[SQUEAKING] [RUSTLING] [CLICKING]

DAVID PERREAULT: OK, good afternoon. So we now have magnetic components, like transformers, at our disposal. And once we have transformers, there's a lot of interesting things we can do in power converter design that we couldn't just do with inductors or capacitors.

And the material I'm going to talk about today, which are nominally called isolated converters, is the topic of *Principles of Power Electronics* chapter 7. And The notion here is, how do we design isolated power converters? When I say isolated power converters, what do I mean? Well, there's three motivations for an isolated kind of topology or the kind of topologies we're going to talk about today. The first is galvanic isolation.

If I'm going to build something that's going to plug into the wall and power my laptop, I would really like it that if lightning strikes outside, I don't get electrocuted. So what you would really like is some kind of saturating isolation barrier between you and the actual stuff that's connected to the wall.

And so if you take any laptop adapter or computer adapter, the transformer in that basically has thousands of volts of isolation to protect against something like a lightning strike. And in fact, it has at least three layers of isolation built into it, such that if any one of them fails, you have enough. So that's one important reason why you might want physical, galvanic isolation for safety reasons.

The second reason that we often use transformers, and whether or not you have galvanic isolation, is for large conversion ratios. So if I want to step down or up 20 to 1, something like that, yeah, I can do that with a straight-up buck converter or something like that. But it turns out we can do a lot better if we have some voltage and current scaling, which we can do with a transformer.

The third reason that's very common is that we can do multiple outputs. So a typical power supply for your computer or something, maybe you want plus 12 plus 5 minus 5, so you can supply a whole bunch of different stuff at once. And yeah, you could build separate power converters to do that. But wouldn't it be nice to build one converter that does it all in a more compact form factor? And having transformers at our disposal lets us do that.

And lastly, which I don't put up here, it turns out it's just transformers open up the range of topologies and structures you can put into a converter and thereby help you design some interesting things. So let's take a look at an example-- or we'll take a look at two examples today of the kind of things you do with a transformer and a converter.

So if we thought about it, a basic converter that we've analyzed before, if I have Vin, I might have my switch here, and then I'll call this Vout. And our main energy storage element in this converter for transferring energy is this inductor L.

And we said, if I analyze this converter, the voltage across the inductor L, V sub L, has to have a 0 average balance. And what we get from that is that Vout over Vin is equal to minus D over 1 minus D. So it has a negative gain. The output voltage is negative if the input is positive. And I can make the output voltage smaller or larger in magnitude than the input based on how I select my duty ratio.

So OK, I have of AC waveform at VL in the middle of my circuit. I could throw a transformer in there. So what happens if we do that? Suppose I come in and I just say, all right, let me throw a transformer in there. So here, I'll put in-- here's V sub L again. It would help if I had a switch.

So I'll just throw a transformer in the middle of this circuit, N1 to N2. And all I've done is put a transformer in. And I'll make this Vout. All right, so if I do this, here, I have VL again. And so what has this thing done to my conversion ratio?

Well, if I think about it, in the first part of the cycle, if I look at the average voltage across VL, I get-- that's equal to D times Vin plus 1 minus D times N1 over N2 times Vout is equal to 0. And if I rearrange this, what I get is Vout over Vin is equal to minus D over 1 minus D times N2 over N1.

So it's the same conversion ratio that I got up here. But because I put a transform in the middle, I get this scaling by the transformer turns ratio. And what that will let me do is get a certain voltage conversion ratio that gives me an extra way I can scale the output voltage compared to the input voltage, just fixed scaling that's set by the turns ratio. But nonetheless, it lets me pick my duty ratios the way I want. Any questions about that, rescaling?

What else can we do here? Well, very conveniently, now, in this case, in addition to giving me a scaling, it says that now notice that this voltage is not reference at all to this voltage. So ideally speaking, there's no way for current to flow, say, from here to here or from here directly to here. So I've got some the potential to get galvanic isolation.

But it also means that this node and this node are no longer referenced to one another. And I can put my grounds wherever I choose in this circuit now. So one thing I might choose to do is, if I look at this circuit, the gate drive for this circuit is referenced like this. I have to generate a voltage with respect to this node to drive this switch.

And that's kind of a pain because this node is flapping up and down with respect to the negative of my input. So that's an inconvenient place to have to drive the switch. And I've got to usually put in a level-shifting gate drive or a flying gate driver to do that. That adds cost and complexity.

Wouldn't it be nice if I could put the switch elsewhere? Well, look, I have Vin, this structure, and the switch in series. I could just rearrange that. So perhaps I could just simply do this-- Vin-- OK, I'll come along here. And let me just put my transformer and my inductor first. And I'll put the switch here.

So now, this switch, if this is an in channel, his input is referenced right here. And my gate drive is very convenient to implement. So that's one nice thing I can do. What's another thing I could do here? There's nothing that says which way this output has to be referenced because, in the original circuit, I was forced to this inversion between output and input by the orientation of the inductor.

Well, here, I could just flip this transformer around, if I wanted. And in fact, I can play the same trick. I could put the diode here or I can move it over here. So let me just flip this guy upside down. So I'll do it like this. Here's one dot. Now, I'll turn this upside down and do this. And I'm going to move the diode through. And I'm going to draw it like this. And I'm going to define a new output voltage, like this.

So what does that do for me? Well, OK, in the first part of the cycle, I put Vin across the input. So I get D Vin is across the inductor. And when the diode is on, now, I'm applying minus Vout scaled by N1 over N2. So I get Din plus 1 minus D minus Vout times N1 over N2 equals 0.

And this just gives me Vout over Vin is equal to D over 1 minus D times N2 over N1. So I've gotten the same thing as I did before. But because I was able to flip the way I did the transformer, I got rid of this negative sign. So if I want a positive output from this converter, now I can get a positive output relative to the input.

If I still want a negative output, no problem. Nobody ever said I had to define Vout this way. I could define a new Vout inverted from that and time my output reference here. I can reference the output and the input to this circuit to different potentials and reference it any way I want because it's an isolated converter. And I'm good. So I can get positive outputs. I can get negative outputs, any way I want to do it. Any questions about that? Yeah?

STUDENT: I guess, how strict is the galvanic isolation? How does that protect against like induced surge?

DAVID PERREAULT: OK, so what would happen? Imagine that lightning strikes your circuit here. This ground, this node goes crazy because whatever this was tied to had some huge voltage across it. I'm applying that voltage. Suppose this is the ground you're connected to. That's applying a voltage here.

Ideally, for an ideal transformer, that's just an open circuit. No current can flow this way. What would happen in reality? Maybe if there was a differential voltage, this transformer would saturate. But whatever happens, to the extent that this acts like an ideal transformer, you're not going to get current flow from here, through here, back to ground, and through you.

In reality, this isn't perfect. This ability, the ability of the transformer to take voltage this way, depends upon how much insulation you have between the primary and secondary. And that's what's regulated. So it's a few thousand volts typically for a laptop adapter. And like I said, even if you have a fault on one of those layers of insulation, the other one should be big enough to block a few thousand volts. That answer the question?

So the nice thing about the transformer is it lets us reference the output any way we want to the input. In addition to galvanic isolation, I can change the polarity. All very nice. But wait, there's more. What else can we do? Well, let's look at this thing.

One thing I always have to pay attention to with the transformer is the fact that it has some parasitic magnetizing inductance. I ignored the magnetizing inductance in this thing. I treated it like an ideal transformer. Where would the magnetizing inductance be? If I referenced it to the primary, it would be right where this inductor is.

Well, what says that I can't just then take this whole thing, OK, and build the transformer just like this. Here's my transformer. And then this L becomes L mu 1. And this becomes I mu one. And I use my magnetizing inductance of my transformer as my energy storage element. Done this way, this is often called a flyback converter.

I believe where the term comes from is back in olden days when you used to have a cathode ray tube and you'd have some really high voltage causing the cursor to swing or fly, this was the kind of converter that was often in that because it got used to generate the high voltages. So it got into being called a flyback converter, as far as I understand it. But a flyback converter is essentially just an isolated buck boost converter.

How would I design the transformer for this kind of thing? Well, what we would want to do is now, like an ideal transformer, I don't want any energy storage in it. The magnetizing, the parasitic, I usually want it to be infinite, if I can make it that way. But now, keep in mind that, in this converter, this yellow guy here is our energy storage element.

So if I'm going to store energy in it, I usually would like to gap my magnetic structure so that it can efficiently store that energy in a small space because we put the energy storage in the gap. So the way we might build a transformer for this application-- this is an ideal transformer. This is an energy storage transformer.

So what I might do is I might come up here and say, OK, I'll build some core, but I'll put a gap in it. And I'll put N1 one turns here. And here's V1 and I1. And then I'll put N2 turns here. And I'll have my dock goes this way, the way I've oriented the windings. I'll have V2 and I2 and N2.

And the notion is-- where is the energy stored in this? Well, physically, there's some current in winding 1 and some current in winding 2. And between the two of those, they're storing some-- they're having induction between the two coils. And there's some energy stored in the field, in the H field, which will mostly appear in the gap.

So maybe there's a tiny bit in the core. And this is H that I'm drawing. But most of my energy is stored here. How is that reflected in this circuit diagram? It's reflected in the magnetizing current. 1/2 L mu 1 I mu 1 squared reflects the energy stored in the core and in this gap, mostly in the gap. It make sense to everybody?

So the idea is, if I didn't have a second winding and I had current in here, the current in the winding 1 would be precisely related to the energy stored in the gap. If I had no current in winding 1 and I had an energy storage gap, I'd have current in this winding that would carry current. And that 1/2 L I squared looked at from this side would represent that energy.

So basically, I can think of this as an inductor from either side, but it's sort of like an inductor with an extra winding. And I can carry current in this winding to match that energy source or I can carry current in this winding to match that energy storage. And of course, the amount of current I need depends on the number of turns. So I can rescale the amount of current I have. Does that make sense?

So what are we going to do? In the first part of the cycle in this converter, I turn on this switch. This magnetizing current basically circulates this way. And I'm applying Vin across the magnetizing inductance. And the current, I mu 1, is linearly increasing.

So if I plotted I mu 1, I mu 1 would linearly increase in the first part of the cycle because I'm applying Vin. In I mu 2-- I'm sorry I2, on the secondary side with the diodes open-- so there's no current in the secondary winding. When I turn the switch off, if I thought about it, if I look at it, this circuit model, what's happening is the magnetizing current's circulating out of this dot and into this dot.

So there's current in the secondary now, which is supporting this magnetizing energy storage. Because of the polarity, the voltage gets applied. And the current in the magnetizing inductance ramps down. So this is what I mu looks like. And I'll draw this as I mu 1. And I'm pretending it's a 1 to 1 turns ratio for the moment.

Actually, I mu 1 is always going to look like this, the magnetizing current. If my winding 1 and winding 2 had the same turns, what I would see is, in the first part of the cycle, this would be I1. And in the second part of the cycle, I would have I2 would carry the current. This would be I2 here.

So I've got a continuous magnetizing current and hence continuous energy storage. But I can carry that in the first part of the cycle. I put energy into the transformer by the first winding. In the second part of the cycle, I pull that out of the transformer via the second winding. So it's same kind of operation. I'm just using two separate windings instead of one winding. Questions?

Let's see this in action. We actually have a flyback converter for you to see. So Mouncy's kindly put this together. And what we're showing you is precisely the two currents in the two transformer windings. Now, what you're going to see is, if you see the primary winding is channel 1, that's in yellow.

And you can see the current in primary 1-- the current in the primary is ramping up. That's because I'm storing energy in the magnetizing inductance. And that's at 2 amps per division. In the second part of the cycle, we're showing you the purple waveform is the current winding 2. And you can see it's ramping down.

But you notice, that's 1 amp per division. And the energy in the core-- the energy stored in the gap actually is continuous. And it's ramping up and ramping down. But it's reflected based on different input and output currents. And that's because I can use a turns ratio, in this case, a 2 to 1 turns ratio to help me do that. So we actually can get this nice scaling and think of this energy storage transformer as an inductor plus an ideal transformer. Questions? Yeah?

STUDENT: What's the blue curve?

DAVID PERREAULT: The blue curve? I don't actually know what the blue curve is.

STUDENT: Primary voltage.

DAVID PERREAULT: That's the primary voltage. Ah, OK. So one thing you would take away from this-- and it's a little bit hard to see. And I think there's some offset going on in here-- is that you have a positive and negative. So you have a purely AC voltage across the transformer, which is hard to see because it looks like there's a little offset in that.

But it's supposed to reflect that you have a positive voltage in a part of the cycle and a negative voltage in the other part of the cycle. So when blue is high, the magnetizing current is rising. When blue is low, the magnetizing current is falling. OK, thank you.

So that is how we would build a flyback transformer. It's not like an ideal transformer. It's an energy storage transformer. So it's more like an inductor design. So you want to design it with a gap to make it small. There's a lot of the same design considerations as for an inductor, but you're going to have a second winding.

And like we said, because we have this nice isolation, I can reference the secondary either for positive or negative output voltages I choose. We get our nice ground reference active switch. The other thing I didn't mention is that why would we want this turns ratio? Because it can help us really design the converter better.

Let's suppose I had a 1-kilowatt design. And what I want is for Vin to be 100 volts at 10 amps and Vout to be 10 volts at 100 amps. So it's a 10 to 1 step down. If I tried to do that with my original converter-- and forget about whether this is plus or minus.

Suppose that doesn't really matter-- what would it look like? What would the stress on the switch look like? Well, for a for buck boost, what I'd end up with is V switch and V diode being 110 volts. And I switch and I diode would be 110 amps. So that's more than 10 KVA of switch rating there and diode rating.

On the other hand, suppose I designed a flyback and I used a 10 to 1 transformer. So I'm going to get my scaling-- instead of just by using some extreme duty ratio, I'm going to get my scaling by putting it into the turns ratio. What does the turns ratio do? That rescales the high current seen at the secondary to the low current at the primary and the high voltage to the primary seen as a low voltage at the secondary.

And what I would get is-- instead of the direct sum of the input and output voltages, what I would get is V switch would be equal to 100 volts plus the 10x scaled version of the output voltage. So it would be 200 volts. And this would be at 20 amps. Same thing, it would the 10 amps at the input plus the scaled 100 amps down by 10 at the output would give me 20 amps.

And V diode would be 20 volts at 200 amps. So what it's let me do is instead of needing a switch that has both high voltage and high current, I get a high voltage, low current switch and a low voltage, high current diode. And I might be more easily able to buy those components. Or at any rate, I can choose my turns ratio to rescale voltages and currents to be more favorable.

If I just thought about in terms of KVA. This is 4 KVA instead of 12 KVA or something, So it's much less VA. But it also means I can go pick a high voltage, low current switch and a low voltage, high current diode. And this would be easier to source. Any questions about that?

So this kind of trick that we basically started with my indirect converter, throw a transformer in the middle, and we can get something that can perform better is the heart of the idea of isolated power conversion. We can do this with all kinds of converters and synthesize new ones that don't have a counterpart in the non-isolated regime.

Let's take a look at another example. Let's think about a buck converter and play the same game with a buck converter. And that plays out a little bit differently. But we'll see it has some of the same advantages and some different design trade-offs.

Let's think about-- in a buck converter, what do I have? I have an inductor. And this inductor is my energy storage inductor. And here's Vout. And what I'm really doing is I've got some voltage, Vx, that I'm synthesizing here. That's a pulse voltage between 0 and some other voltage 2 that I filter and then get my output.

Well, why don't I play the same game? I'm going to throw a transformer in the middle of this thing. It turns out I'm going to need another diode here because I cannot apply a non-zero average to this transformer. So I need this diode. It's a new diode. I can play the same game and put my switch as a ground reference here. And so here's Vin.

So what happens? Let me call this N1 to-- I'm sorry N1 to N2. So what does Vx look like? When the switch is on-- I'm going to plot Vx. When the switch is on, I'm applying Vn at the primary. So let me call this the voltage across the transformer.

I get N2 over N1 times V transformer-- or I'll call this V21, V transformer 1-- N2 over N1 times Vn. This guy is going to be turned on. This guy is going to be turned off. So I'm going to get this voltage as being N2 over N1 Vn. And then when I turn this switch off, this diode is going to turn off, the load is going to carry through this diode, and Vx is going to go to 0.

This is going to be Dt. And that's going to last until t. And this is the voltage, Vx. Well, what's the output of Vx? This inductor has to have an average voltage of 0. So what I get is V2 has to equal D times N2 over N1 Vin. So this is V2-- I'm sorry, Vout is equal to N2 over N1 D Vin.

So it works just like a buck converter. And all I've gotten-- or what I've gotten out of putting this transformer in here is this scaling. Instead of applying the input voltage directly here through a switch, I'm applying a scaled version of the input voltage. And I get this nice rescaling. And I also get the electrical isolation. This port is no longer referenced to this node. So it's some of the same advantages.

That's great. But notice that I again have a transformer here. And so I better think a little bit carefully about what the magnetizing inductance does. So let me come back here and say, OK, let me put in my magnetizing inductor. So here is L mu 1. And here's I mu 1.

In the first part of the cycle-- so this is my real transformer model now. keep in mind, this inductor, L mu 1, is not my energy storage element the way it was in this converter. Here, I was using this as an energy storage element. Where is my energy storage element in this converter? For energy conversion purposes?

STUDENT: By L?

DAVID PERREAULT: Yeah, it's this inductor. This guy here-- basically, I'm applying a positive volt seconds across in the first cycle, storing energy here. In the second part of the cycle, I'm taking it out. So this is the energy storage I'm using for power conversion. This magnetizing inductance is purely a function of the fact that I don't have an ideal transformer. It has some magnetization to it. So it's a parasitic of a transformer. But I better think about what it does. And here's the catch.

I turn on this switch. In the first part of the cycle, I'm applying a positive voltage, Vt1 here, which is appearing here, Vt1. That means this magnetizing inductance ramping up. The current in the magnetizing inductance is ramping up. Well, what happens in the second part of the cycle?

When I turn this switch off, in the flyback converter, it circulated out of this door and into this dot-- or I'm sorry-- here, it can't do that because if the current flows here, there's no way for it to flow into here because this diode's here. So suddenly, I better provide some place for this magnetizing current to flow.

And another thing I better think about is, in order for this transformer to work, the average volt seconds I apply across the transformer better be 0. Otherwise, it won't operate in periodic steady state. I have to respect this inductor, in terms of its need to have 0 average voltage to get to periodic steady state.

So what would this look like? Well, let me-- actually, I'm going to change the color here. Let me call this V mu 1. That's the voltage. So what does that look like? And then let's think about what the magnetizing current looks like. In the first part of the cycle, I turn the switch on. And I'm applying Vin as V mu 1. So here's V mu 1. And I'm applying Vin.

So what has to happen? In the second part of the cycle, I better do something so that, over the course of the cycle, the average voltage across this magnetizing inductance is 0. Well, I've provided no means for that to happen in this circuit. And probably, if I built it this way, unhappy things would happen.

So what can I do? I've got to provide some other place for that magnetizing current to flow. And in the process, I need to apply a reverse voltage on V mu 1. Now, there's a lot of ways I could do that. One very popular way is to do something like this, is to provide a voltage here and maybe put, say, the equivalent of a Zener diode here. And then I will put a reverse diode here.

And so what this does is this lets current, this magnetizing current, flow into this orange path against some Zener voltage, Vz, and back up here. So this orange path is another path for current to flow through. As a remembrance, I might think of this path that I just added as being equal to this, a zener voltage, Vz. So you could think of it this way, where the Zener breaks down and creates a voltage, Vc, when it's got current flowing into it this way. That make sense to everybody?

So what would happen here if I did this? When the switch turns off, I mu 1 is going to flow this way. And the voltage across the primary is going to go to minus Vz. And what would happen to the current in that magnetizing inductance? So let me plot I mu 1.

When I turn on the switch, it's going to ramp up. Let's assume it ramps up from 0, like this. And then I turn off the switch. This current, the magnetizing current, cycles into this. And it ramps down because I have a negative voltage. And eventually, what I would like is for this to hit 0 at some time.

So if this is Dt, and t is over here somewhere, when would this happen? This would reach 0 basically when the average volt seconds-- this area equaled this area. Net volt seconds on my inductor would be 0. And then it would just stay 0. The current would have gone to 0 in the magnetizing inductance. And that's fine. And so the transformers are just open circuited at that point. Any questions about that? Yeah?

STUDENT: Why did you choose to use Zener diodes and not like one freewheeling diode?

DAVID PERREAULT: Zener diodes instead of what?

STUDENT: Why would you not use one freewheeling diode instead of the Zener diodes?

DAVID PERREAULT: Ah, because-- think about it. A freewheeling diode has a forward drop that's like 0.7 and a reverse drop. You don't want to try to put a current through a diode backwards, right? The Zener is designed to hold a constant voltage when it's breaking down in reverse.

And I might not use a Zener. I might use some other element that can absorb energy in the reverse direction. So I could have replaced it with, for example, a capacitor, and then bled the capacitor to Vin, for example. So there's a lot of different circuits. Or maybe I should have-- maybe I should have drawn it differently.

But essentially, there's a lot of circuits. I've just got to give this current a path to flow into a voltage source that's going to apply enough negative voltage to drive the magnetizing current to 0. A lot of ways I can do that. The Zener was just my model for the easiest one to show you. Does that explain things? Other questions? Yeah?

STUDENT: So in this case, is the Zener diode just acting like a sink, like a resistor?

DAVID PERREAULT: It's just acting like a-- yeah, like a resistor, except that it's a fixed voltage. It clamps it. And the reason I was drawing-- you could replace that with a capacitor, and then bleed that capacitor back down to some average value, like Vin. So you could have connected it like this, too. You would have needed-- sorry, you would have needed a-- you would have still needed a diode there.

I've got to be careful to let this ramp down to 0. What happens if I don't? If I don't, suppose I don't apply-- suppose I choose too low a Zener voltage. What would happen is, in the first cycle, the magnetizing would ramp up. And it'd come partly the way down. And then it would ramp up and come partly the way down. And it would start to walk away on me.

And keep in mind, the magnetizing current is proportional to the flux in the core. And eventually, that flux would exceed the saturation flux density of the core. And then the core would saturate. And then your converter would blow up. Bad things would happen. So whatever this clamp is going to settle to, it's got to settle to a big enough voltage that it can drive the magnetizing current back to 0 each cycle.

So what does that say? Well, what is this peak magnetizing current? I mu 1 peak ought to be equal to what? Well, V is equal to L dI/dt. So this would be V1-- or Vin dt over L mu 1 is the peak current I hit here. Does that make sense?

And lambda 1 is equal to L mu 1 I mu 1 is equal to N1 B in the core times the cross-sectional core area. Lambda's LI. And it's also NBAC. So we can calculate the core flux, VC, as being equal to-- or the peak core flux as being L mu 1 I mu 1 over N1 AC. And we've got to keep this peak core flux below the saturation flux density of the core.

Actually, I should have substituted. I could rewrite this as Vin dt over N1 AC. That's another way to write it. So what do I need? Well, what I need is-- what's the minimum? Zener voltage. I need to do this? What I need is Vz times 1 minus D has to be greater than Vin times D, in order for that volt seconds to go to 0 because otherwise I won't get enough negative volt seconds to offset the positive volt seconds. And that means that Vz has to be greater than or equal to Vin times D over 1 minus D. That make sense to everybody?

So what does that say about what happens to the switch in this circuit? Well, if I look at the circuit, the switch-- obviously, when the switch is on-- if I think about this as being Vswitch, when the switch is on, he has 0 volts. When the switch is off and the Zener is conducting, he has Vin plus Vz across him.

So the peak switch voltage I'm going to get is going to be what? It's going to be equal to Vin plus Vz, which is equal to Vin plus-- let's suppose I use the minimum value, Vin times D over 1 minus D. I could rewrite this as Vin times 1 minus D over 1 minus D, if I wanted. That's the same thing.

And this gives me equal to Vin over 1 minus D. All right, so if I pick a big enough Zener voltage based on this requirement to get to the 0 volt seconds balance on my transformer, I get this voltage. So if I was at D is equal to 0.5, that would give me Vswitch is equal to 2Vin. If I went up to a 75% duty ratio, that would give me Vswitch is equal to 4Vin. That's getting kind of ugly, My switch voltage is bigger than my input voltage considerably. What would it be if I just built a regular buck converter? Anybody recall that offhand?

STUDENT: 1 minus V to the n?

DAVID PERREAULT: It actually would be just Vn, because, in a normal buck converter, the switch is just blocking the input voltage. And the diode is circulating in the second part. So it's got the input voltage across it. Here, even a 50% duty ratio has twice the input voltage. It gets worse. It keeps getting worse at higher duty ratios.

So I'm going to pay a price in the isolated buck converter. And I should have mentioned, by the way, an isolated-- this converter is called a forward converter. And that equals isolated buck. And I have no idea why it's called a forward converter, but that's what it's called.

The forward converter has much greater stress. So when I put the transformer in the middle of it to give me galvanic isolation, suddenly I've paid a penalty in my device voltage stress. And I've paid that penalty because I need to reset the transformer. And that's a different trade-off compared to this design where, coincidentally or not, the magnetizing inductance turned out to be just the energy storage element I wanted.

Here, the transformer is not doing me any favors. It's just there because that's what I need to get the isolation. I've got to pay for that. Yeah, Jack?

STUDENT: Would you use the core converter or the buck converter?

DAVID PERREAULT: Ah, that's a very good question. That comes back to-- and we'll talk more about this. That comes back to how big it is. So we're going to come back to this. But remember, a buck converter is a direct converter and has very low stress on its switches and low energy storage in its components.

The flyback converter is based on an indirect topology, which has lots of energy storage. So it turns out that, depending upon the design regime, a forward converter can actually be a lot smaller because the magnets-- keep in mind, this transformer doesn't really need to store any energy. The only real energy storage element, which is the size-limiting element, ought to be that inductor. And that inductor is smaller than this flyback transformer.

So you'd pick it for the same reason you might do a buck converter instead of a buck boost converter. We'll come back to design trade-offs moving forward, like when might you choose what topology. Great question. Any other questions?

Let me just come back to this means of resetting the core. So we've reset the core. We have increased voltage stress on our switches. The other thing we have is increased dissipation because what am I doing here? Every cycle, I'm storing a little bit of energy in that magnetizing inductance. Magnetizing current ramps. I put energy in the magnetizing inductance. What do I do with that energy?

I dump it into a Zener diode. I throw it away. So I hate throwing away energy. But this circuit, that orange circuit, is throwing away energy. Well, how much energy do I dissipate? And by the way, this process of driving the magnetizing current back to 0 is called resetting the core.

How much energy do I lose in resetting the core back to 0 flux density? Well, that would be 1/2 L mu 1 times I mu 1 quantity squared. So that would be 1/2 L mu 1-- what's I mu 1? I wrote it up there. That's going to be Vin dt over L mu 1 squared.

This works out to be 1/2 L mu 1 times Vin squared D squared t squared. And then if I wanted to say what's the power dissipation, I have to multiply that by the frequency of 1 over t. And what I get is 2 L mu 1 times Vin squared D squared t.

So if my t is really small or I have a high frequency, I dissipate very little energy in resetting the core for a given size. If my magnetizing inductance is big, I don't store much energy in the core, and then I don't dissipate much. So in this design, I would like my magnetizing inductance to be as big as I can. I want this to be as close to an ideal transformer as possible in order to reduce the amount of energy I store in the core and throw away. Any questions about that?

So just one or two final points here-- of course, I don't like throwing away energy like that. And there's a lot of other ways that you can not throw that energy away. I put energy in the magnetizing inductance. Maybe I can take it back out. And there's lots of ways I can do that. One way I might do that-- and there's others in the notes-- is the following. Maybe I do this.

I will, in the first part of the cycle, apply a positive voltage through a pair of switches. In the second part of the cycle, I'll turn on this. This is Q of t and this is Q of t. So I apply a positive Vin across the transformer, just the way I did up there. In the second part of the cycle, the switches turn off and the diodes turn on. And I return the magnetizing inductance energy to the input. This can work up to a duty ratio of 50%.

Or I could create another winding. And instead of throwing the energy into a Zener diode, I could throw it back to the input. That's another way I could do it. So there's lots of ways to recover that energy. And the trade-offs of how you do that separates different versions of the forward converter from one another.

So I don't want you to walk away with the notion that says, I have to throw away the energy stored in the transformer. I don't. I can recover it. But it adds complexity and adds some trade-offs. Any final questions? OK, we will pick up isolated converters again next class. Have a great day.