[SQUEAKING]

[RUSTLING]

[CLICKING]

DAVID PERREAULT: OK, why don't we get started? So what I wanted to do is continue the discussion of inverters that we started last time. And what I'm going to show you is some of expansions on the way you can think about controlling the inverters to get better performance out of the waveforms.

So we introduced the basic voltage source inverter structure, which is four switches, And very typically, we'll use bidirectional-conducting single-directional blocking switches like MOSFETs. Like this, for example.

And if I want to synthesize some voltage Vx across the load, if I have switches S1, S2, S3, and S4, if I have the switches that are on the S1 and S2, I put positive VC across the load. If I put S2 and S3 on, I get 0. If I have S3, S4, I get negative VDC across the load. And if I have S4 and S1, I get 0 again.

And we showed last time that we can use this to synthesize either plus 0 or minus repeatedly across the load, and then use that to at least, very crudely, approximate some kind of sine wave, for example. And why do I focus on a sine wave? Very often we want to synthesize something that if at least if I filter it, it will look like a sine wave because, for example, if I'm making a UPS inverter, maybe I would like to replicate what the grid does with my inverter.

And when I show this as a load, what is this? I don't know, it depends on the application. It could be a motor winding. It could be some low-pass filter, for example, that's going to some load. So this could be Vx and this could be V out across the load.

So we said last time that we often think, especially when we're synthesizing periodic waveforms, we often think in terms of the Fourier series than what we're doing to shape the harmonic content of the waveforms. So we said, OK, one form of the Fourier series for some signal f of t is simply equal to b0 over 2 plus the summation from 1 to infinity of a sub n sine of n omega 0 t plus b sub n cosine of n omega 0 t.

Where if we recall, the sine terms always odd in time, and the cosine terms are always even in time. So if I happen to want an odd waveform, then I should make the pattern f of t-- and that means I want the pattern of f of t to be odd. That means I will only have the a sub n terms. And if I want the pattern f of t to be even, I only have the b sub n terms.

More importantly, we saw that we can often do interesting things with half-wave symmetry. What does half-wave symmetry mean? Half-wave symmetric waveform means that f of t is equal to minus f of t minus t over 2 where t is the period. That means if I go back half of a cycle in the waveform, the waveform is flipped.

So for example, this waveform is both odd and half-wave-symmetric. Why? Because if I go back-- oh, that's a terrible drawing because this should go further. But if I go back at any point half a cycle, I flip across the axis and I get to the same point on the other side. And the reason I'm interested in half-wave symmetry is because if it's half-wave symmetry, then the a2K and the b2K terms are 0.

And the reason I'm interested in doing that is suppose I want to synthesize something that looks like a sine wave, and then I want to put it through a filter, it's very hard to filter out the second harmonic because the second harmonic is only a factor of 2 different than the fundamental and frequency, and I'm trying to use perhaps a low-pass filter, it just gets hard to attenuate that.

If I can get rid of the second harmonic specifically, I can make my filtering easier. And if I can get rid of the-- if I make it halfway symmetric, I get rid of the second, fourth, sixth, et cetera, and I really reduce the amount of stuff I have to worry about filtering. So I can get much purer output waveforms by doing that.

So if we're going to synthesize some pattern for my inverter to synthesize-- to create-- making it half-wave-symmetric is significantly advantageous if I don't want any even harmonic components in my output.

And what we said was that, if I come back to this kind of filtering-- so if I think of the transfer function from Vx to Vo-- so magnitude of Vo over Vx, ideally speaking, there's going to be some kind of low-pass filter where I want to put the fundamental here so it's in the passband, but 2, 3, 4, 5, 6, et cetera. I usually only want this component and I would like to filter everything else. We can get rid of these by the half-wave symmetry. And then it's just a question of what about third and fifth and so forth?

What we saw last time was one more trick. We said I can synthesize 0 plus and minus. If I only switch once per cycle, I can create a waveform that looks like this. So this is pi, this is 2 pi, this is some angle omega t.

If I synthesize an angle, I may have delta, pi minus delta, pi plus delta, and 2 pi minus delta. If I synthesized a waveform that looks something like this and so forth, that is half-wave-symmetric. So this is VDC. This is minus VDC. This waveform for Vx is half-wave-symmetric.

And the advantage I have here is I can have S4, S1; S1, S2; S2, S3; and S3, S4; and then I'm back to S4, S1. I've switched each device on and off once per cycle, and hence, I've got the lowest switching losses that I might get for synthesizing such a pattern.

So if I care a lot about the loss in switching, which I might if I'm either a very high power where I have high voltages or very high frequencies, this is a pretty nice pattern to have. And we said my one control handle in this pattern, if I use it, is this angle delta. And by picking delta, we can do a few things.

One thing we said we could do is if I make delta bigger, the fundamental component gets smaller. And if I make delta smaller-- I'm sorry, if I make delta smaller, the fundamental component gets bigger. So I can control the fundamental of the output that way. The other thing we said we could do is control the harmonics.

Because we said if I do it like this-- so for an odd waveform-- and I'm only picking it to be odd just because it makes the Fourier series description simpler, But for an odd waveform, what I get is the n-th harmonic component is simply going to be equal to-- which way did I-- did I do it in terms of angle or did I do it in terms of-- I guess I did it-- OK, 2 over T integral over the period of Vx of t sine of n omega t dt.

By picking delta, I can choose at least one of these to mess with. And so I can calculate the amplitude of the n-th harmonic essentially as the waveform times a sine of the right frequency integrated. And the example I showed you last time is, if I thought about what-- say-- suppose I focused on the third harmonic-- so n is 3, the third harmonic would look like this. Or, I'm sorry, the sine 3 omega t would look like this.

And when I picked delta-- this angle delta to be exactly 30 degrees, or pi over 6-- so this example is delta equals pi over 6. We notice that when I look at the intersection between Vx of t, and I multiply it by the pink waveform, which is sine 3 omega t, basically I get this positive area, and then I get this negative area multiplied by the white waveform. And when I multiply them and integrate them, I get 0.

So I can look at this waveform and say, hey, if I pick that angle just right, the overlap with this sine 3 omega t gives me just such that I kill the third harmonic. And this kind of trick, we're going to see, we can expand in multiple ways to give us higher performance. But before I go on, is there any question about how that arises or anything up to the present point? That's the quick review of last lecture.

OK. So how might I go about it? Well, the reason I did this-- a principal reason I did this was because I said, OK, I've gotten rid of the even harmonics, but I've still got to worry about 3, 5, 7, et cetera. If I picked my angle just this way, I would pin 3 to 0. So that would kill the third harmonic.

And that means, since the fourth is gone by symmetry, the lowest, I have to deal with this fifth. Now I'm starting to get some nice space here. And that lets me get much more purer filtered waveforms at the output compared to this kind of pulsey shape I'm generating.

But what else could I do? Maybe I can play that game and get rid of more harmonics by switching more. So I've only switched each device once per cycle, but suppose I'm willing to give up on that and switch more times per cycle on and off. That means I can create more times when I have positive or 0 or negative in any given time.

I would like to do that perhaps in a way that helps me get rid of some higher harmonics. So now that I've gotten rid of the third, my lowest are the fifth and the seventh. Maybe I could figure out some way to get rid of the fifth. Well, how could I do that? Let's think of a slightly more sophisticated pulsing waveform than the white one.

Here's-- let me do this. Suppose I came and I said, you know what? If I put a 0 right here-- so let me do the same thing. I will put a positive step here. But what I'm going to do is I'm going to look at this point. And if I cut out a little bit on each side of this, I don't change the fact that the third harmonic is gone because as long as I make sure the amount of positive in this multiple of the third harmonic balance is the amount of negative area with the third harmonic sine wave, I will maintain 0 third harmonic.

So maybe I could do something like this. I will create a pulse waveform that does this. And maybe I'll do that again on this side. And I could-- and I would now want to keep my waveform half-wave-symmetric, so I'll do the same thing on the other side and do this. All right.

Now if I've done this in a right way and I just make this symmetric about 60 degrees, and I put in some other angle-- maybe I'll call that capital delta, capital delta, I haven't introduced any third harmonic again because the multiple of this pink-colored waveform or orangey-colored waveform with this sine 3 omega t, the interval of it's still going to be 0, it's still orthogonal. Any questions about that?

What do I do with delta? I can pick that-- what do I do with capital delta here? Maybe I can pick that so the fifth harmonic goes away. And in fact, I'll show you the one result-- and this is just a very simple example. This is what you would get. And in this case, I'm going to pick this waveform capital delta to be exactly 12 degrees. And because my artistry is not so good, I've decided to resort to the board-- I mean to the figure from the book. But this is the same. You can see this is the third-- this is how I cancel third harmonic.

Here's sine 5 omega t. And if I multiply this original one pulse per half cycle waveform by sine 5 omega t, you can see that the negative area doesn't cancel the positive area, and hence, I have some fifth harmonic.

But, if I then put in my nulls right here, like I said, centered about 60 degrees, it turns out, if I use that capital delta being 12 degrees, I can make the negative area exactly cancel the positive area and kill the fifth harmonic. So if I use this waveform-- and it's, again, half-wave-symmetric, it has three pulses in each half-cycle instead of one pulse in each half-cycle, I could not only keep the third harmonic killed, but also kill off the fifth, which would then leave the lowest harmonic the seventh.

That makes it easier for this filter to kill it, or equivalently, for the same filter, I get more purer sine wave at my actual output over here. Any questions about that? This kind of trick where I'm going to introduce new pulses in each half-cycle is called harmonic elimination. And we can often view it as exactly through this method, is how do I synthesize pulses that satisfy this orthogonality with each harmonic?

Now, is this the best I can do? Well, first of all, if I synthesize this waveform, how many times do you think I switch each device per cycle? Without working it out, you can essentially-- each time you get a pulse per half-cycle, you have to add on some switching transitions, so you get higher switching losses.

So what I'm really doing is I'm trading switching loss for lower filtered output components. Now, is this as good as I can do to get rid of the fifth? No. It turns out that-- and you can write equations and start solving them to do this. And I've given-- in KPVS chapter 8, there's two references. There's a classic Patel and Hoft reference that introduced this general idea, and then there's a more recent Chasen reference that really goes into detail about the best ways to do this.

Is each time you put in one pulse and a half-cycle, you can ultimately pick one harmonic to eliminate. And when we talk about one harmonic, we're keeping everything half-wave-symmetric, so we care about one odd harmonic. So we're assuming our evens are all gone. I only have odds.

So I could actually pick this waveform because I have 2 degrees of freedom-- the little delta in this example, gamma, I could kill the fifth and the second, fifth and the seventh, or the third and the fifth, but only have two pulses and a half-cycle, and so have fewer switching transitions than I do in this example waveform. And generally, the rule is, for each pulse per half-cycle, I get to pick one odd harmonic to eliminate. Any questions about that?

AUDIENCE: Is there like a practical limit to how high of a harmonic [INAUDIBLE]?

DAVID PERREAULT: Yeah, that is an excellent question. There is because if I want to eliminate the 97th harmonic, what that means is I've got to control the timing resolution just so that I make that multiple with the 97th harmonic integrate at 0. So the higher the number of harmonics I want to eliminate, the more precise the timing requirements become.

So you can imagine, how would you do this? You'd have a lookup table that steps along and it says at every time slice, which switches should be on? And the number of time slices I need to break it up into accurately enough to murder those low-frequency harmonics gets worse and worse and worse. The other limit is, eventually I switch so many times that it's-- that my switching loss goes crazy and I don't like it.

The other thing I'll point out is if I took this to its logical conclusion-- so suppose I came off and I said, OK, I want to get rid of a bunch of harmonics. So imagine my pulse waveform looked like this, and I'm just going to-- I'm not going to be quantitative now, but maybe I would have something that looked like this, a pulse and another pulse, another pulse. And these are all very controlled widths.

And then I do this. Something like that. I don't think I have the right number of pulses here, but I have something that's shaped to generate a set of pulses that make this, at least at low frequencies when I filter it, look closer to a sine wave. Maybe these middle pulses would tend to be bigger than these edge pulses. And I pick the pulsing times and positions exactly to give me this magic cancellation.

What I am doing, if I think about this in the frequency domain, is I've got my fundamental that I want. I've got some filter that's going to then cut off. And what I'm doing by doing this is I'm eliminating a bunch of the low-order harmonics. But you can see that this has a bunch of high-frequency content. I'm switching up and down and up and down and up and down. That suggests to you there's a bunch of high frequency stuff there.

So if I look at the original waveform Vx, this waveform-- In fact, if I looked at its total harmonic distortion, it actually is higher. What I'm doing is I'm killing off the low-frequency stuff and then I'm really growing the high-frequency stuff. So it's not like my waveform actually has less harmonic content. It actually has considerably more.

And depending upon how you choose to-- what angles you choose to kill off your low-order harmonics, you will end up with more or less stuff at high frequencies. But undoubtedly, you're going to get more high-frequency stuff because you've got a lot of switching going on.

The thing about that is, is if I think about a low-pass filter, it's easy for me to murder the high frequencies in a cut-off. It's hard for me to eliminate stuff that's near cut-off. So I'm making the challenge of basically pushing the frequency content up and keeping the stuff that's hard to filter low. So I'm not getting rid of high-frequency content, I'm actually increasing it, but what I am is getting rid of the stuff that's hardest to filter. Any questions about that?

OK. So that's one strategy I can use. What else could I do? And actually, in my original waveform here that we showed, we saw a little bit of a hint of this. And here's the idea. Suppose I have some waveform x of t that I might express as the summation of n equals 1 to infinity x of n sine of n omega 0 t plus phi sub n. It has some Fourier series.

Then if I had some delayed version of this waveform-- let me call this x of t minus t1, what would his content look like? Well, I just go to this expression, I substitute in t minus t1. So I would get, OK, this is the summation of n equals 1 to infinity of x sub n sine of n omega 0 t minus t1-- so I'll say this is n omega 0 t minus n omega 0 t1 plus phi n.

So if I define some delta phi 1, the phase shift at the fundamental associated with this time shift t1, that would simply be omega 0 t1. That is, if I'm shifting by a time t1, I'm shifting the fundamental by a phase omega 0 t1. What am I shifting the n-th harmonic by? This is the fundamental shift. The n-th harmonic, delta phi n, is equal to n delta phi 1. So this is the n-th harmonic phase shift.

And so here, you can see, because the n-th harmonic-- this thing-- and maybe I should be careful, define delta phi 1 as being minus omega t1, and maybe this is minus n omega delta phi 1. So this is delta phi 1-- or n delta phi 1 is the amount. I'm shifting the n-th harmonic. Does that makes sense to everybody?

So why am I telling you this? Suppose I did some game like this-- and I would have said that this is maybe not the most common way to play this game, but you can actually find people who have built converters this way, especially for high power. Suppose I had some DC input voltage. And I will build an inverter. Here's the first inverter. And I'll give him an output voltage Vx1. And now let me build a second inverter for switches. And I'm going to give him an output that's Vx2.

And what I'll do is I'll transform or couple these two outputs like this. And let me just imagine, this is a one-to-one transformer. And here's another one-to-one transformer. OK. So this is Vx2. That's a one-to-one transformer. That means that this total Vx is simply equal to Vx1 plus Vx2.

So I've got a first inverter generating a first pattern and a second inverter generating a second pattern. So what is the harmonic-- what is the content? If I said that-- suppose I say Vx1 is equal to the summation of n equals 1 to infinity-- let's assume I'm just doing odd waveforms of V sub n sine n omega 0 t plus phi sub n.

That means that Vx2, if I shift by t1, Vx2 is just going to be summation of n equals 1 to infinity of V sub n sine n omega 0 t plus n delta phi 1 plus phi n where delta phi 1 is just equal to omega 0 t1.

All right. So now I have these two waveforms and I add them. So now I'm going to get Vx is simply equal to the summation of Vn times sine of n omega 0 t1-- I'm sorry, omega 0 t plus 5 phi n plus sine n omega 0 t plus phi n plus delta plus n delta phi 1.

All right. Well, what happens if I make-- the difference between-- the phase difference between this waveform and this waveform is precisely n delta phi 1. At each harmonic, I've got a phase shift that's-- the n-th harmonic has a phase shift that's n times delta phi 1.

Well, what happens when n delta phi 1 is pi, or 180 degrees? What's going to happen? This is going to be 180 degrees out of this and they're going to cancel. So if I'm clever, if I go build two waveforms that are shifted in time by just the right magic amount such that when I add them, there are 180 degrees of-- the harmonic that I care about is 180 degrees out of phase, it's going to cancel. This trick is called harmonic cancellation.

Let's go see an example of this. So what I've done is let's pretend I've synthesized those two waveforms. And suppose the two waveforms I've synthesized with each of those bridges, each switch is switching once per cycle, so it's got a delta of 30 degrees, and I do the first guy. And then I do the second guy, but I'm shifting him by 36 degrees. I'm offsetting him by 36 degrees. What's 5 times 36? 180.

So then when I shift them, then I add them, in the bottom waveform you see the result here. And this waveform-- actually, that looks a lot more like a sine wave, doesn't it? That's because I've cancelled the fifth harmonic. In fact, not only have I canceled the fifth harmonic, I've canceled the 10th, although we didn't have 10th. I've also canceled the 15th, the 20th, the 25th, and everything.

So basically, unlike harmonic elimination where I'm playing this game by getting something that has no low-frequency content but has a bunch of high-frequency stuff, harmonic cancelation cancels out some waveform you care about plus multiples of that, so it looks a lot more like a sine wave.

I've now taken each of my devices-- I've still only switched them once per cycle, I've just got twice as many devices that are half the size to process the given amount of power. So I've of paid for this trick with a little bit of complexity. But I get a waveform out that is very much closer to pure and much easier to filter to get what you want. Any questions about that as a trick? Yeah?

AUDIENCE: [INAUDIBLE] seems like you'd be really careful about whether we actually end up out of phase with one another. If you're in a high-power situation where your wires are heating up a bit, does that change this? Do have to worry about that sort of thing?

DAVID PERREAULT: Yeah, I wouldn't worry so much about the wires heating up, but your broader point is a good one. Just as I'm kind of limited by timing angles with this guy, how much I phase-shifted, if I don't control that very well, if there's delays between the circuit, depending upon how much absolute time that is, I'm limited-- essentially, this harmonic is limited by how accurately I control that t1. So I want to be very good about shifting this the right amount.

Now, I will say that this kind of trick, I do need some better hardware to do it. I can't synthesize this level. This level is sometimes called a three-level waveform. And you say, well, there's not three levels here, but the way they count it is one-half of this waveform is 0 plus VDC over 2 and plus VDC. One polar side has three levels. So they call that a three-level waveform. With a three-level waveform, I can cancel-- I can choose to cancel a harmonic.

Now, what we'll see later is sometimes I might choose the third, sometimes I might choose the fifth, it depends on what I'm doing. And in fact, even if you come back to this original waveform that I drew, this waveform, the original white waveform that had those 30-degree shifts, what I could really view that is one-half of this bridge generating a square wave and the other half of the bridge generating a square wave that's 60 degrees out of phase at the fundamental and sends three times-- at three times the frequency at the third harmonic-- or six, ninth, 12th, et cetera, it'll be 180 degrees out of phase.

So in fact, the pulse waveform, the once-- one pulse-per-cycle waveform that I showed you, you could really view it as a cancellation because I have half-bridges that are each generating square waves, and I get a harmonic cancellation between those square waves, killing the triple n harmonics.

But yes, as I go up in frequency, it becomes harder to do. And I need fancier circuitry to cancel lots and lots of harmonics, but sometimes it's worth it. And people-- as we'll see, people actually do quite fancy circuits to help them do that. Other questions?

AUDIENCE: In this example, the third harmonic is still cancelled because of the shape of the first two?

DAVID PERREAULT: Yeah, exactly. That's the beautiful thing about this. Is once I've cancelled the waveform, and then I take some cancellation and then I add it to some other waveform, I can't introduce new harmonics. I'm just taking some existing set of Fourier coefficients.

The most that can happen is they add up and stay constant. In other words, if I take half-sized waveforms and add them up, the most I'm going to get is back to the original. Other than that, I'm just going to get some degree of cancellation. So I don't introduce new frequencies by doing this trick, I just kill frequencies. So yes.

So my original white waveform, because it's harmonic cancelation of the half-bridges, I have no triple n harmonics, no 3, 6, 9, 12, 15, 18, and so forth. I don't have any evens because of the half-wave symmetry. And then if I do this trick, I kill off all the 5n harmonics. And you can keep that game up. For a more complicated circuit, I'd kill even more, and the waveform just becomes-- it starts to become very small steppy, close to a sine wave, and you get very beautiful waveforms. Yeah?

AUDIENCE: Does the 6-degree displacement matter?

DAVID PERREAULT: Does the which?

AUDIENCE: Because it's a sine wave, but it's displaced by 6 degrees. So--

DAVID PERREAULT: It's a wave-- oh, yeah. So actually, if you look in the lecture notes, instead of displacing it by 36 degrees, I displace one by plus 18 and one by minus 18. And you get the same cancelation and then it stays odd. Yeah. So, yeah, I don't have to have 0 plus a delayed. I can have minus half the delay and plus half the delay and it still stays as an odd waveform. Excellent question.

AUDIENCE: So do you also use this trick to just increase the AC output voltage?

DAVID PERREAULT: You could, yeah. So, yeah, what would be what would be another benefit of this? The Vx has twice the amplitude of VDC I could synthesize. Another way-- and that's just for this particular implementation, which is only one way to do it. We will see next class other circuits that their benefit is they-- for a given input voltage, they use lower-voltage switches to get the same output. So there's a lot of ways you can take advantage of the complexity you inherit.

The downside to this one is principally that I have transformers that are rated for the output-- that are rated for the frequency I'm outputting. In some cases I might not like that, but there's other circuits that get around that.

Let me point out that this notion-- this cancellation notion is a very widespread one. It gets used in a lot of kinds of circuits. Let me show you another one that maybe is completely different application space, but suppose I had a-- suppose I had a buck converter that looked like this. And here's my output capacitor. And here's my load.

And maybe this output capacitor is a microprocessor. So maybe this is the 12-volt input, and I'm delivering voltage to my microprocessor. This current here is a triangle wave. So maybe this current looks something like this. It's got some DC value and it's got some ripple at the switching frequency.

Maybe, if I came in with a second unit-- and I will build another parallel guy here, and I will switch him with some phase shift and he'll have an output current. And maybe I make this output current-- here's T over 2. And here's-- gotta be careful here, here's 3T over 2. Here's 2T. Maybe I will shift this one. So that he starts half a cycle later like this.

What total current goes into the output and capacitor? Well, it's the sum of this one and this one. But if I basically make orange and pink shifted by 180 degrees of the fundamental, that means the fundamental ripple will cancel. If there's second harmonic component in the pink waveform, the second harmonic of the orange waveform will be shifted by 360 degrees at the second harmonic. So the fundamentals will cancel, the second harmonics will reinforce.

And the net ripple-- I'm not even going to try to draw it here, but it would basically be-- have a fundamental that was at twice the switching frequency. So I get something that's both smaller amplitude-- and you can show that the amplitude will be, at most, half-- and twice the frequency, which makes it four times as easy for that capacitor to filter it.

So this same kind of trick of harmonic cancellation-- here, I'm cancelling the fundamentals because what I would like is a DC output current. This technique is called interleaving. It's very widely used, and in fact, most motherboards, if you look at them, they don't have a buck converter or something driving the load. They'll have a whole bunch of buck converters lined up, and they phase-shift them all just such that the first n harmonics will go away, and the ripple frequency will be much higher than the switching frequency of the individual converters. That also means that you can play with response speeds of that because one will react much quicker than if they were all in phase.

If I put these two converters in phase, all I would get is twice the ripple current at the fundamental. Instead, I get, at most, half at twice the frequency. And I can play that game out to n different converters interleaved.

So, this trick of harmonic cancellation is really neat. It's widely used. It's used in DC-DC converters. It's also used to kill off unwanted harmonics in inverters. Harmonic elimination is also used. There's nothing that says you couldn't do the two of those together. You saw that, Instead of using that just one pulse per half-cycle, I could use some pulses per half-cycle to get-- eliminate some harmonics, use some phase shift, eliminate some more, and I can intermix those two and they get very nicely, easily-filtered waveforms. Any questions about that?

OK. Just to demonstrate all this, Rafa has been kind enough to set up a demo. So I'll let her show you some actual experimental waveforms from an inverter that was built by a student who took this class.

RAFA ISLAM: OK, so, what are we looking at-- am I too loud? Sorry. What are we looking at, at the top is-- guess what? What inverter is it? I s an inverter board that has four switches. And we're probing at the output voltage. So, we had a DC input voltage of 15 volt, and then we're switching it.

And as you can see, as we saw in class, it uses the three levels, 0, positive, negative, to create something that somehow resembles a sinusoid. And as you can see, it has half-wave symmetry, so we do not have any a2K, b2KR, the even harmonics. So we only have to worry about the odd harmonics.

Now let's-- at the bottom down here, we are looking at the FFT of the voltage waveform. So the voltage magnitudes at different harmonics. Now, if I move my cursor, at the first spike where it happens, it's really hard to see, but you can see on the top-right that it's happening at 600 hertz, which means that's our switching frequency, And it's the fundamental.

And then, let's see where the next spike happens. The second-highest spike happens at 2.9 kilohertz, which is very close to the fifth harmonic. What does that mean? That means we do not have any third harmonic. So we eliminated the third harmonic from the circuit.

Now, let's do another thing. It's going crazy, but let's see. OK. Now, like we saw in the class, if we introduce pulse-- or notches on both sides of the waveform, it still have a symmetric. So we're still doing the same thing. But interestingly, if we move to the second high spike, it's almost about 4.2 kilohertz, which is the seventh harmonic. So we erased-- we eliminated third and fifth harmonic.

Now we can take this a step further. Let me run it, and stop it. OK. Yes. So now if move all the way back, that will be the second spike occurs at 5.3 kilohertz, which is like the ninth harmonics. So we eliminated all the lower third, fifth, seventh harmonics. You will notice that they're getting a bit-- so the higher harmonics are getting higher in magnitude, but that's OK because we care about the lower harmonics more because it's easier to get rid of-- the higher harmonics will need smaller filter components or smaller devices for applications. That's all.

DAVID PERREAULT: Thanks. So I guess what we've seen today is harmonic elimination where we introduce extra pulses carefully timed. We've also seen harmonic cancellation where we take multiple waveforms and shift them and add them up to a murder the harmonics we don't like. Those can be both used together.

What we'll start seeing next time is firstly, well, other ways we can do this kind of harmonic cancellation or harmonic elimination game, more sophisticated circuits.

And after that, we'll start talking about, well, what happens if-- we've posited this on the whole thing I want to make as a sine wave, which is often true. If I'm going to run a lot of motors, I want a sine wave. If I'm trying to generate something for the AC grid, which is supposed to be sinusoidal, I want a sine wave. But there's times where we don't want a sine wave, so what do we do in those cases? And we'll pick those topics up next class, so have a great day.