, because I have this sinusoidal current, approximately sinusoidal current, the current-- and I've made it inductive. I phase delayed it with respect to where the voltage is. I get naturally the opportunity to do zero-voltage switching.

So in most modern series resonant converters, because we're interested in zero-voltage switching, we will operate them up in this range, above resonance by some degree, and modulate power over this range, by going down the curve this way.

Now, it turns out, if I wanted to go the other way, I could actually do zero-current switching. If I wanted to operate below resonance, I could do zero-current switching. But we're often interested in getting zero-voltage switching because I can get rid of losses associated with the device capacitor switching. Questions about that?

All right. So we can get zero-voltage switching. And by doing that, we can go at pretty high frequencies. And then we can use frequency modulation, frequency control to control the power into our load. Now, what is our load? Well, I haven't said what this load is. This load could be any number of things. It could be, for example, the equivalent resistance of an induction-heating load, for example.

And thereby, by modulating frequency, I modulate power. And that's how an induction heater can work. And I can run at high frequencies because of that.

Now, what's nice about this series resonant inverter circuit? Well, the first thing I said is we get zero-voltage switching for our devices, which is really helpful for efficiency. Notice also that if I modulate power, how do I-- let's assume R is fixed for the moment. It's a fixed resistor.

Let's assume I modulate the power by modulating the frequency. I get lower power by making this resistor current lower. But that also means that the device currents and the inductor current and the capacitor current also got lower. So this kind of characteristic has the nice habit that-- has the nice habit that as I'm reducing power, all my currents in my devices and components all go down with-- as I reduce power. So I can keep efficiency high as my power is getting lower and lower. And that's a nice characteristic of a series resonant converter.

Another nice thing is these device voltages are both limited to the DC input voltage. However, a slight warning, if I were to look at, say, the capacitor voltage, if I were to ask about VC, VC can actually be much bigger than the peak value of VX because these two components are in resonance.

And in fact, if you remember, we said that the capacitor voltage in a series resonant network can be Q times-- Q of omega 0 times the fundamental input voltage. So if I have a Q of 10, then whatever the fundamental of this voltage is, if I ran at resonance, VC would be 10X that. Or if Q is 100, it would be 100X that.

So you've got to be careful. The device voltages are nicely limited. But you've got to be very careful about these two components, can have pretty big voltages on them, depending upon the quality factor of the network.

Now, we would like quality factor to be high so that we get sinusoidal currents. If you imagine that the quality factor of this was really low-- that is, resistance was really big, for example-- then instead of looking like this pretty curve, it would look like this. And then maybe I don't do a good job of attenuating my harmonics. And my current wave forms get distorted. And then perhaps I don't get the right phase shifts for zero-voltage switching and all that.

So you want Q to be high enough that you get good attenuation of harmonics and low enough that you don't have big stresses on these components and big parasitic losses in those components. Questions about that?

Now, what is a challenge with this? Well, this works beautifully. And I should say one other thing. There's a limit that relates how far above resonance I have to be to the size of these capacitors and the amplitude of the current.

Basically, this integral is basically underneath the orange curve of the inductor current. Between here and where it crosses 0 is exactly the charge that I can deliver onto these capacitors for soft switching. So I need a certain amount of phase shift and/or a certain amount of current amplitude in order to get zero-voltage soft switching if I'm going to use this load network to do my soft switching. There are other ways to do it as well. But that's something you got to pay attention to.

But here's a challenge. Suppose now I don't control this resistor very well. If this was an induction heater thing, the equivalent resistance I might see might depend upon the thing I've put on my network to heat, how much energy I'm going to dump into it.

If this resistor gets too small, the quality factor of the network gets really high. And then I'd better stay away from resonance. Otherwise, I'll get huge voltages on my components-- on my inductor and capacitor. On the other hand, if I make R too big, suddenly the network quality factor gets too low. And I get this frequency attenuation. I don't get good attenuation. I've got to go to really high frequencies to attenuate things.

So a challenge of these resonant networks is keeping the load resistance in an acceptable range for what you're trying to do. And that's a trick of design. Any questions about that?

I should say that I've shown you a series resonant network. You can use other topologies. And they give you different characteristics in terms of the behavior you'll get of the resonant network. So let me just show you a different example.

I could do the full dual of this thing. But let me show you a different kind. This is a series resonant converter. Here's a parallel resonant inverter. I'll have VDC again. And for simplicity, let me put in C infinity. This is just a blocking capacitor.

So I'm going to get a voltage on the other side of this that I'm going to call VX prime. VX prime is, again, just going to be a square wave. And it's going to go from-- it's going to go between VDC over 2 and minus VDC over 2. I'm putting a blocking capacitor in there just to extract out the AC component, which I'm using to drive the network.

And then here's my parallel resonant network. This would be called a parallel resonant inverter. Instead of having a blocking capacitor here, I could have done this in different ways, including using a full bridge, et cetera. But I just want to illustrate this.

Now, why is this a parallel resonant network? If I thought of VX prime as a voltage source, if I make VX prime 0, L, C, and R here are in parallel. So this is a parallel resonant network driven by a voltage source inserted in series with the resonant inductor here. So that's how somebody would think about this and in terms of a resonant converter.

And how might I think about the behavior of this? Well, maybe I could plot-- VC and VR are the same thing. So maybe I could plot the magnitude of V sub R over VX prime versus frequency for this network. So I'm looking at the transfer function between here and here for this network.

At DC, clearly, VR equals VC, or at low frequency, because the inductor becomes a short. At really high frequency, this rolls off at 40 dB per decade. So what you're going to get is something that does something like this. It's going to go for one. It's going to peak up. And then it's going to fall.

And this peak, if the network quality factor here-- and quality factor here is now R over the square root of L/C. It's the other way around. This peak is going to be near omega 0, which is 1 over the square root of LC again.

So again, we get this high-frequency selectivity of the voltage gain from my drive, which has a fixed amplitude set by the DC voltage, to the voltage I put across my resistor. And again, if I'm operating up here in this regime, I'm going to have an inductive input impedance coming in. So again, I can soft switch these devices, zero-voltage switch these devices. And now I can, again, by controlling frequency of the drive, control the amplitude across my resistor and hence control power. Any questions about that?

Now, how does this network differ from the series resonant network? Well, notice one thing. In this series resonant network, the largest voltage I could ever put on VR is the fundamental that I drive with, because it's just a voltage divider between the resistor and the reactive components.

Here, I actually have-- because of the resonance between L and C, I can actually get voltage gain. I can get a voltage that's much bigger than my input voltage. So if I want voltage gain out of the thing, maybe this parallel network looks good. And how much this peaks up is a function of resistance.

So this is for R big. Maybe I'll call that R big. Maybe this is R medium. If I had a big resistor, it might look like this. And if I had a small resistor, maybe it'd look like this.

But here's the point. I can get voltage gain, at least if I have the right resistance value. And sometimes we use this. So this kind of network actually is often what's used if you're going to have a fluorescent bulb.

So if you think about it, like one of these fluorescent bulbs here, what is it? It's a gas of-- it's a tube with low-pressure gas in it. If the lamp is off, that has a really high impedance, because it's just two electrodes with some gas in between it. And you've got to get a really, really big voltage on it to break down the gas and so-called strike the lamp.

Well, how can I do it? If I take this thing and I put this thing as an open circuit and I drive this half bridge right near the resonant frequency of L and C, I'm going to build up a really big capacitor voltage here. That capacitor voltage could be tens of times as big as my DC voltage.

Eventually, the fluorescent lamp breaks over. And then you've ionized the gas. And then it looks like a resistor but not a huge resistor, a small resistor. And I go from the green curve maybe down to the-- oh, sorry-- I go from the green curve maybe down to the white or orange curve. And then I can modulate the amount of power and light by moving frequency.

So this kind of network would be at the core of many fluorescent lamp ballast drivers. And we're taking advantage of the resonant voltage gain I can get from this high Q tank. And it's particularly high Q when the lamp isn't struck. So sometimes I want the big voltage, even though I got to rate this capacitor and inductor for it. Any questions about that?

So I can get frequency-dependent voltage gain and power control in either of these networks. This network has the opposite characteristics of this network, in the sense that if I make R too big rather than too small, I get very peaky resonances. And if I make R too small, this thing starts to give me poor frequency selectivity and hence poor attenuation.

People choose one or the other, depending upon what they're trying to do. Or I could choose something in between. So, for example, one thing people might do is say, OK, let me have a network. And maybe I'll make it look like this. I'll have two Cs and an R. So maybe I'll call this C1 and C2, and this is R.

So if R is small, then it shorts out C2. And I can ignore that. And it looks like a parallel resonant network. If R is really big and I run to a high enough frequency, this branch looks sort of inductive when I'm above this resonance. And then I have the equivalent of a parallel resonant network. This would be called an LCC or a series parallel resonant network.

And that kind of network's used too, to balance what happens at large and small resistances, for example. It has some sort of hybrid combination of series and parallel. You can also have LLC, where there's two inductors and one capacitor. That's another, actually, extremely common resonant network.

So the easiest thing to get your brain around is the series and parallel kind. There are other kinds that people use because they give particular characteristics for different ranges of load resistance or for different ranges of operating power, for example. Any questions about that?

Now, a lot of converters-- I mentioned things like, where do they use these things? Induction heating is common. Driving fluorescent lamps, where you want sinusoidal power delivery into the lamp. That's usually pretty low frequency. Wireless power transfer, if I'm going to go across a link where I want sinusoidal fields.

Another example, however, is just straight DC to DC conversion. I didn't say what this resistor was. But imagine I use a network like this one. I take DC. I chop it up, generate a square wave.

If I have a high Q tank, then this current becomes sinusoidal, or close to it. And that's where I make my fundamental harmonic approximation. And by the way, for power transfer, if this current is sinusoidal, we said we can only transfer average power through voltages and currents at the same frequency.

So even though VX has a bunch of harmonic content, as long as this network filters to make the current sinusoidal, then the only component of this thing that matters is the fundamental component of the drive voltage because no other harmonic component delivers average power through the network. So the fact that I'm mediating power through a sinusoidal, in this case, current is very valuable.

So how would I build a DC-DC converter? Well, maybe I'll use an inverter, create a square wave, use a high Q network to extract a sinusoid. And then I can use that to control voltage gain, because I can control the amplitude of the current by varying frequency. And then I just run it into a rectifier.

So maybe I take this thing. And I say, OK. I say, let's build a converter. And this is going to be soft switched, which is one of the reasons why I'm doing it. I have L, C. And then what I'll do is maybe I'll just put a transformer here.

And then on the other side of this transformer, I'll put a rectifier-- in this case, a full bridge rectifier-- and make that V out. And this is transformer. And this is transformer. So if this is, for example, I sub L, maybe this is then IL prime, which is exactly just I sub L scaled by the turns ratio or the inverse of the turns ratio.

What does this network-- if I were to say, What does this impedance look like, looking in here? well, if IL is a sinusoid, basically, I'm going to take a sinusoidal current. And then I'm going to rectify it. So then IX here would look like what? It would look like exactly like a rectified sinusoid of amplitude. Let me call this I sub L.

So if I sub L has amplitude I sub L, then this just looks like a rectified version. The DC current-- I'll call this IX. The average value of IX-- and I'm running out of time. So I don't have chance to work this out. The average value of IX is simply going to be equal to 2 over pi times IL. I'm sorry. Yeah, times IL.

So in some sense, what am I going to see here? I'm going to deliver some average current into my output. What is the voltage that appears? If this is IL prime, let me plot IL prime for you.

IL prime maybe looks like this. What does this voltage look like? Let me call this V sub y. Well, when IL prime is positive, I have V out. When L prime is negative, I have minus V out. So the voltage he sees looks like this. Does that make sense?

So the current into the rectifier generates a square wave voltage. But I'm only transferring power in this network. The fact that there's a square wave voltage here and here doesn't matter. It's the fundamental component of that voltage that matters for power transfer. The fundamental of this orange square wave is-- basically, it looks something like this. It's exactly in phase with the current.

So essentially, this whole rectifier network reflected through this transformer looks like an equivalent resistance. And I'm back exactly to this original model I had. And the only thing I've done there is I've said, I don't care about the harmonics of this, because as long as the current's close to sinusoidal, almost all the power is in the fundamental.

So I've run out of time there. But I'll come back next class. And we can talk a little bit more about how we might model DC-DC converters in this way. But let me ask, are there any questions before we wrap up for the day? All right. I will see you tomorrow.