[SQUEAKING]

[RUSTLING]

[CLICKING]

DAVID PERREAULT: OK, why don't we get started?

[SIDE CONVERSATION]

We're going to switch topics today, and we're going to talk about a different class of power converter circuit called an inverter. So inverters, or DC-to-AC converters, are important for a lot of applications, right. So if you're going to build a motor drive, a lot of motors need to run off AC.

If you're going to have an uninterruptible power supply to power your AC-powered devices when the grid goes out, you need it. If you're getting power from a wind turbine or, for example, a DC solar panel, you need to take that and convert it into AC in order to feed the power into the grid. So there's a lot of applications where you need to come from DC input and put out AC output. This is the topic of *KPVS* chapter 8, and we're going to spend the next few lectures talking about some of the issues associated with DC-to-AC conversion.

Now, before we jump into that, let's just have a really brief review of expressing waveforms, periodic waveforms, in terms of Fourier series, just because it's going to be really useful in thinking about, What kinds of AC waveforms might we want to synthesize, right? So if I have a periodic waveform f of t, right, I might express that as some DC term plus n equals 1 to infinity of a sub n sine of n omega 0 t plus b sub n cosine of n omega 0 t, where this is the angular frequency associated with the fundamental period capital T. So omega 0 is equal to 2 pi over the period.

And then we can go find, using orthogonality, the expression to get the Fourier series coefficients. So a sub n would be equal to 2 over T the integral over t of f of t sine of n omega 0 t dt, and b sub n would simply be 2 over T integral over t f of t cosine of n omega 0 t dt. OK. So I can take any periodic waveform, break it down into some DC fundamental and harmonic description, and one way to do that is in terms of sine and cosine components. And we'll see why we picked this particular representation, shortly.

OK. So it turns out that different waveforms have different special characteristics, all right. So I'd like to think about a few different kinds of waveforms, and some of this, you've seen. Some of this maybe will be a little bit less familiar.

The first kind of waveform we might think of is an even waveform. Right, what does it mean for a waveform to be even? If I have T, an even waveform looks symmetric about T equals 0.

OK. So it flips about T equals 0. So maybe I have a waveform that looks like this. Say this is T over 2 and this is minus T over 2. And it might look like this, for example. OK. So if I just flip it about T equals 0, nothing changes.

OK. Well, why might I care about an even waveform? Because all the a-sub-n terms are 0 in that case, right. One way to think about that is, how do I find the a-sub-n terms?

I take f of t, if this is f of t, and I multiply it by sine n omega t. So if I multiplied it by sine omega t, maybe I'd be multiplying it by something that looks like this. And then I take the white and the orange and multiply them and integrate them. And whatever's over here exactly is the negative of what's over here, and I get 0 in the integral when I integrate it out.

So one way to think about it is that an even times an odd is odd, and then when I take the integral of an odd waveform, I get zero. OK. Another way to think about it is sines are odd waveforms, and this is an even waveform. So it makes sense that I ought to build an even waveform out of even components, right, and the cosine terms are the even components of my Fourier series. So an even waveform will only have b-sub-n terms, only cosines in DC.

OK. Of course, we can also have an odd waveform, right. Even is x of t is equal to x of minus t. Right, it flips about the T-equals-0 axis. Odd is x of t is equal to minus x of minus t.

OK. So what does that mean? An odd waveform would mean, if I had this, then I should have this. OK, and then I could replicate this cycle to cycle, something like this, for example, OK, so where this is minus t over 2 and this is t over 2.

OK. So basically, I go across the axis and then flip down. I flip both this way and this way, and I get some symmetry. OK. And so that's a-- that characteristic, what do I have about that?

Well, here, right, this is composed of only odd waveforms. I could make the same kind of argument and say that b-sub-n's ought to equal 0. OK. So I only build an odd waveform out of sine waves.

Why? Because sines are odd, and hence, those are the subcomponents that I get. OK. Any questions about that?

So, many people will be familiar with even and odd. There's another decomposition that we can think of, which is one where we talk about something that's half-wave symmetric. And what does half-wave symmetric mean?

That means x of t is equal to minus x of t minus capital T over 2. OK, so what does a half-wave symmetric waveform look like? A half-wave symmetric waveform looks like this.

Suppose I have something that looks like this between 0 and T over 2. OK. If I go back half a cycle, I flip it. All right, so here, I'll slide back half a cycle and I flip it, and I'll get a waveform that looks like this.

OK. So here's what my half-wave symmetric waveform would look like, and so forth, OK, where this is minus T over 2. So if I go at any point in the waveform and I go back half a cycle, I flip.

OK. Well, why might I be interested in half-wave symmetry? Well, that's because all of the a-sub-2-k's and b-sub-2-k's are equal to 0. OK, all the even harmonic terms are equal to 0.

OK. Why would that be the case? Well, how would I find, say, the second harmonic component of this thing? I would multiply it-- for example, suppose I wanted the a-sub-2 component, I would multiply it by sine of 2 omega t, which would be multiplying it by this and multiplying it by this and then integrating over the full cycle.

And you can see that the product of orange and white here, this half of the waveform, is exactly the complement of the product of the orange and white in this half of the waveform. When I integrate them, I get zero. OK. The same thing would have been true had I had a cosine wave. OK. So the point of being half-wave symmetric is that because of the orthogonality involved, all of the even terms are zero, OK, so it has no even harmonic.

Now, the complement to this is something I would call a half-wave repeating, OK, and it looks like this. If I had something that was doing this in one half of the waveform for T over 2 to 0, it would just repeat half a cycle back-- that is, x of t is equal to x of t minus capital T over 2.

OK. So if I have defined a period capital T, that just means the waveform repeats twice in that capital period T. OK. Or another way to think about it is the fundamental period of this waveform is actually t over 2, OK, but if we defined-- if we're looking at across some period T, this comprises only a-sub-2-k's and b-sub-2-k's. That is, a sub 2 n plus 1 and b sub 2 n plus 1 is equal to 0, right.

So this has no even harmonics. This kind of waveform only has even harmonics. It has no odd harmonics or fundamental. OK. Any questions about that? Yeah?

AUDIENCE: Is it only the case if we define the period to be T?

DAVID PERREAULT: Yes. All right. Now, why might I do that? Because, firstly, we can sometimes decompose waveforms, right. I could say that, OK, I could come up with some waveform f of t, OK, and I could say-- so I could take some arbitrary f of t and come up with f of t is equal to some even component plus some odd component, OK, and decompose that into different parts, where f even is equal to x of t plus x of minus t over 2, and f odd is equal to x of t minus x of minus t over 2.

OK. So essentially, I can decompose a waveform into one term that basically is all of the cosine components in DC and one element that is only the sine terms. OK. So I get this decomposition, and because it's sines and cosines split, the even and odd components of the waveform happen to be orthogonal.

OK. Likewise, I could make a decomposition of f of t, any waveform f of t, to have a f of half-wave symmetric element plus a "f of half-wave repeating" component. And again, this is going to be the fundamental and odd harmonics. This is going to be DC and even harmonics. OK. And those are time waveform decompositions, but they're into different parts of the Fourier components. OK. Any questions about that?

OK, so that's just a little kind of review, and perhaps an extension of different ways we might think of getting the components. We'll see in a while why we might think of decomposing things that way or think carefully about whether my waveform is even or odd or half-wave symmetric or not. OK. But let's start talking about an inverter.

What would be the basic structure of a three-phase inverter? Well, one basic structure might be to have some DC waveform. And of course, by the way, whether I talk about this structure as an inverter, flowing power DC to AC, or as a rectifier, flowing power AC to DC, it really just depends upon the power flow direction. And in fact, the same circuit structure can do either thing. OK. How you implement the switches, however, may be different.

OK. And in fact, where did the term "inverter" come from? It came from the notion of an inverting rectifier. The first kind of power electronic solid state-- or, actually, it wasn't even solid state, it was a tube-- power electronic component that people were able to build was a rectifier.

And they eventually figured out that with certain kinds of controlled rectifiers, they could go DC power to AC power. So they called that an inverting rectifier, and then they eventually just started calling it an inverter. OK. So that's where the term comes from.

But here's a basic structure. OK, maybe I would have four switches, s1-- let me get my switch numberings right-- s2, s3, and s4, and we'll see why we number them this way. And here is my load, in this case, if I'm going to go from DC power to AC power. And let me call the output here vx.

OK. So I'm going to come from some DC voltage, and I'm going to deliver power at AC into some voltage vx. OK. What voltages vx can I synthesize with this structure? Well, let's think about this. If I have switches on, what voltage vx do I get?

Well, if s1 and s2 are on, I get plus vdc. If s2 and s3 are on, I get zero, right, because I've just shorted out the load on the bottom. If s3 and s4 are on, well, then vx becomes minus vdc. And if s4 and s1 are on, top two switches, I again get zero, right.

So I sort of have two ways I can apply zero voltage across the load. I can apply a positive voltage, and I can apply a negative voltage. All right. So I can go sort of one way, the other way, and two ways, I can get zero.

OK. And what we're going to see is that means given a DC voltage, I can put AC on the load. OK. And this is a very common single-phase inverter structure. If I have, say-- a typical thing is if I have an inductive and resistive load, right, maybe I would implement it this way.

OK. I would have, say, a MOSFET here and a MOSFET here for my switches. And keep in mind, these guys, while I don't usually draw it, they have internal body diodes like this. OK. So this would be a typical structure, where internally I have these diodes, OK, and here's vx again.

OK. Just to illustrate this kind of structure being very common, what I have here is sort of one of these things you plug into the cigarette lighter in your car to generate AC to power your laptop or something when you're on a trip or something. And you know, this is always dangerous, giving me a power converter, because usually I'll just take it apart.

But what you'll see is, on one side of this thing, there's kind of four switches, and you'll see the-- in fact, we were talking about insulation pads last time. I'll pass this around and you can see the insulation pad here. And then you'll see this transformer, and you'll see a set of diodes here, which are right here. That's an isolated DC-to-DC converter. So that takes the 12 volts or 14 volts from your car battery and generates a higher voltage.

And then there's four more switches, which are the ones here. Those are your four MOSFETs, and those are going to generate AC. And it goes to two plugs so you can plug in your toys and play your gaming system or whatever you want. So this is just to illustrate one very simple example of an inverter, OK, and it'll have exactly this structure, right.

So we have an isolated DC-to-DC converter to get a voltage gain, and then this inverter. OK. What would this-- when I'm drawing this load vx, what am I meaning? Well, it depends what my load is, but I could imagine maybe I would have an inductor and a capacitor and some resistor that's getting my AC load, right.

So this filters out higher harmonics, or this could be a machine winding where there's sort of a phase inductance from the machine winding and the resistor. It just sort of depends on what you're driving for a load, OK. Or it could be an inductive filter, and that could run into the grid, right.

So that's the basic notion of what the structure of an inverter is. Why don't we think about, How could we well approximate a sinusoid by switching these transistors, S1 to S4? And the case I'd like to start with is perhaps the simplest one.

I'd like to switch each switch on and off only once per AC output cycle. And let's imagine for the moment that what I want is something that approximates a sine wave at the output or crudely approximates a sine wave at the output.

OK. Why am I focusing on switching only once per cycle? Well, the number of times I switch per cycle is going to have to do with my switching losses. Right, we talked about switching losses.

And so especially at very high power levels, I really want to minimize the number of times I switch per cycle in order to reduce those switching losses. OK. So the obsession with not switching very often comes from mitigating those losses, and so I want to just treat the simplest case. And this is actually what one might do at very high power levels, where you really don't want to switch very often, OK-- or a very high frequency levels, I should say.

OK. So let's think about what we might do. Let me plot things in terms of electrical angle. OK, so here is-- here is-- so there's pi and 2 pi. This is omega t. This is electrical angle.

And what I was hoping to synthesize is some sine wave, right. So maybe it would look like this. An ideal sine wave, if I could synthesize it, would look like this.

OK. Now, I clearly can't synthesize that with my inverter, but what could I do? Well, I can generate a positive voltage, right, so maybe what I would do is-- let's just suppose, starting some time here, I will apply plus vdc. Maybe I'll do that at some electrical angle delta.

OK. So in this time period, I will synthesize plus vdc, and what I'm going to do is I'm going to do this. I'm going to do this between delta and pi minus delta. OK. And how would I do that in this time period? What switch pattern would let me synthesize plus vdc?

AUDIENCE: s1s2.

DAVID PERREAULT: s1s2 will give me plus vdc. Now I want to synthesize zero in this time period, and I'm going to do that between pi minus delta and pi plus delta. OK. I can get zero just by leaving switch 2 on and going to switch s3 so I can have s2s3.

OK. Now I'm in the negative half of the cycle, so maybe I want to-- maybe I want to make this minus vdc, right. So I will then switch here, and from pi plus delta to 2 pi minus delta, I will have minus vdc. And I get that with what switch pattern?

s3s4. So I've turned off S2, and now I've turned on s4. And then I can get back to synthesizing zero with s4s1. Right, so here's my pattern, OK, and it looks like this. OK. Does that make sense to everybody?

So what have I done? Each switch turns on-- if I look over at 2 pi, one AC cycle, each switch turns on once per cycle, each switch turns off once per cycle. OK, so that's the minimum I can sort of do and synthesize this kind of waveform.

Now, what can you tell me? I drew a sine wave here, right, and I want in some measure for my synthesized AC output voltage of my inverter, this vx-- right, this is vx-- to try to approximate that sine wave in some fashion. This is v sine omega t.

Well, sine omega t is odd, right. So if I want to do a good job with as least kind of unwanted harmonic content as I can, it makes sense that because sine is odd, I also ought to use only odd components. Right, so I ought to synthesize it with an odd waveform.

And what do I know about this waveform? This waveform is odd. And I should-- maybe I'll just draw it out here, right. It is indeed-- this is minus delta. This white waveform here, vx, is indeed odd, right. It reflects-- if I flip it across T equals 0 and I flip it, I get the same thing,

So what I know is this white waveform, it's odd. It's comprising only sine components. So it comprises only sine omega t, some amount of sine of 3 omega t, some amount of sine-- I'm sorry. It has only sine terms, as far as I have told you so far.

OK, there's no cosine terms in this thing. So that means it's good because I'm kind of building it out of its-- the things I would want to build it out of. Any questions about that?

What else did I do in this waveform? Well, you notice that this half of the waveform, for the negative sign, Is exactly the flip. I come back half a cycle and I flip it for the first half of the cycle, right. What characteristic has that?

It's half-wave symmetric. So what that means is that this white waveform that I've synthesized has no even harmonics, right. So if I did a Fourier decomposition on this white waveform, what I know is it has-- well, it has no DC, it has no cosine terms, and it has no even harmonics. Right, so the lowest harmonic component could only be the third, and then the fifth and the seventh and so forth.

OK. So the reason I chose this pattern just this way, for both being odd, because I was trying to-- happened to be trying to match a sine wave, but more importantly, that I made it a half-wave symmetric, I've gotten rid of even harmonic components. And if I imagined that I was going to come up here and say, oh, you know, I'm going to take this vx here and try to synthesize some output voltage vac by filtering it, if I can get rid of my even harmonics, I can more easily filter that waveform, right.

When we thought about sort of DC-to-DC converters, I'm trying to separate out DC from any AC stuff. That's kind of easy, right, because they're kind of infinitely separated in frequency, or at least on a log scale. If I'm trying to separate out some fundamental that I want to create, and I want to get my fundamental here but I've got second harmonic here, I need a very good filter to keep 1 omega t and kill 2 omega t, right.

Well, by making it half-wave symmetric, I don't need to kill 2 omega t. I just need to kill 3 omega t. All right. So there's a large motivation to control the harmonic content of your waveforms by picking waveform symmetries, and hence the interest in half-wave symmetric waveforms. Questions?

OK. Why did I bother? And by the way, I should've said, if I had made my angle delta equals 0, OK, at delta equals 0, this would just be a sine wave, right. So at delta equals 0, what I would get is I would get my voltage v x would simply equal vdc times summation n equals 1 to infinity of 4 over pi n sine of n omega 0 t, right.

Where did I get that from? That is just the Fourier series for a square wave. OK. You can look it up in any book.

And so what that says is that, first of all, it's a sine wave series because it's odd, right, so I knew all the even terms went away. Because it's half wave symmetric, a square wave is half-wave symmetric, then-- or 50% duty cycle square wave is half-wave symmetric-- then it doesn't have any-- this is "n odd only" summation.

And that means it's 4 over pi sine of omega t plus 4 over 3 pi sine 3 omega t, and so forth. It has harmonics that sort of fall off as 1 over n, but only odd components. Does that make sense to everybody?

OK. I came in and I introduced this angle delta, right, and I said what you could do for delta equals zero and so forth. Why do I have it there? What could I do with my angle delta? Right, I have my one control variable that I can use, and I'm still switching each switch only once per cycle.

OK. Well, what can I do? I can basically vary delta between zero-- that's my perfect square wave-- and something less than pi over 2. OK. And I can really use delta to do kind of two things.

One, I can vary the fundamental. And two, I can control harmonics. I can't do both at the same time, but I can use that as a control variable without switching more times per cycle.

OK. What would I do in terms of varying the fundamental? Very often, if I'm driving a motor or something, right, how hard I'm driving the motor kind of has to do with the amplitude of the waveform I'm driving it with, right, so if I can have some means of amplitude control, that's a good thing. OK. Let's just think about, What does the fundamental of here look like, right?

So vx, I said we can express vx as the sum of odd harmonics only, right, odd harmonic sine terms only. What is v1? Right, so vx of t, I could express as being v1 sine of omega t plus v3 sine of 3 omega t plus v5 sine 5 omega t, and so forth, right.

But if what I'm mainly interested in is controlling the fundamental as the thing I'm driving, what is that fundamental? Well, we come back-- basically, we come back to this expression here, OK, to figure out what v1 is. So why don't we write v1?

v1 in this expression would simply be equal to 2 over T-- in this case, I'm doing it in electrical angle of 2 pi-- integral over 0 to 2 pi vx sine of omega 0 t d omega t, right. Because I have this-- so I'm going to multiply that by the sine wave. Actually, conveniently, I've drawn the sine wave up there, right.

I can just say that's going to be equal to-- this is 1 over pi, but I can do it over only half the cycle, and I can get two over pi the integral from delta to pi minus delta of vdc sine of omega 0 t d omega 0 t, right. All I'm doing is I'm multiplying-- essentially, I'm multiplying this green waveform, or a unit height version of this green waveform, by the white waveform and integrating it to find v1. And because the two halves of the integral are the same, I can just do it over half a cycle and double it.

OK. And if I do that, that becomes very convenient because this just becomes minus cosine. So what I get is I get 2 over pi vdc cosine of delta minus cosine of pi minus delta, right, which just gives me-- I could rewrite this as being equal to 4 vdc over pi cosine of delta. That makes sense to everybody?

So what am I saying? If I made delta equal 0, that's my square wave case, right. I just get a fundamental that's 4 over pi vdc, right. That's exactly what I said before for the square wave case.

As I keep increasing delta, I make it nonzero further into the cycle this way and further into the cycle that way, I reduce my fundamental. Why? Because basically, as delta becomes bigger, I'm reducing the amount of overlap between the white waveform and the green waveform. And when I multiply and integrate, I get a smaller number, and that goes as the cosine of delta.

OK. So what I can do is, if what I cared about mainly was the fundamental amplitude of my output, I can modulate that for a fixed DC voltage by modulating delta. OK. I have a means of controlling the fundamental amplitude. Does that make sense to everybody?

I want to drive my motor easier, I use a bigger delta, I drive it with a little less fundamental amplitude. If I want more fundamental amplitude, I use a smaller delta, and the most I can do is a square wave where I get a fundamental that's 4 over pi times vdc. Questions?

What else could I do with this thing? Well, I could pick delta to control the fundamental. Another way to control the fundamental would be to directly control vdc, right.

So in that inverter I'm passing around, right, they have an isolated DC-to-DC converter. Well, guess what? They can use that if they want to control the vdc that they get, right. So if you have a DC-to-DC converter before your inverter, you get to control this because you have a converter that can control it.

All right. So maybe I don't need to use delta to control the fundamental. Maybe I can do something else with it. Well, the other thing I can do is harmonic control.

Let's ask the question, What does v3 look like? Well, v3 is equal to 2 over 2 pi integral from 0 to 2 pi of vx of t times sine of 3 omega 0 t d omega 0 t. And likewise, so what I'm doing in this case is I'm going to multiply this waveform by sine 3 omega t, right, so I'm going to multiply it by something that looks like this.

Right, and then I'm-- that's horribly asymmetric. But I'm going to multiply it by sine 3 omega 0 t and then integrate it, right. Well, OK, because that's again half-wave symmetric, I can write that as simply being equal to-- this is 1 over pi, but then I can double it and only do it over half the cycle.

And I get 2 over pi the integral from delta to pi minus delta vdc sine of 3 omega 0 t d omega 0 t. OK. It's the same game all over again, but what I get is 4 vdc over 3 pi times the cosine of 3 delta. OK, that's just the result of that integral.

OK. So I can again-- you know, I can-- once I've determined delta, I determined the fundamental and I determined the third harmonic, right. But what can I do with this? Well, if delta was 30 degrees, or pi over 6, what would be the cosine of 3 delta?

What's the cosine of 90 degrees? Zip, right. So if I pick delta is equal to 30 degrees, v3 goes to 0.

That's kind of nice, right. Why is that nice? I'm trying to make something that looks like a sine wave and has-- kind of limit the harmonic content so that I can filter it, right. By picking delta's 30 degrees, I can make v3 to go to 0.

What am I doing there? If I come back here to this picture, I said I'm multiplying the white waveform by the blue waveform, but notice I drew, actually, delta is exactly 30 degrees. What happens when it's 30 degrees is this positive area in the multiplication is sort of a half-sine bump and a half-sine bump, exactly cancels this in each in each half cycle. And when I do that, boom, the third harmonic goes away.

All right. So what am I left with if I do that? Right, if I thought about my system, suppose I put up some filter. Like, here's some filter, and here are some vac that I want, for example.

So here's vx, and here is some vac that's filtered, that I might care about. Or in some cases, I might care about ix, which is also related to vx by some filtering. OK, it depends what I'm interested in.

But what I can think about that is taking some values of vx and then running it through a filter transfer function. That might be vac over vx, and maybe I can make it look like some cutoff, right. Well, what do I generally get?

I get a fundamental, then I get a second harmonic and a third harmonic and a fourth harmonic and a fifth harmonic and a sixth harmonic, right, so 1, 2, 3, 4, 5, 6. I want to put the fundamental within the cutoff of my filter because I'm trying to get fundamental to the output, but I don't want I want to filter off all the harmonics, right.

Well, naturally, by half-wave symmetry, I've gotten rid of 2, 4, and 6. So I've killed these just by how I've picked the pattern of the waveform to be half wave symmetric. OK. Now, if I magically go pick a delta of 30, then I kill off this guy.

OK. By picking delta exactly 30, I kill off the third, and so the lowest contents I have to deal with are the fifth and the seventh. It's a heck of a lot easier to filter the fifth than it is the second or third. OK. So I can get much cleaner output voltage waveforms, even though I'm not switching very often, by being very clever in how I pick my switching angles. Any questions about that?

And we are going to see-- and this can all be related back to some games about how I'm picking the precise waveform I synthesize with the states I have, which are basically plus vdc minus vdc and zero. OK. Let me just give you a little bit of extra kind of color about inverters. And we're going to talk about expanding out on this in a lot of different dimensions as we move forward, but I wanted to give you sort of an idea of, like, what's the fundamental-- no pun intended-- smallest thing I can do to get nice waveforms?

OK. One thing relates to how I control these switches in the real world, and I mention this because there's the theoretically controlling the switches and then there's the practical considerations. OK. If I come to this thing, suppose I put this kind of filter in here, right, so suppose this is equal to this box that I'm drawing. So basically, I've got an inductive load, right.

So if this load is somewhat inductive-- or maybe it's resistive-- this is what a motor winding might look like. I've got to be careful never to open a circuit that winding, right. So suppose I have s1 and s2 on, right, and I wanted to do that switching pattern.

What's the next thing I'm going to do? What would be my next state after s1 and s2 is on? s2s3, right, so I'm going to turn off s1 and turn on s3.

OK. Now, when you think about doing that in the real world, you've got to be a little bit careful, right. If I ever turned on s1 and s3 together, unfortunate things would happen, right. That's called a shoot-through, and if you do it too long, you will kill the switches, right, because you'll short-circuit the DC bus and you can source a lot of current into that. So you've got to make sure s1 and s3 are never on together and s2 and s4 are never on together.

At the same time, you really, really don't want to open-circuit that load. But the nice thing about this structure-- and by the way, this is sometimes called a, quote, unquote, "VSI," or Voltage Source Inverter, because you're coming from a DC voltage, OK, and generating AC-- is that I can have s1 and s2 on.

First, I turn off s1. If I turn off s1, say this current's positive, he still has to flow somewhere. But he can just commutate from s1 into this diode, right, and so I don't have to worry. And then once the diode's on, I can turn on s3, right.

So basically, I will have my q1 of t. I'll turn the switch 1 off, and then I'll have q3 of t. And I'll turn him on after some so-called dead-time delay between the two switches.

OK. Or even if the current was coming this way, if I turn off s1, the diode's on, and then I can turn on s3 and it'll just turn off this diode naturally. Right, so one thing I want to emphasize is that in the real world, you're always having some controls to make sure you're not shooting through your switches. OK. That's just a practical detail that you take care of when you lay out the controls for your inverter. Any questions about that?

AUDIENCE: What about other switches with no diodes?

DAVID PERREAULT: Ah, well, then you could get unhappy really quick, right. So if I had IGBTs-- and by the way, IGBTs are very common for driving inverters. What they will do is they will go put external diodes across them, because otherwise you will blow them up.

Right, so in fact, later, I'll bring in an inverter module for a Prius, and you can actually see the IGBTs, and right next to them are the diodes that they put in to do it. That's an old Prius inverter. The new Prius inverters uses silicon carbide FETs, I think.

So that's one way to do this. And as I said, this is called a voltage source inverter. It's not the only way you can build an inverter, OK. What would be another way? Well, here's another trick.

Suppose I took a DC voltage source and I put it in series with L big, and I'll make this inductor so big that this I becomes approximately equal to IDC, right. If I have a huge inductor here, I can sort of make a voltage source in series with an inductor look, at least on a short time scale, like a current source, right. So I might think of this thing as being a current source now, right. So here I have some current IDC, and now I might want to create an AC current from that. I could do that again with a set of switches.

OK. Maybe, however, what I would want is switches that do this. I'm picking a different switch type just for fun. OK. These switches can carry unidirectional current.

But they can block voltage in both directions, right, because they will not ever carry current that way, and if I try to put a reverse voltage on them, this diode will block and everything will be happy. OK. So then I could have a current source essentially going in, and then instead of having a filter that looks inductive, maybe I will have a filter that looks capacitive, something like this. And here I can have iac or-- or vac or an iac.

OK. So what I'm going to do is I can switch this DC current into the load this way by having these two switches on. I can switch this current into the load the other way by having these two switches on. Or if I turn these two switches on, the load gets no current, or if I switch these two switches on, the load gets no current. That make sense?

So instead of synthesizing some pulsed DC voltage that's positive and negative, I can synthesize a pulsed AC current that's positive and negative. This would be called a current source inverter. Now, in practical applications, voltage source inverters, especially at low powers, tend to be much more common because they're simpler to realize. You don't need a big inductor and everything else.

People do, however, at high power, sometimes like current source inverters because if these switches fail, you don't immediately short everything out, like from a DC voltage source, and get a huge pulse of current. Things take time to ramp up through this current, which lets you blow fuses or shut things down or whatever. So at high power, sometimes people like versions of current source inverters, but more frequently, people use voltage source inverters.

And interestingly, by the way-- I talked about dead time, where these two switches have to be off at the same time for a little while and we let current go through the diodes. Here, I'd better never have a time when all four switches are off, because then I'd be open-circuiting this guy, right. So what I might do is, if this switch and this switch were on, I will then briefly turn this one on also, and then I can turn this one off, right, so I have overlap in my switch-on times instead of dead time in my switch-on times.

OK. But you can use, apply all the same concepts I talked about, about synthesizing pulsed-voltage waveforms, to synthesize pulsed-current waveforms. We'll spend most of our time talking about voltage source inverters, but I just wanted you to know there are other ways to play these games.

Any final questions before we wrap up for the day? OK, we'll pick this up tomorrow. Have a great day.