[SQUEAKING]

[RUSTLING]

[CLICKING]

DAVID PERREAULT: OK, why don't we get going? So just as a brief reminder about where we started last class, we started to introduce some tools to think about switching circuits and, in particular, techniques for time domain analysis of such circuits. So the first thing we said was we said if we had diodes in a circuit, we can't really tell them when to turn on and off. They turn on and off based on what's going on in the circuit.

So we came up with this notion of the method of assumed states to instantaneously figure out what's going on with an individual diode of the circuit. And essentially, we take a guess, maybe an educated guess, and set up the diode states to be on or off and replace them by open or short circuits. Then we calculate the voltages and currents in the circuits. Then we check if the switch conditions are violated. That is, we say, Does a diode have a forward positive voltage when I think it's off? which we know it can't. Or does it have a negative current when it's on? which we know it can't?

And if we found out that one of those switch conditions violated, it's time to make a new assumption. Otherwise, we were happy with the state, and we keep going. And we work this through time to figure out what's happening as devices are turning on and off over some switching cycle.

The other idea we came up with last class was this notion of periodic steady state, which is like sinusoidal steady state, except we don't have sinusoidal waveforms. It's basically, in each cycle that we're operating, the waveforms just are repeats of one another. It's settled down to this perfectly repetitive operation. And that's often-- not all power circuits operate that way, but mostly they do.

And one of the advantages of thinking about that mode of operation when it's running in steady state is because you can start to say a lot about the circuit waveforms. And that can help you figure out what the circuit is going to do or what it's capable of in periodic steady state. So, for example, what we found-- if we're in periodic steady state, suppose x is a voltage. We know that the average rate of change of this voltage is 0 because it's just going up and down. And that means if it was a capacitor, because the average rate of change of voltage is 0, the average current through a capacitor in periodic steady state 0.

Likewise, the average voltage across an inductor in periodic steady state is 0. So we can start to identify certain characteristics of circuit operation when it's in periodic steady state. And we'll elaborate on this further in some upcoming lectures when we start talking about converter analysis. So that's just a lightning review of what we talked about last class. Any questions before we move on?

I'd like to pick up from where we were last class. As examples of device circuits with diodes in them, we started talking about rectifiers, and we introduced this notion of a half wave rectifier. And I'd like to elaborate on that a little bit. So here's the circuit we introduced.

We had a sinusoidal voltage source, Vs sine omega t. We had a first diode that I'll call D1. And maybe I'll call this VD1, and I'll call this I1. I have a second diode. We'll call this Vx and I2.

And then we have an output filter and an actual output that we'll call, say, V sub d. And so maybe we will think about this voltage as being something we studied what it was doing, Vx. And maybe we're interested in I2, the current through this diode, and perhaps I1, the current through this diode.

And what did those waveforms look like? Well, we did our method of assumed states analysis. We said, OK, here's my voltage waveform, my sinusoidal voltage waveform. So I'm going to plot this versus electrical angle, omega t. So this is Vs sine omega t.

And what we found in our analysis is this. We said once the voltage waveform crosses 0 positive here, D1 must be on, and D2 must be off, because otherwise we would violate the method of assumed states. If I assume D2 was on, then D1 would have a positive voltage across, and I know it can't be true. So what we found is that in this time period, I have D1 on, and in this time period I have D2 on.

So that meant that our voltage Vx looked like this. In the positive part of the cycle, when D1 is on, it basically just tracks the input voltage. And in the negative half of the cycle, I get 0 because D2 is on. And this just repeats.

And then we went further to say, OK, what is the output voltage Vd? And what we did was by basically saying the average voltage across the inductor has to be 0 in periodic steady state, we know that the average voltage of Vx is the average voltage Vd. If I assume that inductor is really big and the ripple current is really small, the output voltage is roughly constant, and the value it's going to take on-- by analyzing that, we said the average value of Vd is simply going to be equal to Vs over pi.

Now, what's happening practically is let me imagine that this current ID is almost constant, This is a really big filter inductor. And we often do that when we start to analyze power converters. Let's start by assuming we get great filtering, and then we can figure out what happens when we back off from that. So let's assume that this current is almost constant.

So maybe I would plot ID looking something like this. Maybe in reality it has some ripple in it. And what happens? Well, in the first part of the cycle, D1 is on. So I get a current, I1, that does this. In the first part of-- in the first half of the cycle, sorry--

In the first half of the cycle, this is my input current. So this is I1. So the diode 1 carries the current. In the second part of the cycle, diode 2 carries the output current. So here's like this. And so they just alternate carrying current for half the cycle. First diode 1 carries all the current, then diode 2, then diode 1, and so forth.

And that's the conclusion we came to about what's happening with the circuit. So basically, in the first half of the-- first half of the cycle, D1 carries the current. And then immediately the current switches to diode 2 in the second half of the cycle and just keeps flopping back and forth, commutating back and forth.

Let's now start to elaborate on that a little bit. And I'd like to consider a specific case. I'd like to expand this circuit that we're considering a little bit. And what I would like to do is add a little bit of inductance on the AC side. So instead of having a perfect sinusoidal voltage source like this-- here's Vs sine omega t again-- I am going to include an inductor that I'm going to call LC.

And then I'm going to connect this to my rectifier that I had before. So here is again D1. Here's again D2. And here's my output filter. And I have the same kind of waveforms I had before.

I have Vx, I2. I have I1, which is now this current, I1. And then I have my output voltage. I have ID and Vd. So why would I go to the effort of introducing this particular variation on the theme?

And the answer is because this often happens. Where do we see-- from here on what I have is a rectifier. We saw that basically I took a perfect AC voltage, and then I turned it into something with a DC component, and I filtered it, and I extracted the DC. Well, we do that all the time in all kinds of things. If you're plugging your laptop adapter into the wall, at the front end of that thing is a rectifier, which is converting AC to DC.

All kinds of other applications have that. So if you have-- in fact, it's true for the wall. It's also true if I build-- what we'll see later in class, if I build a high-frequency, resonant DC-to-DC converter, what I do is I create really high frequency AC signals like a megahertz, run them through a transformer, and then rectify them in some kind of rectifier like that. It doesn't have to be that exact rectifier, but you do it.

In both of those cases, you may have inductance on the AC side. Well, why? If I'm plugging into the wall, I've got all the wall wiring going back. And then somewhere back behind there is a transformer, which has what's known as leakage inductance. So generally, you're not looking back into a perfect voltage source when you're looking into the wall. There's some source impedance. And that's typically inductive.

Likewise, in the high-frequency converter I mentioned, it has a transformer in it. And that transformer has some parasitic inductance. And you're stuck with that. And so you're stuck with what that does to you. The last example I'll show you where this kind of thing turns up is in any kind of generator. So this is an automotive alternator.

So what it does is it has an electromagnet that essentially spins inside a set of coils, generates a big voltage. And then there's a set of rectifiers. These are the diodes right here. They turn that AC back into DC. So it goes mechanical energy input to AC voltage back to DC voltage. And that's what charges the battery in your car.

Now, this is a three-phase device instead of a single phase, and we'll talk about three-phase later. But the basic concept is exactly the same. And the challenge in here is you have all these coils inside, and, again, there's leakage inductance. So you're stuck with extra inductance on the AC side that you don't want. So in practice, if I'm going to rectify, I often-- not always, but often-- there's some inductance here, whether I like it or not. And so I better know what that inductance does to my circuit.

So it's important as a practical matter, but it's also kind of useful to look at from understanding how to use these analysis tools. Any questions about that?

OK, so let's think about how I might model this. Now, when I think about it-- maybe I'll call this inductor LD. Typically, LD is much, much bigger than LC. This is a parasitic inductance that I'm sort of stuck with. This is a big filter inductor. And for the moment, I'm actually going to think about this thing as being close to infinite. So let's just remember that this is kind of a smallish inductance that I'm stuck with. This is a really big filter inductor usually.

And what we can do in order to analyze this circuit is maybe I'll make a simplification just for us going through it. And I sort of already did it over there and didn't really mention it. Maybe what I'll do is I'll come in here and I'll say, OK, here's my voltage, Vs sine omega t. Here's my leakage inductance, or I call it L sub C for Commutating inductance for reasons we'll discuss. Here's my diode D1. And here's my diode D2.

And I'm just going to replace this whole second piece with a constant current ID. So I'm going to assume this filter inductor is so big that I can ignore the ripple in that current. So I can think of the load of this thing as being a current source. Now, it's a very special current source. The question is, what is the value of that current? Well, in reality, what it is, is it's-- the average value of Vx is the same thing as VD divided by R would be this current.

So this ID is actually equal to the average value of Vx divided by R will be that current. So it's kind of a funny independent current source. It actually depends upon this average value. But we're analyzing the periodic steady state case. It has some value. Let's just call it constant at that value. Any questions about that?

So what do I have in this circuit? Well, what I want to do is go through and analyze the behavior of this circuit over time, just the way we did before. And if I think about it, I have two diodes. There's four possible states.

One possible state is that both diodes are off. But because I have a current here, both diodes can't be off. Another possible state would be both diodes on. A third possible state would be D1 on and D2 off. And a fourth possible state would be D2 on and D1 off. That's our universe of possibilities in analyzing this thing. So let's go through and analyze and see what we get as we go along.

OK, so here's the waveforms. I'm going to use the same color coding. Here's my voltage waveform. And here is my current. So here's omega t. And I'm just going to assume my load current rid is constant.

All right, so what did I have at just before t equals 0? Over here, just before t equals 0, D2 was on. So let me just assume that coming up to this point here, D2 is on.

So when D2 is on, let's see, what do we know? Vx is 0. Vx looks like this. Since D2 is on, D2 is carrying all the current, so it looks like this. Here's I2. And the question happens, what happens now when the voltage crosses 0? OK, well, let's just draw that out again.

So we said, all right, what I'm going to have is this is my method of assumed states. I had this device open. This device is a short circuit. And here's my load current here. And this is VD1. This is VD2. And this is Vx.

And it would help if I included my commutating reactants in here. Here we go. LC. And I should add in my current, I1.

OK, so what happens when Vs sine omega t crosses 0 positive? Well, what happened over there was D1 had to turn on. And I'm going to argue that D1 still has to turn on. Why is that? Because if I assume he's off, there's no current through here. There's no dI/dt in this inductor, and hence there's no voltage across that inductor. So what that means is essentially Vs sine omega t drops through 0 and then appears as VD1.

So basically, as soon as this voltage crosses 0 positive, the diode 1 voltage would go positive. And we know that diode voltages can't be positive. So basically, as soon as this voltage crosses 0 positive, this diode is going to have to turn on. But what do I know here? So I can say, OK, he turns on. So now I'll assume he's a short.

In the other circuit or the earlier version, D2 immediately turned off. But can that happen here? Keep in mind that if I had I1 of 0 minus is equal to 0-- because he had no current through him. This diode was open. Right after t equals 0 plus, well, he's an inductor. His state doesn't want to change. Unless you put an infinite voltage across him, he's still going to have 0 current.

So that must suggest that I1 of 0 plus is still equal to 0. If I1 of O plus is equal to 0, and this is Id, that means I still have current going through this device. I can't make that go open, because there's no current going through here. And so this Id has to go somewhere. So now what I find is I can-- if I work through that argument, that just says that both of these devices have to be on.

So I'm going to have a new state where I have both D1 on and D2 on. And essentially what I have is now this circuit is-- some of the current from Id is going to go through here. Some of it's going to come from the source. And this current I1 is going to change over time. Essentially, the input voltage, Vs sine omega t, is being impressed across this inductance. Any questions about that?

So what does that mean? Well, I can calculate-- what I get is dI1/dt-- L dI1/dt is equal to Vs sine omega t. So that means I ought to be able to calculate I1 of t is equal to Vs over L, the integral of sine omega t dt.

But what I'm going to do is I'm going to change my variables. Let me change my variables to omega t, so I'll put an omega here and omega here. And I'm integrating from 0 to some time omega t. Maybe I should go back and change this symbol to theta just to make it a little clearer. But that's the integral I'm calculating.

So what do I get? What I'm going to get here is I'm going to get Vs over omega L times cosine of omega t minus-- I'm sorry, cosine of 0 minus cosine of omega t and cosine of 0 is 1. So this just becomes 1 minus cosine of omega t. So now I know what I1 of t or I1 of omega t looks like. Does that make sense to everybody?

And essentially, right as he crosses 0 positive, I have no voltage across this because it goes as a sine wave. But then the voltage starts to increase. And hence the current starts to increase as the integral of the sine. So what's going to happen? I'm going to get this waveform for I1 one of t. If I were to plot that over here, it would look something like this. It would start off as 0. And it would come up, and it would keep going up like that. That make sense to everybody?

And what's I2 of t? Well, I2 of t-- I2 is simply equal to Id minus I1. So basically, I2 started out as Id. And he does the exact complementary thing, and he slopes down. He initially has 0 slope, and he's doing this, and then he keep going like that. Any questions about that?

Well, why did I stop drawing things? Because keep in mind, we have our method of assumed states going on. Once I1 hits Id is exactly when I2 hits 0. I would say by this calculation that presumably it would keep going and I2 would keep going negative. But I2 can't go negative because there's a diode here. So as soon as I2 hits 0 and tries to go negative, D2 is going to turn off.

So I'm going to hit some point here, right here, where-- and I'm going to call this some time u, omega t is equal to u-- where basically D2 is going to turn off. And maybe then I'll only have D1 on. Does that make sense, everybody? Because otherwise, he would have a negative current in. That's my third assumption.

Well, how can I find that time? I can find that time by a simple integral. I can say, OK, what do I know? I know that I1 of t equals Id. That's when this happens is that. And that's equal to Vs over omega L times 1 minus cosine of u.

And so I can rearrange this, and I can find cosine of u is equal to omega-- this should be Lc-- omega Lc Id over Vs. I'm sorry, cosine of u is 1 minus.

This angle u is what's known as the commutating angle. And it has units of electrical degrees or electrical radians. And why am I saying that's the commutating angle? Because what's happened here? If I were to draw what's going to go on now, I have D1 on, D2 off.

I have a constant current out here that's now going to go through D1, and I'm carrying a constant current. So what happened is in this original circuit break, I was carrying-- diode 2 is carrying the current, then immediately diode 1 switches and carries the current, then diode 2 switches and carries the current, et cetera.

Once I add inductance here, it doesn't switch instantly, because it can't, because there's inductance which doesn't like to have its current change through it instantly. So I get some new period in which the current switches between going through this path and going through this path, what we would say commutates from this branch to this branch.

And if I were to do the same of analysis, what I would find is, guess what, when I hit omega t is equal to pi, it would do the same thing. And this current would ramp down like this. And I2 would ramp-- I2 wasn't carrying any current in diode 2, then picks up the current and does this, and then it switches over. And this would happen at an angle pi plus u.

So all I get is some finite time in which the current switches between the two diodes instead of just, bam, happening instantly. Any questions about that?

AUDIENCE: So in the previous example, we just had the filter inductance. Do we get the same phase shift over the period where D1 is on?

DAVID PERREAULT: So to repeat the question, the question is, did I get the same phase shift? And the answer is no. The difference here isn't the fact that this is no longer finite. I actually assumed it was kind of infinite over here too. The difference is that I have that commutating inductance in there, and one of the effects of that commutating inductance is to smear the currents a bit later. Does that address your question, or did I misunderstand it?

AUDIENCE: No, no. It was good.

DAVID PERREAULT: OK. All right, so why am I making a big deal about this? Why am I even mentioning it? Yeah, OK, we get another diode state, and it happens. And that's true, but it turns out to have reasonably important consequences in a lot of designs. Why is that? Well, let's think about-- let's come back, and let's look at this voltage Vx here. Well, what does Vx do? What is Vx when both D1 and D2 are on?

Anybody want to take a crack at that?

AUDIENCE: Wouldn't it be 0?

DAVID PERREAULT: Yes, right. D2 is on. This is a short circuit. V2 better be 0. So before, I got this nice half sine wave bump. What's going to happen is between 0-- for the entire time the current's commutating, I've got 0 here. Once it's only D1 one on, then Lc has a constant current in it, and so it has no voltage drop across it. And then I get the remainder of this. And the second half of the cycle, it does the same thing as last time.

So what happens is once I have this commutating inductance in there or commutating reactance in there, I take a bite out of my half sine voltage. And remember, this is the thing that we're averaging to get our output voltage. So now let me say, what is the average voltage? What's the average of Vx, which is the same thing as the average of Vd?

Well, I can calculate that. The average value of Vx with commutating reactance is going to be equal to 1 over 2 pi. The integral-- from when?-- from some angle u to some angle pi, Vs cosine of omega t d omega t.

OK, so what does this end up being? This ends up being 1 over 2 pi or Vs over 2 pi times-- oops that should be sine, sorry. The voltage waveform is a sign. This should be equal to times cosine of u minus cosine of pi.

Well, if I work that out, then what's the cosine of u? Well, conveniently, I have that here. That's 1 minus omega Lc Id over Vs. What's cosine of pi? It's minus 1. So this becomes Vs over 2 pi times 2 minus omega Lc Id over Vs.

So if I rewrote that, what I can say is the average value of Vx once I filter it is also Vd, the output of the rectifier. So Vd then, then becomes Vs over pi times 1 minus 1/2 omega Lc Id over Vs. Sorry, that's a little bit of a mess.

But it should be basically just this. By the way, this comes up all the time in these kind of rectifier applications. This is a unitless expression. I'm subtracting it from 1, so it better be unitless. Omega Lc Id over Vs, or we might write it as Xc Id over s is known as the reactance factor.

And what it's-- and actually, let me just rewrite this because it's a mess.

What it says is this. Suppose Lc was 0. This term would be 0, and I'd just get Vd is equal to Vs over pi. So that makes sense because my first analysis was with Lc equals 0. But as any of the load current or the commutating inductance or the frequency increase, this tends to degrade my output voltage.

So suppose I was-- I generate this high-frequency voltage and then I rectify it, expecting to get-- in this rectifier, it would be Vs over pi as my output voltage. And suddenly I do that, and what happens? Well, I get this droop that's load dependent. So if I was to plot this, what I would see is this. I would see--

Let me plot this versus-- I could plot it versus different things, but let me plot this versus Id. In my original rectifier, if I plotted Vd versus Id, what I would just get is Vs over pi. No matter how much current I draw from this rectifier over here, I'm going to get Vs over pi at the output. So I could kind of reliably generate that AC voltage, rectify it, and I'd get what I want. And very typically, I'm trying to get a voltage out of a system.

What this says is that the voltage that I get, Vd, actually droops versus current. And in fact, I'm going to get 0 voltage once the current gets to be equal to 2 Vs over omega Lc. So actually, my actual characteristic looks like this when I have commutating inductance.

If Lc goes to 0, this point moves off to infinity, and I get the straight line I was hoping for. This phenomenon is called load regulation, meaning that my load current somewhat determines my output voltage. It's as if I had hoped to create a voltage source, and I don't quite get a voltage source. I get a droopy voltage source.

Now, do I care? Well, if Lc's really small, and for full current, I only drop 1%, no, I don't care. If Lc gets too big, however, maybe I have a problem. In fact, this actually limits the amount of power I can get out of that source. Because if you think about it, if I draw too much current, I get 0 voltage. So I'm not really getting any power at the output.

And in fact, we once had that. We designed a really high-frequency resonant power converter, and we had rated it for, I don't remember how many it was, like 500 watts or something. And what we found out is we couldn't actually get more than 400 watts out of the thing. Why? Because the transformer leakage inductance was making it droop just enough that it was stealing our ability to deliver the current we wanted.

Or as we delivered more and more current, the voltage would droop. And then I wasn't getting enough power, so we weren't making our voltage rating anymore. So this can be a practically important phenomenon, both for line frequency rectifiers where you're trying to get power out of the wall or even a high-frequency megahertz power converter.

Now, first of all, let me stop there and ask if there's any questions about any of this concept so far.

OK, how would I model this? What would be the DC equivalent circuit model of this thing? Well, if I thought of-- if I wanted to think about, for example, everything over here in an average sense, like, What is the IV characteristic looking back here?-- well, Vd is also the average of Vx here-- I might think of this as a voltage source, Vs over pi, in series with an output resistance.

How big is that output resistance? It's really Vs over pi divided by 2 Vs over omega Lc. So what I get is an effective output impedance, omega Lc over 2 pi. This has units of resistance. Omega is reactance. It has units of ohms. So omega Lc over 2 pi has the right units to be a resistance.

And then I could connect this thing to, effectively, my inductive filter or more simply my load current Id. So this is not a bad model for how on the AC side-- looking back from the DC side or looking back from the side of this filter how this thing will behave on average.

Why is it drooping? Why is there this effective output versus-- well, first of all, this is a DC equivalent model. There is no loss here. I think a resistor-- I think it got lost, right? I'm not burning power anywhere. There's no loss. There's no watts being turned into heat.

What's happening instead is that each time this voltage swings positive, I've got to take some time to charge up this inductor to the right current. And that time eats away from the time at which I generate my positive pulse, which is rectified to give me output voltage. So I'm of eating into my ability to synthesize a DC output voltage because I have to charge him up.

So if I have a higher frequency, it's a higher percentage of the overall cycle because it takes a certain amount of time with voltage to do this. Or if I have a bigger inductance, it takes more time. Or if my voltage is smaller, it takes more time-- my source voltage is smaller. So it all comes back to this unitless factor omega Lc Id over Vs. If that factor gets bigger, the droop gets bigger.

It's also, by the way-- if I wanted to figure out-- imagine I came to this rectifier and I dropped a short circuit on it. If I told you take that thing and make the resistance go to 0, you'd think, well, I'd get infinite current, wouldn't I? Because I'm basically taking a voltage source and putting a short circuit on it, and you get infinite current.

Even if you're commutating reactance is small, it's what's going to limit-- ultimately, there's a limit to how much current that will synthesize. So if you wanted to calculate the short circuit current, that's how you would figure it out. You'd have to include-- even if it was a small reactance, you'd have to include that AC side reactance. So maybe, in that sense, it's a good thing if your currents don't go off to infinity. They only go off to some really big number that you don't like.

But it influences all kinds of things. I mentioned we had a problem with the high-frequency resonant converter we built. Or if you were thinking, I'm going to rectify the line voltage to get a voltage I know out, and I'm getting droop, I probably don't like that. That shows up in a big way in these automotive alternators. It turns out that the reactance is really, really very big. So the output of this thing is supposed to charge basically a 14-volt automotive battery.

How big do you think the AC voltage, the effective AC voltage is to do that, this Vs? And whereas you might think you wanted to synthesize a rectified voltage of like 14 volts, it doesn't. It's more like 70 or 80 volts when it's under full current load. So really, you have something where that alternator is really generating a really big voltage with a really steep droop to it.

And so it actually almost looks closer to a current source or somewhere between a voltage source and a current source. And in fact, that can cause trouble in an automotive application because there's something called a load dump. Imagine you're charging your battery with lots and lots of current. So what they do is they crank up that voltage Vs. That voltage Vs is controlled by an electromagnet which is then regulated to get the right voltage to give you the charging you want.

But if your load suddenly goes away, that's way too much voltage, and you get this big spike in DC voltage. Why? Because what happened is you were operating down here, and suddenly the current went away, and you went over here. And now you've got this big voltage. And guess what. That big voltage is being slapped across all your electronics. So all the electronics in your car, despite the fact that they're designed for 14 volts, all those modules, every single damn thing in your car has to be rated for 80 volts-- it's kind of crazy-- all because of this crummy alternator that has massive amounts of load regulation in it.

So there's all kinds of examples. And like I said, I showed it to you in the simple half-wave rectifier. This is an even-- this is a three-phase rectifier that the math for is all about the same. It does the same kind of thing.

You can also get this in other contexts where instead of series inductance, shunt capacitance, such as owing to diode capacitance, can also mess with your ability to rectify voltage and get energy out of an AC system.

So that's just-- I wanted to show you some of the effects of how we think about analyzing a rectifier and using the method of assumed states and some of the things that happen in practical rectifiers. And we're going to come back to this because we're going to look at those as parts of different kinds of power converters. But perhaps I'll pause there and ask if there's any questions. Yeah.

AUDIENCE: Do you know if it does this by adding a capacitor in parallel after the inductance?

DAVID PERREAULT: Oh, could you play some game to reduce the effect of the source impedance?

AUDIENCE: Yeah, like the [INAUDIBLE] for the diode current.

DAVID PERREAULT: Yeah, you could try. That would tend to be a very-- I mean, it depends on the application. The challenge with that is it tends to-- in that kind of application, you'd need a really big capacitor because it's relatively low frequency. So yes, you could play some games like that. There are other ways you can fix the problem, too. So the answer is yes, that's a very clever idea. And you can apply that, but it's very application dependent. So, yeah, there's ways to fix the problem, yes. Or you could just design a better machine that doesn't have so much leakage. That would be another way to do it. Other questions?

OK, so that's all I wanted to say for today. What we're going to do next time is we've looked at this rectifier from the DC side, like what is the characteristics when I take AC energy and turn it to DC. The thing we haven't looked at is what about this poor AC grid? And what happens when I start pulling weird currents through it like from some rectifier? And that turns out to be quite important for energy efficiency. And so we'll pick up that topic next class. So have a great day.