[SQUEAKING]

[RUSTLING]

[CLICKING]

DAVID PERREAULT: OK, why don't we get started? So we're going to continue talking about three-phase power conversion systems. And I should have noted that what we're talking about is contained in *Principles of Power Electronics* chapter 9 for reading. And just as a reminder, we talked last time about all the advantages you can get from three-phase systems, and we'll see that again today.

But just to remind you, I might have three voltage sources-- Va, Vb, these are all of t, and Vc. I bring out three phases, and I may also have a neutral.

And if I wrote Va of t is equal to Vs sine omega t, Vb of t is equal to Vs sine of omega t minus 2 pi over 3, so 120 degrees lagging, and then Vc of t is equal to Vs sine of omega t plus 2 pi over 3, so this might be 240 degrees lagging or 120 degrees leading, depending upon how you would like to look at it.

We said we could represent any such individual signal as a phasor. So we might say Vx of t is equal to the real part of Vx hat, which is the phasor, e to the j omega t, which represents the sinusoidal nature of it. So Vx hat contains the magnitude and phase.

So for example, in this example, VA hat would be equal to Vs, its magnitude, e to the minus j pi over 2, because with respect to the real part or with respect to a cosine, it's phase shifted by minus pi over 2. And I could make equivalent phase-shifted versions for VB hat and VC hat.

And if we draw that on a phasor diagram, what I might get is something like this. So now I'm going to put it in the phase plane. And I'll have the real axis and the imaginary axis. So VA hat will look like this. It's a sine. VB hat would be like this, 120 degrees shifted. And VC hat would look like this.

And we said, OK, these are the phasors. These represent the magnitude and phase of the individual signals. And then when I multiply by e to the j omega t, I'm essentially rotating it by an angle omega t. And to get the instantaneous time values, these guys are rotating, and I take the projection onto the real axis. So at t equals 0, sine omega t is not rotated. Sine omega t just projects to 0. If I weighted 90 degrees or omega t is equal to 90 degrees, VA hat would have rotated up here. I'd project it onto the real axis, and I'd get Vs.

So we often think about three-phase systems in terms of their phasors. And the benefit is we can add and subtract phasors when we're combining signals, and we'll see that we'll do that a lot in order to figure out different combinations of things. So this is just a little bit of a review of last class.

We also said that in addition to considering just the line to neutral voltages, I might also think about the line-to-line voltages. So I might think of, for example, the voltage between here and here as being VCB.

If I looked at VCB, what would VCB look like? It would be VC minus VB or VC plus negative VB. So just take the opposite of that. And I would get VCB hat. And I could likewise get two other phasors, like this and like this.

Actually, let me look at that. I think-- yeah, I did get that wrong. VBA goes that way. I should be careful with my angles here. It goes this way. So these guys have a 30-degree phase shift. These angles are 30 degrees.

Actually, this is 30 degrees from this guy, so I should be careful. So VCB is going to be a cosine. VAC hat is going to be phase shifted here. And VBA hat is going to be phase shifted here. So what I end up with is a 30-degree phase shift. And the length of these phasors is going to be the square root of 3Vs.

So if I look at the line-to-line voltages, they are square root of three larger than the line of neutral voltages, and they are phase shifted by 30 degrees. And in fact, how do we get these? We're essentially taking differences of two voltages. But if we use transformers, we can add any kind of combinations of VA and VB and VC. And we could construct arbitrarily phase-shifted versions of these waveforms. And that's kind of a neat trick that gets used a lot. And we'll see one little step of how you might do that today.

So that's a quick summary of, OK, what do these three-phase waveforms look like? And we're going to see that now I have lots of wires, lots of voltages. It becomes a little bit complicated to keep track of everything. And so what we'll see is people have come up with means of keeping track of what's going on with the different phase voltages.

So why don't we start talking about power electronics using three phase? And I thought a nice place to start would be to start with simple rectifiers. At the beginning of class, we talked about AC, and we had single-phase rectifiers. Let's compare and contrast a three-phase rectifier to a single-phase rectifier.

So we want something that's going to convert AC to DC. So what might that look like? Perhaps I could construct something that looked like this. Here's the simplest notion. Suppose I took Va with respect to the neutral, Vb with respect to the neutral-- and maybe I won't mark it as ground, but I'll mark it with an x-- Vc with respect to the neutral, and Vc with respect to the neutral.

And why don't I just put a diode from each? This would be the equivalent, the three-phase equivalent of a half-wave rectifier. And now I'll connect this up and maybe I connect it to a big inductor LD, so I get an almost DC current Id. And we'll connect that back to here. And clearly I have my load resistor here, RL.

So what would this thing do ideally? Well, basically, whichever diode is going to be on is going to be the maximum of Va, Vb, and Vc. So if I call this-- let me call this just for nomenclature Vd1-- Vd1 is simply equal to the maximum of Va, Vb, and Vc, because this diode is going to or things. The method of assumed states with diodes would tell you that.

So what are these things-- what do these waveforms look like? What would that output Vd1 look like? So let me plot these things. If I said Va was a sine wave-- so the sine wave looks like this. And just for reference, when I plot these things for three-phase stuff, it's often convenient to break things up into pi over 6 integrals, 30-degree intervals, just because it becomes easy to plot things. So if I took Va, it would look like something like this.

And here's the pain of dealing with three-phase systems is you've got lots of waveforms to plot. So forth. Vb would just be Va lagged by 120 degrees or 4 pi over 6-- 1, 2, 3, 4 units here. So it would be doing something like this.

So Vb would look like this. And then Vc would be, again, a log-- another 1, 2, 3, 4. So it would look something like this.

And what this equivalent to the half-wave rectifier-- what would it do? So if this is Va, this is Vb, and this is Vc, all this half-wave rectifier would do would be to pick off a Vd1 that's just the maximum, whichever voltage is the maximum.

So Vd1 would look like this and so forth. So this is Vd1. OK, does that make sense to everybody? Now, this kind of equivalent to a half-wave rectifier is maybe one step of what you could do.

But what would happen if I then said, well, let me not connect it this way, but let me just connect it differentially. So I'll connect my inductor here, and then I'll go to another set of diodes like this and connect this to Va, Vb, and Vc.

And now I'm going to make my output-- I'll make this VD2, and I'll make this voltage VD. So if this set of diodes made Vd1 the maximum of Va, Vb, and Vc, what would this set of diodes do? This is making-- this one will forward bias with whoever's largest. Can anybody see what this is going to do? Which diode is going to turn on?

AUDIENCE: Minimum.

DAVID PERREAULT: It's going to be the minimum, right. Whichever voltage is lowest between Va, Vb, and Vc is going to turn on. So Vd2 is going to equal the minimum of Va, Vb, and Vc. So this guy over here would come off and pick off the bottom of these guys. So it might come off and say I'm going to-- I'm going to select this and this and this.

So here's Vd2. And sorry, I know that's not a very visible color. So I got one set of three diodes picking off the maximum, the other set of diodes picking off the minimum. And the voltage across my filter inductor LD, which is going to give me my approximate-- this is LD here, and I'm going to get an approximately constant current that I'm going to call ID-- is really driven by the difference between Vd1 and Vd2.

So VD is equal to the max of Va, Vb, and Vc minus the minimum of Va, Vb, and Vc. Now, clearly I'm not using different voltage sources, Va, Vb, and Vc. I'm just connecting this back over to here, for example. Does that make sense to everybody?

So if I did that, it turns out that this is the same thing as the maximum of the line-to-line voltages and their negatives. So let's take a look at that, and let me just express that slightly differently just so you can see it.

I'm going to draw a little bit differently. I'm going to draw this same circuit. It's got six diodes in it. And let me draw that over here just so we can see it. So here I have-- it's going to look a little less messy now.

Here's my neutral connection. I'm going to have Va and then two diodes, one picking the positive, one picking the negative; Vb, one picking the positive, one picking the negative; and Vc, one picking-- this is Vc, one picking the positive and one picking the negative.

And now I'm going to have my filter inductor, Ld, my almost DC current Id, and then my output voltage. And this is the voltage that we've been calling V sub d. So that's just a different way to draw the same thing.

But what we can see is this voltage Vd is going to be whichever is the maximum of Va, Vb, Vc goes here. And the minimum of Va, Vb, and Vc is here.

So I'm really driving this thing with the line-to-line voltages. In other words, the differences between Va, Vb, and Vc are what are driving this rectifier.

And so we could actually draw this as something slightly different. We could rewrite how this is done. And let me add a little bit of context on this that'll make sense in a second. Let me give these diodes numbers. This is D1, D4, D3, D6, and D5, and D2. And I'm picking these numbers for a very specific reason. And we're going to see this in a minute.

But basically, this is going to pick off the maximum of the line-to-line voltages and the maximum of the negative of the line-to-line voltages. So that's essentially the same as this characteristic here. So let me draw what that would look like, and maybe this thing will become a little bit more clear. So let me now plot the line-to-line voltages.

And again, I apologize for lots of sketching here, but that's just the way it is with three-phase systems. OK, let's come back and look at our line-to-line voltages. OK, here we go. At t equals 0, VCB is at a maximum. So VCB is going to look like this.

And so VCB looks like this. So this is VCB.

The next line-to-line voltage phase that rolls around is VAC. And he's delayed by 2 pi over 3. So 1, 2, 3, 4. He's going to be his maximums here.

So he's going to do something like this. And we said this was going to be VAC.

And then the next one to rotate around is VBA. So let me put him on. VBA is going to be delayed by another four units, 1, 2, 3, 4. 1, 2, 3, 4. And he's going to be at maximum here, so he's going to do something like this.

And we said that was VBA. Now, what is this rectifier going to do? I said it was going to pick off the maximum of the line-to-line voltages and the maximum of the negatives of the line-to-line voltages.

So if you wanted to look at it as things rotating around, we had our line-to-line set that looked like this. Here's our line-to-line set. So this is-- right? This is VCB. This is VBA hat. And this is VAC hat.

But I also have his negatives. So I have the opposite here that looks like this. So this is V hat CA. This is V hat BA. And this is V hat BC.

So essentially I could think of this thing rotating in time, both the orange and yellow, that the line-to-line and its negatives, and the rectifier is just going to pick off whichever is maximum at any given time. So if I have, for example, here is VBA, VAB does something like this.

If I have VCB, VBC does something like this. And if I have VAC, I have VCA does something like this.

And what this rectifier is going to do if I want to now come get Vd, this voltage Vd is going to just be the maximum of all the line to lines and their negatives. So it's going to do something like this.

And here's out to 2 pi. So this is Vd. OK, does that make sense to everybody? I apologize for the lots of drawing, but I wanted you to get convinced that the whole point of having these six diodes is that Vd, as I've written it over here, is the maximum of Va, Vb, Vc minus the minimum of Va, Vb, Vc.

But this could also be written as the maximum of the line to lines and their negatives. So VCB, VAB, VAC, VBC, VBA, and VCA. VCA.

That's all the line to lines and their negatives. And that's what I'm getting with this right here. Now, why am I harping on this? A few reasons. Let's start to think about this as compared to-- oh, before I do that, let me just tell you a couple of things, just for bookkeeping.

We've named our phases A, B, and C, originally, such that A rotates. Then after A maximums, B maximums, and C maximums, and so forth as we're going around. So it goes A B, C, A, B, C, right? When I start to do this and I do the rectifier, I get two effects.

The way these maxima rotates between the positive and negative line, the line maximums, C becomes A, then B-- and B stays constant. Then B goes to C, and A stays constant. And then A goes to B, and C stays constant. Then C goes to A, and B stays constant. And then B goes to C, and A stays constant and so forth. So I'm either changing this letter or this letter as I go along.

So that's how we know what's going to maximize. And then the other thing that's happening is these diodes are numbered so that they go sequentially. And you say, well, why do I focus on this? It's because if you're suddenly poking scope probes into one of these circuits, you really want to know what one's going to conduct next, like, how is it going to run?

And so you number your diodes-- and in different circuits, you might number your switches-- such that they conduct sequentially. So for example, when VAB is at a maximum right here, I have D1 and D6 conducting. What's the next one that's going to conduct? Its D1, D6, then D6. Then it's going to be D1, D2.

It's going to be VAC is going to be next. So it's going to go 6, 1; 1, 2; 2, 3. So then it's going to be VBC max. And the conduction order is 1 2; 2, 3; 3, 4; 4, 5; 5, 6; 6, 1, so forth. So we sequentially number our devices so that you get consecutive segments conducted.

Why do I focus on that? Just because it's a real pain in the butt to keep things straight if you don't be smart about how you number things. And so I wanted to bring the convention to your attention. So let me stop there and just say, are there any questions so far about what this rectifier is doing?

OK, so now let's come back to why I care about three phase to begin with. What's wonderful about three phase? Well, let's just compare this rectifier to the rectifier we considered at the beginning of the term. This is a three-phase bridge rectifier.

How would that compare to a single-phase rectifier? What would a single-phase rectifier look like? A single-phase full bridge would have four devices, like this. It would have an inductive filter. And here would be Vd. And here would be Vac.

So what would Vd look like in this? When Vac is positive, Vac looked like this. Here's Vac. What would Vd look like in this circuit? Vd would give me the full wave rectification of this. So Vd would look like this. It would look like this bump and then the negative of it.

Well, OK, what's the fundamental ripple frequency? If, for example, Vac was 60 hertz, what's the fundamental ripple frequency in the rectified output? 120 hertz, right? So I got to size this inductor to filter a full-scale ripple at 120 hertz. OK, well, I can do that. I can get a big inductor and go do that.

What happens over here? Well, if I counted it, this is a half a pulse. 1, 2, 3, 4, 5, 5 and 1/2, 6 pulses per line cycle. So that means that the fundamental ripple frequency of the three-phase bridge is at 360 hertz, three times as high. Yeah, three times as high. I can multiply.

And keep in mind, how big is the amplitude on this? This is the full ripple. On the other hand, look how big the ripple is, the voltage ripple, that has to be filtered by the inductor in the three-phase bridge. If I go look at the Ld up there, it has to only take three times the frequency, which means it's smaller. And the ripple is far smaller. The ripple voltage is smaller. So the inductor that I need for my three-phase bridge is teensy tiny compared to the inductor that I need for my single-phase bridge. So I'll be much happier building a three phase instead of a single-phase rectifier.

What did it cost me in terms of devices? Now, it's risky just counting components because not all components are created equal. But roughly speaking, to do this beastie, I needed four diodes. To do the three-phase beastie, I only needed six diodes. So I swapped six devices for four devices, admittedly of slightly different scale. But suddenly, I get much, much nicer performance. Everything becomes good in terms of the output filter.

And that inductor is really big. It's low frequency. I would usually need a really big single-phase inductor. For a three-phase system, I need a very small inductor. Any questions about that? Yeah.

AUDIENCE: What's an application of the three-phase rectifier?

DAVID PERREAULT: OK, sure. Do you guys remember I brought in an alternator earlier in the term when we're talking about power factor? That's actually a three-phase-- an alternator means an AC generator, essentially. So that's a three phase. It came out with three phases. You run into six diodes and, boom, suddenly you have DC. And they control the amplitude of which they generate by a field control. They use an electromagnet that they change the strength of the electromagnet that basically controls how big the AC voltage that you're sending it through is.

So one application of a three-phase rectifier would just be in your car. Every car has one. More to the point, though, anywhere I'm going to go from AC to DC-- so if I want to run a three-phase drive-- now, it depends. I may want to invert back into the line in some cases. But if all I want to do is take power from AC line and then use it for something, when I'm at high power, I come in with three phase, I put a three-phase rectifier in there, and I get DC out.

So if I'm at the front end of my data center, that's probably what I have is a big three-phase rectifier to take that AC and turn it into DC. And this is probably the simplest version of a three-phase rectifier that you'd actually use. People tend not to use halfwave rectifiers because they inject DC back. And likewise, they tend not to use this simple rectifier, the half-- the three-diode version, they tend not to use. So this is kind of the simplest rectifier you'd use for three phase. Other questions?

OK, what's another advantage of this thing? Well, we talked-- we actually talked about this last class in abstract terms. What would be my line current in this case? What would be Iac? My Vac looks like a sine wave. Well, if this Id is constant, approximately, because I've done a good job filtering, I see when Vac is positive, it looks like Id. And when Vac is negative, it looks like minus Id.

Iac would look like a square wave. So I get some kind of power factor out of that. If I calculated the power factor of this thing, it would be about 0.91. Now, the square wave, the fundamentals in phase-- of the currents in phase with the voltage, so it's 0.91 basically because the square wave has third, fifth, seventh, et cetera, harmonics in it.

What would the line currents in this thing look like? Well, let's just go figure out one line current. Why don't I come back and do the line current in-- let's see, what color haven't I used? Let me pick this color. Let's look at the line current here for just-- let me think about this.

Let's pick the line current for phase A. So let's figure out what I sub A looks like. If I come back over here, A is conducting in this interval and in this interval, AB and AC. When AB and AC are maximum, this diode 1 is conducting. And when he's conducting, he's carrying a constant current Id. So IA would look something like this.

It would conduct here. It would start conducting at 30 degrees, continue conducting until here, 150 degrees. Then he would go quiet for a little while. And then when he's conducting negative, he's going to carry negative current. Does that waveform pattern look familiar to anybody?

So this is essentially the current pattern I'm going to conduct for I sub A of t. And keep in mind, I didn't draw it well. Let me draw it-- let me draw it back on my line to neutral waveforms because this has Va. Va is in red. So here's Va.

What does IA look like? IA looks like this. It conducts after 30 degrees. It stops conducting at 150 and then conducts negatively like this. So I can match the red and pink waveforms between the line voltage and the line current, the current in that voltage source. Does that make sense to everybody? So what does that say about his power factor?

OK, well, we can calculate that. And let's just do that for some good exercise here. First of all, what's the average power? I would argue that the average power in this thing could be-- is essentially the product of the red and the pink, which I could write as 1 over pi, the integral from 0 to pi-- and I can do it in a half cycle because the other half cycle is symmetric-- of Vs sine omega t times ID. But its only ID between pi over 6 and 5 pi over 6. That's the average power.

So this is going to give me Vs ID times the cosine of pi over 6 minus the cosine of 5 pi over six, which is going to be the square root of 3. And this is 1 over pi. OK, so that's the average power. What's the RMS of phase A?

If this has a amplitude Vs, what would be the RMS of single phase?

AUDIENCE: Vs divided by square root of 2.

DAVID PERREAULT: Yes, Vs over the square root of 2. What's I RMS of phase A? OK well, it's the square root of the average of the square of this thing. So if I squared the pink waveform-- and this amplitude here is ID-- I would take this thing, I would square it, I'd have ID squared. And then it's at ID squared for 2/3 of the time, 4/6 of the time.

So this would just be equal to ID times the square root of 2 over 3. You could just take the RMS. That gives me a power factor equal to what? It's the average power divided by V MRS I RMS.

And that's going to be Vs ID square root of 3 over pi divided by Vs over the square root of 2 divided by ID square root of 2 over the square root of 3 which is just equal to 3 over pi. And 3 over pi, if you want to calculate it, it's about 0.96.

So whereas having a single-phase bridge-- and if I did it for the other phases, the other phases are just time shifted. So all the phases have the same power factor. So the beauty of this three-phase piece compared to a single-phase piece is instead of getting a power factor of about 0.91, I've got automatically a power factor of 0.96.

Why is the power factor higher? Because look at this waveform. You can see just by eye or by recollection of our harmonic cancellation discussion that this thing has no triple-N harmonics. We said one of the benefits of three phase is because everything is time shifted. Even if your currents-- even if you draw an individual current, all the triple-N's have to cancel because of the three-phase nature. And you're seeing it right here in the line current of the rectifier,

So whereas the single phase will have fundamental third, fifth, seventh, ninth, et cetera, this thing gets rid of the third, sixth, and ninth. And the lowest harmonic content of this is the fifth and the seventh. Any questions about that?

AUDIENCE: I wanted to know about the power factor-- the power factor and the phases are different. Is there a notion of [INAUDIBLE] power factor?

DAVID PERREAULT: Well, everything's-- if the phases are balanced, then they're all the same. And that's the idealized case. When you're talking about power factor, you really only talk about one port of the circuit. So I suppose if you had an unbalanced situation and it's a more complicated situation, you could start looking at the power factor of the different phases being different. But generally, let's just keep it simple and say everything's balanced, which it should be if it's working right. Other questions?

So we've seen what you can do with just basically throwing two more devices at it. Suddenly, three-phase is looking pretty good, especially at high power because more complex, I got more devices. I got 50% more devices. On the other hand, my inductor just got a heck of a lot smaller. And we said that's related to the notion of with three-phase power, if I were drawing ideal sine waves, I'd be drawing continuous power.

Now, I'm not drawing sine waves. I'm drawing this funny waveform. But it's just basically much easier to get close to continuous power. I need much less filtering to give me kind of constant power at the output because I have three phases at my disposal. Whereas in the case of the single phase, basically that inductor is serving to ride through the twice line frequency ripple. I don't need to do that in the three-phase system.

I'm of running out of time, but I did want to give you one more kind of notion of what you can do with three phase. I mentioned that naturally, if I compared the line to neutral and the line-to-line waveforms, I get a 30-degree phase shift.

Well, we often use that kind of 30-degree phase shift to our advantage. Or I can build a transformer set that can grab pieces of Va and Vb and Vc and add them up symmetrically with a symmetrical set of transforms to generate some new set of waveforms with an arbitrary phase shift to it.

And because I have these three phases, I can get new three-phase sets that also add to 0 with this arbitrary phase shift. OK, how would we use that? Well, when people get to high powers, first of all, you can't go out and buy a diode with either enough voltage or enough current for what you want to do.

So if you think about trying to build a tokamak for fusion or something and you're going to-- you need serious amounts of power, tens of thousands of amps. Maybe you can't go buy individual diodes with tens of thousands of amps. Now, you get some help because now I have six devices to help me process that power. But maybe I would need more. Or maybe what I really want is really high voltage that I can't do with individual diode voltages.

So here's the kind of trick you can play. You can go and say-- and I can do this with yy or delta y. But let's imagine that I come in with my waveforms.

And I'll build one set of transformers that maybe take the line-to-line voltages and generate a new set of waveforms that are in phase with that and maybe another set of transformers that generate the 30-degree phase shift. How could I do that?

Well, for example, suppose I took Va, Vb and-- Va, Vb and Vc. And I will just go build a transformer that says says, OK, let me take the line-to-line voltages, which are square root of 3 bigger, and then I will go generate a new set, a new y set of-- I'll connect the primaries and delta and the secondaries and y. So I'll make a delta to y transformation.

So what's that going to mean is if I have my fundamental--

[ALARM SOUNDS]

If I have my fundamental of this set, when I run it through the transformer and I can get the 1 over square root of 3 scaling I want, I run it through the transformer, I get another set of three-phase voltages that are 30-degree shifted. So now I have two sets of waveforms that are 30 degrees apart. So if I had a first diode rectifier up here, maybe it would just look like that one. That's this diode rectifier. Oops. This is a transformer.

I'll run it into a first diode rectifier. So this is-- so this is like-- maybe this is delta to delta and this is delta to y. I'll do a first diode rectifier. And his output voltage looks exactly like this purple waveform. I guess I should use the correct color. This is Vd up there.

And now I'll build a second rectifier. There's another six devices. Now I've got 12 devices. And let me make him-- I'll call this Vd prime. Well, if I've shifted the phase of the inputs by 30 degrees, all I'm going to do is shift the phase of the rectified output ripple by 30 degrees.

So the second one, Vd prime-- if this is Vd, Vd prime is just going to do this and so forth. See where I'm going with this? And so now I connect these guys in series, and I hook them up to this inductor and then my load resistor.

And this is Vd plus Vd prime. First of all, I've got much more voltage, which I might want, because each of these volt diodes only blocks half the total output voltage. Secondly, the ripples cancel. So if I had six pulses per line cycle, 360 hertz, now I'm going to have-- the lowest ripple content's going to be at 12 times the line frequency. This would be called a 12-pulse rectifier.

So first of all, I have higher frequency again. 720 hertz is the fundamental ripple. And by the way, the amplitude of that ripple is again smaller. So this inductor again gets smaller.

[ALARM SOUNDS]

And the net result of that is that we get really small filtering. I'm trading numbers of devices and complexity for really good output ripple at higher powers, in this case, higher voltages. I can play the same game with what's known as an interface transformer and get much higher currents if I prefer to set higher voltages.

The other thing I can do, and while this makes a great homework problem and I'm out of time, if you track back and look at the line harmonics for this thing, and you do it right, instead of having fifth and seventh as being the lowest harmonic you can have 11th and 13th be the lowest harmonic or the lowest significant harmonic.

So not only do I make the ripple smaller and my filter smaller, but I make the line current waveform more sinusoidal, and I get a higher power factor again. If you don't like that, fine, do three of them. Get an 18-pulse rectifier. People do that. You want a 24-pulse rectifier? It exists. And what they do is they just use these phase-shifting transformer sets, stack it up in series or parallel with the right technique, and you can get to really high powers.

And suddenly, even though an individual diode is a nonlinear thing and it draws harmonics, you murder all the harmonics, and you get something that just acts beautifully. And that's the game you play at really high powers with lower voltage and lower current devices than you could otherwise do.

So we've talked about three-phase rectifiers, and I tried to use this lecture both to show what you do in terms of numbering devices and in terms of what are some of-- how some of the advantages play in a very simple case when you just have diodes. Next time we'll start to look at more active kinds of power electronic circuits in three phase. Last question.

AUDIENCE: Is it the transformer or is it the delta-y connection that helps with the 30-degree phase shift?

DAVID PERREAULT: Well, it's how you do the transformers. In this case, it's just because I'm taking the line to line, and I'm using that to make a new line to neutral. That's how I get my phase shift. But I could do-- I could do something more sophisticated and get different phase shifts if I wanted. OK, we're out of time. Have a great day.