[SQUEAKING]

[RUSTLING]

[CLICKING]

DAVID PERREAULT: Why don't we get started? So last class, we were continuing to talk about DC-to-DC converters. And we saw both the buck and the boost converter, which could each be considered-- one way to look at it is to consider each of them a connection of a certain so-called canonical cell.

So for example, we could have a structure like this, where we had one inductor, a single-pole, double-throw switch, and one capacitor. And connections of this two-port structure suddenly would let us build a converter. And one example-- and we often implement this single-pole, double-throw switch with two semiconductor devices acting as single-pole, single-throw switches.

So for example, one way we could do this if we connected a source V1 here-- and then we would implement that single-pole, double-throw switch perhaps with a MOSFET and a diode. And we'd have an output voltage here that we connect to a load and call that V2.

So we saw this converter, where we could deliver energy from a source V1 to a load V2. And we analyzed this operation. And we could say, suppose I turn this switch on with some signal q of t or a signal-- switching signal where when q of t is 1, the switch is on. When q of t is 0, the switch is off.

So that's like saying q of t is 1 when the switch is in the down position. And so if we did that, something like this, with some duty ratio-- so here's DT and T, here's q of t-- we can analyze what's going on in part by looking at, for example, the voltage across this inductor.

So if I call this V sub L, we could see that if the switch is on V sub L has V1 applied across it. So I could have a voltage V1. So I apply a voltage V1 in the first part of the cycle. And I will have a positive current in this inductor. And when I turn the switch off, this inductor will then turn on the diode and deliver that current to the output.

So in the second part of the cycle, what do we have for a voltage across the inductor? We have V1 minus V2. So if we assume that's-- V2 is being held almost constant because the inductor and the capacitors are supposed to be big here, then we would have a voltage V1 minus V2 across the inductor in the second part of the cycle.

And what do we know about the average voltage across an inductor in periodic steady state? It's got to be 0. So if I'm going to be in periodic steady state, I need a 0 average voltage. That suggests that this voltage, V1 minus V2, had better be negative in order to get a 0 average voltage across it.

So another way we could look at this periodic steady-state operating condition is to look at the voltage waveform across the inductor and then say, well, hey, I need the average value of VL equal to 0 in PSS. And what that means is essentially that this area, this positive area, must exactly balance this negative area because the average voltage across this inductor would simply be DV1 plus 1 minus D V1 minus V2.

And if I then take and solve this equation, what I get is V2 in periodic steady state must equal V1 over 1 minus D. And since D is a fraction of a time-- this is DT, it's a fraction of a period-- V2 must end up being bigger than V1 such that V1 minus V2 is a negative number.

So the way this converter will operate is if the output voltage isn't big enough, then I will have a positive average value across the inductor. And the inductor current will keep building up until it's delivering enough current to the output to raise the output voltage such that it's in this periodic steady-state operation.

And what we would expect to see for an inductor current-- the ripple on this would be small if I assume the inductor is large. But if I was plotting-- if this is V sub L and I was plotting I sub L, maybe I sub L would go up in the first part of the cycle because I'm applying a positive voltage across it and would go down in the second part of the cycle.

So it would be this triangular waveform, ideally speaking. And I'd be in periodic steady-state operation where it ended up just in the same place it started at the beginning of the cycle. And then that would be periodic steady-state operation.

So this is the boost converter. I can also even look at this. And I can say, hey, if I have my rule here, V2 is equal to V1 over 1 minus D in periodic steady state, what else could I see? I could argue that I2 ought to be equal to I1 times 1 minus D, where I'm defining in this case the DC current here as being I1, the DC component of this input current being I1, which is also IL, and this current being I2. And how do I get that? It's because V2I2 has to equal V1I1. I'm assuming it's lossless in that example.

So we can very quickly get to how we think this circuit ought to operate. Are there any questions about the boost converter?

AUDIENCE: I'm just looking at the notation-- so with the orange curve that we've drawn, I is changing. But then we wrote a capital I1. Can you say more from that?

DAVID PERREAULT: Excellent question. So strictly speaking-- it's a very good question. Strictly speaking, this is I sub L of T. So I've plotted I sub L of T here. And then I1-- if I wanted to put I1 in here, it would be, essentially, its average value. This would be IL is equal to I1.

And of course, if I make the inductor induct bigger and bigger and bigger, there's no distinction. The reason I wanted to plot the ripple here is because in the first part of the cycle, you can see we're putting energy into the inductor because the inductor current's rising. And in the second part of the cycle, we're taking the energy back out of the inductor and putting it to the output. Great question.

So that was an example converter. And you can see that we implemented this single-pole, double-throw switch as a pair of semiconductor devices. I'd like to talk a little bit more about how we would implement that. Typically, I would implement any device like this as some pair of devices, two actual physical semiconductor devices, because what I get is single-pole, single-throw switches from a device. I turn them on or off.

But what I can do with my converter depends upon how I implement those devices. So let's talk about the capabilities of different semiconductor switch devices. By the way, there's nothing that says I have to use a semiconductor device. In theory, I could use a mechanical switch. But it'd just be pretty horrible. And people have tried other things historically. But in the modern world, everybody uses semiconductor devices.

So let's think about the capabilities of different kinds of power semiconductor devices. Perhaps one very common device would be the power MOSFET. And I'll focus on the end channel one because that's perhaps the most common because of its good performance.

So the symbol for this device would be like this. And a power MOSFET, by the way, is a vertical device. It conducts current through the thickness of the device. So it's a little bit different than a typical device on an integrated circuit, which is usually a lateral device. But you can use lateral power MOSFETs, as well, if you're doing an integrated semiconductor process.

How might I think of this device if this was the drain, the source, and the gate? What would it do? Well, this device can carry positive-- it can block. If I thought of this as V switch and I thought of this as I switch, it can block positive voltage and carry positive or negative current.

And in fact, if you look inside a power MOSFET at its structure, for free, what you get is a built-in-- people often don't draw this. But you get a built-in so-called body diode. So whether you want it or not, there's an effective diode here that if you try to put reverse voltage on, it will turn on. And it can carry current in the negative direction, or you can turn the device on physically through its gate and carry current in the channel.

But the point is I can block positive voltage. I can't block negative voltage because of this device, because of this internal parasitic device. But I can carry current in both directions.

The way you might think of a power MOSFET as a simplified model is with something like this. Maybe it has some parasitic on-state resistance, a switch that you control with the gate, and then a reverse diode. So that might be the way you could mentally model a device. And of course, an ideal device would have 0 resistance. But real device has real resistance, and so forth.

A lot of other devices-- actually, a lot of other semiconductor devices that you can put into active circuitry behave in a similar fashion. So for example, very popular lately are gallium nitride HEMTs, high-electron-mobility transistors. The symbol for that is very similar, actually. People use different symbols for these things. Sometimes they look like this. But they behave effectively similarly. They don't have a body diode. But they act like they do. They'll turn on and reverse.

So there's a whole class of devices that will act like this. They'll block positive voltage. And they'll carry positive and negative current. If I thought of the I-V plane for the devices, I might think of if this is the current-carrying direction and this is the voltage-blocking direction, maybe I have four quadrants. This device can block positive voltage and can carry positive or negative current. So it operates in these two quadrants.

What other kinds of devices could I get? Why do I focus on that? Well, suppose I went out and bought an IGBT, an insulated-gate bipolar transistor. These, in recent years, have been very popular for motor drives, things like that. They don't go to very high frequencies. But they're inexpensive. And they carry a lot of current.

And so an IGBT-- the symbol for it looks like this. So it's like a bipolar transistor with an isolated gate. You can think of it as a isolated-gate controlled bipolar transistor.

One could use a bipolar junction transistor. And back in the day, people did. But almost nobody would use these devices anymore because they're kind of horrible. These devices have a slightly different characteristic. These can block positive voltage and carry positive current.

But if you try to shove current in the reverse direction through this or put a reverse voltage on it to do so, you'll generally blow them up. So that would be an unhappy thing to do. If you're going to use that device, don't do that.

I should say there are exceptions to everything. There are something called reverse blocking IGBTs. But they're not very common. So you always have to look at the data sheet. But most can't do that.

So what would I do if there was some chance I might get current going negative here and I wanted to deal with that? Well, I might go and say, let me go take my IGBT. And it can block voltage this way and can carry current this way.

And what I'll do is I will go out and buy a diode. And I will stick a diode in antiparallel with it, for example, so that now this diode can carry current in the reverse direction and can still block in the positive direction. And this hybrid switch can block positive voltage and carry positive and negative current.

So a lot of circuits-- you actually do add diodes to your-- in antiparallel with your IGBTs because the circuit may get into a situation, at least transiently, where you do carry negative current. Yeah?

AUDIENCE: Sorry, can you just remind me, what do you mean by block?

DAVID PERREAULT: So in other words, in this case, if I turn the switch off, if I think of it as a switch that's off, here's V switch And let me repeat the question. The question is, what do I mean by it can block a certain direction of voltage?

If I define this as voltage V switch and I go and turn the switch off, it can allow a polarity of voltage this way. And it will be happy. It'll just stay off. But if I ran around and tried to put a voltage polarity across it this way, bad things will happen.

So it can act as a switch and open circuit itself, but only in one direction of applied voltage. So this one won't allow me to block reverse voltage, either. But it will allow me to carry reverse current because this one-- if I try to shove current through it the wrong way, it'll die.

AUDIENCE: Following on that, then, sorry, if the switch was closed, it would be a short?

DAVID PERREAULT: Yeah. If the switch is closed, an IGBT alone-- if the switch is closed, it looks like a short or some kind of very small drop for positive currents. But it doesn't look like a short for negative currents because bad things will happen. If I add this diode, then it can carry positively through the IGBT and negatively through the diode. And then it's happy as a bidirectional current-carrying device.

AUDIENCE: So then when we're determining what the polarity is across the switch, if it was in a circuit and you had some voltage source, then the switch would act like a load, right? And so it would be in the opposite direction of the voltage source. Is that how we would do it? Because I always think of it in terms of current and then determine the voltage [INAUDIBLE]. That might be [INAUDIBLE].

DAVID PERREAULT: And that's fine. So if you thought of it as being open, if you thought about it as being open, then you could calculate all the voltages and currents in this. If you treat it as an open circuit and you go analyze your circuit and then you say, which way is the polarity of that voltage-- and if it's the wrong polarity, you're unhappy. And if it's the right polarity, you're happy.

So what about if I want-- but this, again, will get me to those two quadrants. What if I want a different quadrant? I could come up here and I could say, let me take my IGBT. And now I'll put a diode in series with it. And to be clear, I mean a separate diode. I take two physical devices, And I use them to make one switch. And I'll call that V switch and this I switch.

This device can block positive and negative voltage. If I put a positive voltage across it, I can turn it off with the IGBT. If I put a negative voltage across it, this diode will naturally block it. But it can only carry positive current. So if that's what I need for the circuit I'm building, that's what I would do. Yeah?

AUDIENCE: So are these just considered semi-controlled?

DAVID PERREAULT: This would be considered a-- it's a fully controlled device under these conditions. Yes, it does act like a diode in the reverse direction. So if your circuit happens to do that, then it's uncontrolled. You can't tell it to turn on. That's right.

I can extend this one level further. So a very common thing I might do is take two MOSFETs in antiparallel, like this. And just to remember, inside of my MOSFET, this guy has a diode this way. And this guy has a diode this way. So by controlling these two gates, I can block positive and negative voltage or carry positive and negative current.

So this switch can do anything. It can just look like a switch, turn on whenever you want, and turn off whenever you want. And there are other implementations that will do that. I put a couple of other implementations that people often use in the lecture notes.

So I certainly can get a switch that will do absolutely anything that I tell it to do. Why would I not want to do this all the time? It's expensive-- more loss, more device drops. I got to buy twice as many switches.

So if I only need one MOSFET, I only have to block in one direction, I certainly don't want to add the capability. So designers are very sensitive to, what's the minimum thing I need to do in order to get the capability I need?

So depending upon how I implement my switches, different converters will do different things. And when we're going to go-- coming back to this notion of I just drew this or I built a-- I designed a converter and I just draw some abstract switch, you don't necessarily know what that converter can do or you don't know what it will do, necessarily, unless you know more things.

So very often, what might you need to know in order to figure out what a converter is really going to do? Well, you might need to know the switch implementation. You might need to know the control. If I don't tell you how I'm controlling it, you may not be able to tell what it's doing. You might need to know-- even then, you might need to know the external networks. So you might need a whole bunch of information to really analyze the behavior of a converter.

So let me illustrate what I mean by that. Suppose I were to show you this converter. I have a voltage source V1 here, an inductor, and maybe I'll implement my single-pole, double-throw switches, two switches. And here I go. And then I'll have a capacitor. And I will have some other voltage. I'll call it V2.

Can I tell which way power is going to flow in this converter? Can I tell even what the polarity is? Is V1 positive or negative? Not really. I don't have enough information.

Now, if I then came back and said, well, you know what-- here's some more detail. Here's V1. I'm going to implement this switch as a power MOSFET. And I'll implement this switch as a power MOSFET.

And just to remind you, while it's not necessary to draw this, and people don't normally-- but I will just remind you that inside this device, it has this magic-- it has this internal body diode. Whether you like it or not, there are diodes there because I've used the MOSFET.

If I look at this network, can I tell which way power is flowing? I would argue you can't because think about it this way. If I left this device off and I switched this MOSFET, I could use it as a buck converter to transfer energy that way. That's exactly the buck converter circuit we had-- or if I turned this switch off and just switch this device, it would be acting just like a boost converter, throwing energy this way. And by the way, I might not do that. I might actually use both devices. In fact, this circuit can actually act as a buck converter or a boost converter.

Just to illustrate that, I brought one with me. This beast is actually made for a certain kind of car that had two battery voltages in it. And it's actually five such converters. Here's the inductors. The two MOSFETs are bolted down to the heat sink. There's five copies of this. They're so-called interleaved. They're paralleled and operated in a certain manner.

But you can actually-- there's actually a switch on the front of this thing. If I can switch it up, it controls to boost. That means it regulates the high voltage from the low voltage. Switch the other way, it goes the other direction, or you can control it from our computer. So the notion is you can build circuits that are bidirectional power flow capable if you choose.

What could I tell about this thing? Well, I can tell a couple of things. In periodic steady-state operation, I know that the magnitude of V2 has to be bigger than the magnitude of V1 because we showed if I'm boosting, V2 is bigger than V1. If I'm bucking from this side to this, this voltage is bigger than this voltage. So that I know because of periodic steady-state analysis.

What else can I tell about it? I could also argue that I can tell you the polarities of allowable voltages here. Why? Well, let's look at V2. If I told you I was going to make V2 negative, what would be the problem with that? The two diodes would just turn on and short the negative voltage source out. And then bad things would happen.

So V2 must be positive. I can actually even look at V1 independently of that and tell it must be positive. Why? Because the average voltage in periodic steady state at this node must be the same as this node, and likewise. So that means this has an average voltage of V1. And that means this diode would turn on if I tried to make V1 negative.

So I can tell something about this. I can tell what polarities of voltage are allowable. I could build a buck converter or a boost converter-- went from negative voltage to negative voltage. I just have to change my switch implementation, or I could build one that, for example, would allow either polarity of voltage. What I would have to do then is go rethink how I implement these switches.

Of course, if I came back to you and said, I don't really have two voltage sources or two batteries here, this guy over here-- he's actually a resistor. Well, then you can tell what it can do in steady state, anyways, because I can't source energy from at least positive resistors. So I would know that this converter was designed to flow power this way, at least on average.

So that's a little bit about what people think about in switch implementation. You've got to go for what voltage amplitudes and polarities you need and then you-- and what current and what power carrying directions you need. And then you work back from that to the simplest switches you can use to give what you want. Any questions?

So the buck and the boost converter-- whether this is a buck or a boost depends on power flow direction-- are examples of what are known as direct power converters. And they're called direct power converters because in one of the two switch states, we transfer energy directly via current from the source to the load.

You can build other kinds of converters. And in fact, if I took this original canonical cell that I drew, this guy, and turned its-- on its end, I changed which ports I was using, its input and output, I could build a different kind of converter. It could look like this. This is one way to do it. It looks like this.

I will have a single-pole, double-throw switch. I will put my capacitor here. I'll put the inductor here. And then I'll put the other port here. So then I can connect up, for example, if I made this V1 and I made this V2. That would be another possible way I could build a converter. And I can make this switch in this position. When q of t is equal to 1, it's in this position. When q of t is equal to 0, it's the other position.

So we could go analyze this circuit. I should say, by the way, that when people implement this circuit, they often-- this is a nice pedagogical description. But they often implement it by splitting this capacitor. So instead of having some voltage Vc here-- if this voltage V-- if V1 is constant and Vc-- and the capacitor is really big so that Vc is almost constant, then clearly, V2 is going to be almost constant.

So this capacitor can act to stabilize voltage V2. But perhaps more common would be to build it this way, have V1 a switch like this. And maybe put a capacitor here and another capacitor here and the load like this and call that V2. So that might be a very typical way to actually implement this circuit.

So let's think about what would this circuit do in the real world. Well, here's my signal, q of t. So I'm going to operate it periodically-- DT, T. In order to analyze the other circuit there, what did I do to analyze its behavior? How did I figure out what its steady state operating characteristics were?

If you came back here, what I really looked at is what was the average voltage on the inductor. So why don't I do that again? Again, I'll plot the average voltage on the inductor here, V sub L. So let me plot V sub L.

So when this q of t is 1, then the switch is in this position and VL is equal to V1. So let me make V1 positive for sake of this analysis. So I have V1 here.

When q of t is equal to 0 and the switch flips, VL is equal to V2. So VL is equal to V2. And I know I need the average voltage on this inductor to be 0. Then that must mean that V2 is going to be some negative number. So V2 is going to be possibly-- look like this.

And what I know is-- so here's the voltage across this inductor. And what I know is that the average voltage here has to be 0. That means that this positive area, this volt-seconds positively on the inductor, must be balanced by this negative volt-seconds on the inductor, or another way I could look at that is I could say that the average voltage V sub L is equal to what? It's equal to D times V1 plus 1 minus D V2. So that means that V2 must be equa to minus D over 1 minus D V1. Does that make sense to everybody?

So I can tell two things from this. One is this is a number-- D over 1 minus D is a number that for D 0 to 1 goes between, basically, 0 and infinity. So the first thing I can say is the voltage V2 must be negative. I'm applying a positive voltage here in the first part of the cycle. So V2 in the second part of the cycle must be negative.

So first of all, I can tell that this circuit is going to invert the voltage. So if I have a positive input voltage, it's going to be give me a negative output voltage in periodic steady state.

The other thing about it, though, as I can tell, is that I said this number, D over 1 minus D, varies anywhere between 0 and infinity. So this circuit-- if I put aside the polarity of the output voltage-- sometimes I want an output voltage that's the opposite polarity of my input voltage-- I can make the magnitude of the output voltage anything I want, bigger or smaller than the input voltage, because this scaling factor, by choosing D-- if I make D equal to 0.5, V2 exactly equals V1.

It's the opposite of V1. If I make it bigger than 0.5, the magnitude of V2 is going to be bigger than V1. If I make it less than 0.5, the magnitude of V2 is going to be less than V1.

So this is a very flexible circuit. It will let me do whatever I want. Whereas a buck converter can only step down voltages and a boost converter can only step up voltages, this, at least in the terms of the voltage magnitude, will do whatever the heck I like. Any questions about that? Yeah?

AUDIENCE: Does the capacitor up top still help to filter out the output voltage?

DAVID PERREAULT: Yes. Excellent question. The question is, does the capacitor still help you-- if I place it here, still help you filter the output voltage? And the answer is yes because if this node is at a constant potential because, say, V1 is constant and the capacitor here is really big such that Vc doesn't have any ripple, then V2 doesn't have any ripple. So yes, this capacitor placed here can certainly help stabilize V2 as long as V1 is stable. So we could build it that way. And sometimes, people do.

So let's think about this. Let's look at an implementation of this circuit. Suppose I wanted to do it for V1 greater than 0, V2 less than 0. So maybe I would implement it like this. Here's my voltage source V1. Maybe I'll use a power MOSFET. I could use an IGBT as well. We can implement this either way. But maybe I'll implement it like this. And this is V2.

So if I thought about the power flow direction of this, what do I know? I know that V1 must be bigger than 0 because of this internal body diode here because otherwise, then V1 would get shorted out on average. So V1 must be greater than 0.

V2 must be less than 0. I1, the average current flowing in here-- if I pretended that this capacitor filtered everything perfectly, this would give me I2 on average. This would give me a current I2.

And what do I know? I know that I2 must be positive. Why do I know that? Because if this is the average or DC current coming this way, no DC current goes into the capacitor. So it must go through this diode. And we know this diode can only carry current in one direction.

So I know that V2 is negative and I2 is positive. So V1 greater than 0, I1 greater than 0, V2 less than 0, I2 greater than 0-- so power can only flow from this side to this side. That's just an example of doing this.

What else could I tell about this converter? If I thought of the voltage on this capacitor, Vc, how big is that capacitor voltage? Well, I could argue that the DC value of Vc-- the DC value-- I can do average KVL around this loop.

So I could say that V1 minus Vc minus V2 is 0 or, written a different way, Vc is equal to V1 minus V2, or if I wanted to take the magnitude here, I could say that the magnitude of Vc is equal to the magnitude of V1 plus the magnitude of V2. Why? Because V2 is negative. So in this example, this capacitor voltage-- because V2 is negative and V1 is positive, this capacitor blocks a lot of voltage if I place the capacitor there.

What can I say about the current? What would I say about IL, for example? And now I'm going to talk about the DC component, capital IL. I'll pretend this inductor is so big, it doesn't have any ripple. And it's instantaneous equally-- equal to its average current.

Well, what could I say? I can do average KCL analysis on this. Imagine I come and I draw a supernode in this circuit. What do I know about that supernode? The average current going into that dotted dashed box must be 0.

So the average current going in here is I2. The average current coming in here is I1. And the only place for those currents to come out is IL. So what I can say is that IL-- the magnitude of IL is equal to the magnitude of I1 plus the magnitude of I2. IL, I1, and I2 are all positive in this example because we've already said I1 and I2 have to be positive.

So basically, the inductor current carries the sum of the input and output DC currents. Does that make sense to everybody?

AUDIENCE: Why don't we use the supernode? Couldn't we just look at the node inside?

DAVID PERREAULT: But this node-- you could. But keep in mind this current I can think of as almost being current-- constant all the time because of the filtering of the capacitor. This current is pulsating. So I'd have to think about it more carefully. So I was just trying to limit myself to currents flowing in that are, ideally, close to DC. Excellent question.

I don't know. The first time I saw this circuit, it bothered me. I was like, why does that inductor really carry the sum of the input and output currents? But let's think about what's going on in this circuit. Let me pretend that this capacitor is doing a really good job of filtering so that it carries all of the AC current. And so the I2 and I1 are almost constant.

What does the current flow look like? Well, let me look at, for example, the switch current flow. So if I looked at this switch current flow, I switch, what does the switch current look like?

Well, in the first part of the cycle-- or the switch current's carrying IL in the first part of the cycle. So in the first part of the cycle, the switch current carries IL. So this is I switch.

And in the second part of the cycle, the switch carries nothing. So the switch pulsates between carrying some big current and carrying 0 and doing this. And what's the average switch current got to be equal to?

Well, there's no average current coming up through the capacitor. So on average, the switch current must carry I1. So this switch has some-- I switch of T is pulsating. But his average value has to be I1.

If I looked at the diode current-- here's the diode current-- when the switch is on, he's carrying 0. When the switch is off, the diode's carrying IL. So he steps up. And he carries all of IL. So he's switching the opposite way.

And by the same argument, the average of the diode current must be I2. So it turns out that IL is the sum of I1 plus I2 in order that it be carried-- it's constantly carrying the sum of I1-- I switch plus ID is always equal to IL. So when I add these two up, I get IL. So that's why the inductor current has to really carry the sum of the average input and output currents.

If I thought about the capacitor, what's the capacitor doing here? Let me plot the capacitor current. And maybe we can get some insight from that.

When the switch is on, IL is coming through here. Where does I2 go, the average current I2? It must come negatively through the capacitor. So the capacitor is carrying minus I2 in the first part of the cycle. And in the second part of the cycle, when this is off, I1 must be going positively through the capacitor, like this. And this is I C of T.

What do I know about the average value of I C of T? 0. So that must mean that DI2 must equal 1 minus DI1, or I could write I2 is equal to 1 minus D over D times I1.

Well, guess what? That's exactly the complement allowing for the sign of the voltage conversion ratio, which comes back to the fact that this thing is supposed to be, ideally, 100% efficient.

So basically, all of the AC currents run around in this loop, allowing DC at the input and output. But the result of that is that the inductor current must carry the sum of those currents. That make sense?

So this is, by the way, known as a buck-boost converter because it can either step up voltage or down voltage or step up current or step down current. It's sometimes known as an inverting buck-boost converter to distinguish it from other kinds of buck-boost converters. But this would be the buck-boost converter.

Let me just show you by way of illustration this operation. So what I created here, if my computer will wake up, is a simulation of a very simple buck-boost converter. So I split the capacitors in this example. But I'm running from 8.5 volts input. And we've set our duty ratio to 0.75.

So let me just simulate this. And let me just look at what the output does. At T equals 0, the output is initialized to 0. And what we can see is the output starts at 0 volts. But then he goes negative. And he goes through all this transient-- and stuff happening. We'll talk about the dynamics of this converter. But eventually, it gets to periodic steady state out here.

So what do we see? There's the output voltage. Here's the input voltage. So it's coming from plus 8.5 volts and going to minus 27 volts. We can see that this inductor voltage is pulsing between the two.

So it's acting-- what is it doing in the first part of the cycle? It's sucking energy from the input and storing it in the inductor. And in the second part of the cycle, that energy is then being thrown to the output. So all of the energy in this circuit is going through the inductor.

The only way energy gets from the input is from the input into the inductor. And the only way energy gets to the output is from the inductor to the output. So it's an indirect conversion in that all of the energy flow is mediated through the inductor.

You can see that here. If I plotted the inductor current, you can see that in the first part of the cycle, the inductor's-- current's going up. In the second part of the cycle, it's going down because I'm charging up the inductor from the input in the first part of the cycle and discharging it into the output in the second part of the cycle.

So this is a very flexible converter. But what we're going to see is that it's also a very high-stress converter. Why? Because the inductor has to carry the sum of the input and output currents. The capacitor, if I put it here, would have to block some of the input and output voltages, or if I have two capacitors, I-- then I have two capacitors, one of which blocks the input and one of which blocks the output.

And notice that the switch-- when it's off, it sees the capacitor voltage or the sum of the magnitudes of the input and the output voltage. When it's on, it's carrying the full inductor current, which is the sum of the average input and output currents.

So I'll go into this more detail next class. But what we find is this is a very flexible converter. But because it modulate or mediates all the power flow through the inductor-- end ups with very high stresses on the inductors and capacitors and switches. And so it tends to be a more expensive converter than a buck converter or a boost converter.

So if I could only do-- if I only need a buck function, I don't want to build this guy. But if I need to raise my voltage above and below the input, maybe this is a great way to do it.

We're out of time. We will take this up. We will see you, remember, next Tuesday because Monday is a holiday. So have a great holiday weekend.