[SQUEAKING]

[RUSTLING]

[CLICKING]

DAVID PERREAULT: OK, why don't we get started? So the last few classes, we were talking about soft switch power converters. And that's-- coverage of soft switching specifically is included in *Principles of Power Electronics* Chapter 24.

What I'd like to do starting today is talk about a class of power converters that are often chosen because they can be soft switched, although it's not required that they be soft switched, and this is the class of power converter called resonant converters. And this is described in detail in *Principles of Power Electronics.* Chapter 10.

And the idea of a resonant power converter is one in which we modulate our either power or current or voltage or process energy through high-frequency sinusoidal waveforms. So in a lot of the converters we do, we have some of square-ish waveform, a PWN kind of waveform. In a resonant converter, we're generally going to use sinusoids. And that's valuable in a whole bunch of applications.

So, for example, if you wanted to do induction heating or wireless power transfer, or, in some cases, some kinds of ballasts for fluorescent lights, typically what one will do is generate some high-frequency, sinusoidal kinds of waveforms, and resonant converters are ideal for doing that.

You can also build resonant power converters that are DC-to-DC converters, where you might go from DC into high-frequency, sinusoidal AC and then back to DC, would give you a resonant DC-to-DC converter. And there's a lot of value in this because we can build circuits that are tuned and naturally give us sinusoidal voltages and/or currents. And also, we can also typically use the frequency selectivity of resonant networks to help us modulate voltage or power.

So there's a lot of different applications for resonant converters, and they have very different characteristics. In some cases, you need to run at a fixed frequency. In some cases, you need to run at variable-- or you can run at variable frequencies. It depends what the load characteristics will do. Will it be fixed in amplitude, or do you have to deliver fixed power? So there's a whole wide variety of these kind of converters. But what we'd like to do to start is lay down the basics.

And on the way to doing that, I just like to remind people of some of the key characteristics of resonant networks today, particularly second order resonant networks. And so I'd like to spend a little time on this because this is going to set us up well for thinking about how we build power converters that naturally use these networks.

Now, we can use different kinds of networks, but let's consider a series RLC network. So perhaps I have a voltage source vs. cosine of omega t. And we can run this into a series LRC network comprising a resistor, an inductor, and a capacitor, where I may have IL and VC. And typically, we're going to think of the resistor as the load, where we're going to want to put the load power. But let's just consider this network generally.

So I might characterize this network by its input admittance. So I might look at the input admittance looking into this network as seen by the driving source. So what would be the admittance?

I could write the admittance as being equal to 1 over the impedance, which would be R plus k omega L plus 1 over j omega C. Or I could rewrite this as 1 over R plus j times omega L minus 1 over omega C.

And so we could write the magnitude of the admittance as follows, as being equal to 1 over the square root of R squared plus omega L minus 1 over omega C quantity squared. And the angle of the admittance we could see is minus the arctangent of omega L minus 1 over omega C divided by R.

So all right. We have expressions for what does this admittance looks like at a value of S equals j omega. What does that look like in the frequency domain?

Well, if I thought about this network, I could plot-- let's just think about the amplitude. I could think of the magnitude of YN. And I'm going to plot this on a log scale versus frequency-- angular frequency. Again, I'll plot it on a log scale.

At really low frequencies, the capacitor dominates the impedance. It is the lowest admittance. So at really low frequencies, I might have an asymptote that goes as omega C. At really high frequencies, the inductor becomes a high impedance, so then it limits the admittance of the resonant network. So at high frequencies we might have something that goes as 1 over omega L.

Now, there's going to be some place where these two asymptotes intersect. Where do they intersect? Well, they intersect right where the inductive impedance and the capacitive impedance cancel, right at this magic point.

If I look here, somewhere here, there's going to be some place where these two terms cancel. And where these two terms cancel the admittance goes to its maximum value. And anywhere away from that, the admittance amplitude must fall because this is a nonzero term in the denominator.

And if we work out what that is-- very easy to show that that intercept point occurs at omega is equal to a value of omega 0. Omega 0 is equal to 1 over the square root of LC. All I got to do is set that-- I can set those two equal to each other and find that value of omega equals omega 0. And this is called the undamped natural frequency.

And I'm going very fast because I think this should be familiar territory to everybody, but I want to make sure we get it fixed in our heads.

What happens to-- at this intersection point, where in this axis is this intersection? Well, if I said, what's omega 0C, which also has to equal to 1 over omega 0L? That's going to be equal to-- omega 0C, if I plug in this value, is going to be equal to the square root of C over L.

Or this is sometimes written where we define Z0 equal to the square root of L over C. And that's known as the so-called characteristic impedance of the network. So this intersection point I might write as the square root of C over L, or equal to 1 over Z0. And it's 1 over Z0. I might also call this Y0, or the characteristic admittance.

So if you give me a second-order circuit like this, especially if I'm thinking about it in the frequency domain, but actually, in general, the first two things I'm going to figure out about this circuit are, what are the characteristic impedance? And what are the undamped natural frequency?

So almost the first thing I'm going to do when I think about this network is calculate these two variables. The undamped natural frequency is essentially when those two elements are in resonance. Their impedance cancels each other. And we can be careful about how we define what resonance means. But we can consider it where the reactive components cancel, and I see a resistive input admittance, for example. Why do I want to think about the characteristic impedance?

Well, look at it this way. One way you might think about this is that the capacitor voltage is equal to the inductor current through the-- times the impedance of the capacitor.

So we might look at that and say, OK, VC, the capacitor voltage, if I'm operating at the natural frequency omega 0-- and let me just look at its magnitude-- is going to be equal to the magnitude of I sub L times the impedance, which is 1 over omega 0C at that frequency.

So if I just rearrange this, I could write the magnitude of V sub C divided by the magnitude of I sub L evaluated at omega equals omega 0 only, I would see that this is going to be equal to 1 over omega 0C, which is equal to Z0.

So we might think of the characteristic impedance as telling us, do I have a circuit that operates at high current-- or high voltage and low current, so its high characteristic impedance, or low voltage and high current, and that's low characteristic impedance? So at resonance, how do the capacitor voltage and inductor current relate in terms of their amplitudes?

Well, they relate precisely by the characteristic impedance of the circuit. Now, all of that is true only at this one magic frequency. But we often think about operation in the vicinity of that frequency. Any questions about that?

OK. How might this circuit behave under different situations? Well, I'd kind of maybe think about different regimes of operation. So one thing I might have, if I looked at this, is the following. Actually, let me do it this way.

So this is omega on a log scale. This is the magnitude of YN on a log scale. And here's my asymptotes. This is omega 0. This is 1 over Z0. And what is this going to look like across frequency?

Well, at really low frequencies and high frequencies it follows the asymptote. But in this middle region, we ultimately get the reactive components canceling. So right at the resonant frequency, it's going to look like 1 over R.

So it kind of-- what it does kind of depends on how big 1 over R is. For a really big resistance R-- so I have R big. 1 over R is going to be down here. And I might get an asymptote. I get a third asymptote here, and I get something that does this. So this is what YN would look like for large R.

Another case I might run into is, well, what if 1 over R is sort of in the vicinity of-- or R is sort of in the vicinity of the characteristic impedance? So maybe 1 over R is here. What would I see then? Well, I'd see something that just-- it's going to hit here at its maximum admittance.

And so maybe its characteristic versus frequency is going to do something like this. It's going to peak up a little bit and then come down. So that's maybe some of medium value of resistance. And this kind of case-- we might think of this as what we're going to say is a medium Q. Whereas, this guy we might call very low Q. And we'll get back to what we mean by Q.

And then the last case, we might run into, which is kind of an interesting one, is-- actually, maybe I should use this color. Suppose 1 over R is up here. So R is really small. Then I'm going to have a maximum case of my admittance up here well above the intersection points of these two asymptotes.

And so I'm going to get some characteristics that's going to do something, at least qualitatively, like this. And this we might think of as the high Q case. Actually, let me put that over here. I'm being very qualitative about this, but this would be the high Q case.

Now, really, what we're saying is, how does R compare to Z0? So in this case, this is R much bigger than Z0. This is R on the order of Z0. And this is R much less than Z0.

So by knowing how your resistor compares to your characteristic impedance, you can tell what the frequency domain admittance of this thing is going to look like, at least in its amplitude. And, of course, the phase response will be very slow or very sharp correspondingly. Any questions about that?

If I were to look at the frequency domain, if I were to look at, say, for example, where the poles of the admittance are-- so I plot YN of S, and then I find out where does that YN of S blow up-- at what complex frequencies it blows up-- what you would see is the following. And I'm not going to prove this.

So here's the imaginary axis. Here's the real axis. And I'm plotting the poles of YN of S. What we would find is that in this green case, we would have overdamped case, particularly, actually, this is when R over Z0 is less than a half. It will be overdamped.

In the intermediate case, what we're going to see is something like where the poles are underdamped, but maybe they're out here like this, something like that. And then the yellow case, where it's super peaky, we're going to see poles that are something like this. They're very close to the J omega axis.

So we're sort of-- have different cases where the dynamics of this, the time domain dynamics, are related to how peaky the frequency domain response is. And those, of course, map between one another. Any questions about that?

So I mentioned the so-called Q of the network. And what do I mean by that? And this is-- Q gets thrown around as a term quite a bit. And you've got to be careful in how you use it. But what do we mean generally? What is the Q of some network that we're driving?

This could be a mechanical system. This could be some other kind of system. It doesn't have to be a second-order electrical network. But generally, what we define is the quality factor. Q is generally defined this way. It's 2 pi times the peak energy stored under sinusoidal drive conditions divided by the energy dissipated in a cycle.

And how the history of this quality factor term came to be is actually in a handout that I think is-- you should have been able to pick up, or it's also posted on Canvas. But this is the underlying modern definition of quality factor.

Let's just say-- and it doesn't only apply to second-order networks like this. It applies to any network you're driving. And it also applies at any frequency you happen to be driving it. But let's think about a simple example.

So suppose I was to take a sinusoidal current, and I'll call this I cosine omega T. Now I'm going to put it into some network. And let me let my network just be R and L. So I'm going to drive an LR network with a sinusoidal current. And I could ask, what is the quality factor of this network under these drive conditions?

Well, it's a series RL circuit. We can just apply this definition, What's the peak energy stored in this network over the AC cycle? It's got to be-- yeah. Maximum energy is stored when the inductor current is maximum, which is I. So E stored is simply 1/2 LI squared. E stored peak is 1/2 LI squared. That's easy enough.

How about the energy dissipated? Well, I would argue that this is IRMS squared R would be the power dissipated on average. So I could say E diss in one cycle could simply be the power dissipation, which is 1/2 I squared R.

That's the power-- average power being dissipated in the resistor times the period would give me the energy dissipated, which would give me then-- I could write this as 1/2 I squared R times 2 pi over omega is the period. And if I rewrote that, then I would get pi I squared R divided by omega.

So now let me just apply my definition of quality factor. Q is simply equal to 2 pi times the peak energy stored, which is 1/2 LI squared divided by the energy dissipated, which is pi I squared R divided by omega. And in the end, what I get is omega L over R.

So what this says is if I'm driving this network, and I say, how much energy is going away into the resistance compared to the amount of energy I'm storing in this network, it's precisely omega L over R. Now, do I want that to be high or low? Well, it depends what I'm doing.

If I wanted a lot of energy storage and very little dissipation-- suppose this boxed item were a model of a real inductor who has an inductance L, but he has a parasitic resistance R, this quality factor then would be a measure of how much can I store divided by how much do I lose when I store it in that inductor normalized with 2 pi.

So in some sense, you could use-- for a real inductor, Q could be a measure of the goodness of the inductor. And, in fact, that's how they started using Q as a measure of goodness for inductors and capacitors. But it works out to have this definition.

On the other hand, if I was using this network to transfer energy from this source into the resistor, then having dissipation in the resistor is a good thing, not a bad thing, then maybe I want the Q to be really low. And, in fact, the power factor gets better when the Q is really low.

So Q came up to be a measure in a sinusoidal drive condition of energy stored in the network divided by energy dissipated over a cycle. Any questions about that?

And I will have you notice that Q is, in fact, in general, a function of frequency. So it gets-- if you're going to talk about the Q of driving something, you really got to say what frequency you're driving at it, usually.

And, in fact, what that tells me is that if I'm going out and buying inductors, and all things equal, if it has a given parasitic resistance, going at higher frequency gives me better energy storage per unit dissipation because my energy storage goes up with frequency, and my energy dissipation doesn't, on average. Yeah, Julia.

AUDIENCE: Does this definition for Q still work if the drive signal is AC but not sinusoidal with a square [INAUDIBLE] driver or something?

DAVID PERREAULT: Yeah. Usually, they don't-- usually, you define it under sinusoidal drive conditions. I'm not sure if anybody ever came up with some other definition, but usually that's what's intended. Sinusoids are sort of for LTI systems or their eigenfunction. So that's what we usually worry about.

So that's the definition of Q. How does that relate to when we talk about the Q of-- if I'm talking about the Q of this network here, and I'm saying it's high Q or low Q network? And this is where we got to be careful about what we mean by Q.

This is the underlying definition. But often, when we talk about the quality factor of a network, especially, say, a second-order resonant network, what's meant by that is the quality factor, if you happen to be driving it at its resonant frequency, or in this case, omega equals omega 0.

So when you're talking about the Q of the network, you say, let me drive at its resonant frequency and talk about what its Q is there. So why don't we go calculate the Q of this network? And I'm going to calculate it at omega equals omega 0.

So when I'm talking about the Q of the network, when I say "of the network," what you should be thinking of is Q of omega equals omega 0. You could find the Q at some other drive frequency, and that would be the quality factor of driving that network. But it wouldn't be what people refer to as the Q of the network itself.

And that's sort of-- and the reason I say that is because it's sort of implicit-- it's sort of an implicit condition when you're talking about the Q of the network. So let's talk about this.

So here I am. I'm going to drive a VS cosine omega T. And I'm going to drive this network at omega equals omega 0. So let me actually-- let's be careful. I'm going to talk about this Q of omega 0 T.

I have RLC-- I sub L, V sub C. At omega equals omega 0, what is I sub L? Well, I sub L, I would argue, at the natural resonant frequency, the impedance of C and L cancel. And my admittance is 1 over R, or my impedance is just R.

So then this should just be VS over R cosine of omega T-- omega 0T. And at that magic frequency, because the capacitor current is exactly driven-- the capacitor voltage is exactly driven by the inductor current, these two at that frequency are exactly 90 degrees out of phase.

So what that means is that when IL is peaking, VC is at its 0 crossing. So we could very easily show that the maximum energy storage would occur when IL was at its peak. So, for example, at omega 0 T equals 0.

The circuit also stores maximum energy when the inductor current is at 0 and the capacitor voltage is at his peak. And it would be the same stored energy because these two these two elements are essentially just flopping energy between one another, and all the power-- the net power-- is going into the resistor.

So we could say the peak energy stored is just going to be simply 1/2 L IP squared, which would be 1/2 L VS squared over R squared. at omega equal omega 0.

The energy dissipated. Well, we can calculate it. As long as I know the current, I have the same energy as up there. That's going to be equal to pi times I squared, which is VS squared over R squared times R divided by omega, which is pi VS squared over R omega.

So then if I were going to calculate Q evaluated at omega equals omega 0, which I'm going to call-- to designate that, I'm going to call that Q0. The Q of the circuit I'll call Q0 to distinguish it from the Q of the circuit operating at some other frequency.

We could write this as 2 pi times the peak energy stored. It's 1/2 L VS squared over R squared divided by the energy dissipated, which is pi VS squared over R omega. And that's R omega 0 because we're at omega 0.

And if I write that out, what I'm going to get is this. I get the two pi's canceling. I get the VS squareds canceling. I get this R cancels with this one. So I get omega 0 L divided by R, which we just said was-- omega 0 L, if you remember, is Z0, my characteristic impedance.

So this is Z0 over R is the quality factor of the circuit. So it immediately comes back to this case. If X0 over R is big, where R is much smaller than Z0-- I'm up here. And so exactly comes back to this.

So if I were to plot this, then, maybe I would come here and I'd say, OK, let me do the high Q case. And I would have this is 1 over Z0. Here's 1 over R. So maybe what I have is something that does this, peaks up like this.

And exactly what we're saying is that the ratio-- I didn't draw that in a very pretty fashion. Maybe it comes down a little quicker like this. What we're saying is that the exact amount I'm going to peak up, the ratio-- this is 1 over Z0. This is 1 over R. The amount that I peak up above the intersection, above the two asymptotes intersecting, is exactly Q of omega 0, which is Q0 here.

So what we can say is that if I have-- and this is why I immediately-- another reason I immediately like to calculate Z0. If I'm in a series resonant circuit, I know that the quality factor of the circuit is Z0 over R, and the amount I'm going to peak up above the intersection of the asymptotes in terms of its admittance is exactly the quality factor of the circuit, or Z0 over R.

So if Z0 is much bigger than R, I know I'm going to peak up a lot. If Z0 is smaller, it's going to be a flatter frequency response. Any questions about that?

I'd like to show you one last thing that comes up. And I should say we could have considered a parallel resonant network. We could have considered other resonant networks. I don't want you to think that they're all precisely the same, but they have a lot of characteristics in common. And, in fact, if I had done the parallel resonant network, actually what you would have found is the quality factor is exactly-- instead of being Z0 over R, it turns out to be R over Z0. It's exactly the inverse.

But there's a lot of value in figuring out the quality factor of the network because it tells you exactly how much is it going to peak up.

But we could ask ourselves one more question. I mentioned that-- and I haven't gotten to why we're going to get soft switching out of this. We'll get to that. But I might be interested in how frequency-selective this network is. Why?

Because if I was going to drive this at variable frequency-- suppose I could control omega over a range-- the impedance of this guy, especially if it's high Q, the admittance, and hence, the impedance changes very quickly with frequency. If I move off the resonant frequency, the admittance drops pretty quickly if it's high Q.

So I might be able to modulate how much current I'm going to get and how much power I'm going to deliver by modulating frequency. In fact, that's what we often do in resonant converters. Not always, but often.

So one thing I might be interested in is how broad-- if I said I'm going to peak up, how broad is this peaking in frequency? So why don't we go calculate how broad that peaking and frequency is.

And the measure I might use to capture that is the following. I might look at this and say, OK, suppose I'm going to drive with a voltage, over what frequency range do I get at least half the power I would get exactly at resonance? So what would that be?

If I'm going to get half the power, that means the current has to go down by the 1 over the square root of 2 because then I get pi squared-- give me a half. So maybe I'm looking for the frequency range over which I have the magnitude of the admittance drops down to 1 over the square root of 2R.

Because the admittance 1 over the square root of 2R, then the magnitude of the current is going to be 1 over the square root of 2-- go down as 1 over the square root of 2, and my power is going to go down by half.

And so then I might end up with some frequency range here, say between-- say this is some frequency range between omega 2 and omega 1, where over this half power bandwidth, I will get at least half the power as I would at the resonant frequency. Does that make sense to everybody? So why don't we go find this half power bandwidth.

What will I see then? Well, what I'm looking for is if I'm looking for an admittance that's 1 over the square root of 2R-- I want these two magic points here-- and I look at my admittance equation, the magnitude of YN I want to be 1 over the square root of 2R.

Here's the magnitude of YN. What I really want is this guy to be R, or minus R. Because then this will be R squared plus R squared gives me 2R squared. Square root, it gives me square root of 2R in the denominator. Does that make sense to everybody?

So what I could say is then what I want is-- I want the two frequencies to be omega L minus 1 over omega C, the magnitude of that to equal R. This is going to define omega 1 and omega 2. Any questions about that? So let's just do that.

I could find-- let me just-- what I can say is let's find the case where I have omega 1L minus 1 over omega 1C is equal to minus R. I'm picking the lower of the two frequencies because this is going getting bigger with frequency. So I want the one that's minus R for omega 1.

So if I multiply through by this, then I get omega 1 squared LC minus-- or plus-- I'm sorry-- omega 1 RC minus 1 is equal to 0. So that's the equation that's going to define it. That gives me omega 1 is equal to minus RC plus or minus the square root of RC quantity squared minus 4 LC all over 2 LC, which gives me minus R over 2L.

This is going to have to be plus to yield a positive frequency. The square root of 1 over LC-- oops. I'm sorry. This should be plus-- 1 over 4 L of C divided by R over 2L quantity squared. And that's omega. This is the expression for omega 1, which is exactly the frequency where I'm sitting right here-- a factor of 1 over square root of 2 down from the peak admittance. Any questions about that?

What would I do if I got the-- would I do to get the second one? I would have omega 2L minus 1 over omega 2C equal positive R. Let me just skip through the algebra because we can do the algebra. I just wanted you to see how you get it. What we get is exactly equal to R over 2L. So omega 2 is equal to R over 2L plus the square root of 1 over LC plus 1 over R over 2L quantity squared.

So notice, just as an aside, omega 1 and omega 2 aren't quite centered at 1 over the square root of LC. It's slightly off of that. But if R becomes small, it's high Q, then it's very close to centered at omega 0.

But here's the point I wanted to make. What is omega 2 minus omega 1? Omega 2 minus omega 1-- what I'm trying to do is calculate what is this width in frequency over which I have at least half the power as I do at the peak? That's sometimes called the half-power bandwidth. And if I get that, that's just going to equal to R over 2L. OK? I'm sorry. It's just equal to R over L. Because R over 2L minus R over 2L, and these other two terms cancel.

Well, what happens-- I mean, the absolute bandwidth maybe isn't as interesting. But how about I go normalize that to the natural resonant frequency? So why don't I just take this and normalize it to omega 0? That's the percentage bandwidth.

If I think of this as sort of my center frequency of interest, this is the percentage of this over which I get half the power. And so all I got to do is put omega 0 here in the denominator. And this is exactly equal to R over omega 0L is just Z0, which is equal to 1 over Q. 1 over Q0, I should say, to be careful.

So what's the conclusion of that? What I'm saying here is if I say what is the bandwidth-- If I wanted to say what is omega 2 minus omega 1 over omega 0, the percentage bandwidth is exactly equal to 1 over Q0.

So if I thought about this network, suppose I could dial the resistance and just look what happened to my response? As I make my resistor smaller, Q naught goes up. As Q naught goes up, two things happen.

First of all, this thing gets peakier in terms of the amount my resonant peak goes up. But at the same time, that resonant peak gets sharper and sharper and sharper. And so I really want to figure out the Q of the network because I want to know, is it doing one of these things on me where I don't get much peaking and I don't get much frequency selectivity? I have to work over a really wide bandwidth in order to modulate, say, power going into the resistor? Or do I get something that's really, really sharp?

But I get two effects out of that. So I just got have to recognize, those two things go hand in hand. Bigger peaking, also corresponds to more sharpness. I may want the peaking. Why might I want the peaking?

Because what we said was, if I work it out, the more peaky it is, the higher the voltage stress on that capacitor, the more voltage I'm putting across the capacitor in the inductor. And, in some cases, we can use that to get voltage gain. In fact, if I were thinking about a lamp ballast, it's not a series network in that case, it's a parallel network, but I might actually use that.

So if you want to like, break over a fluorescent lamp ballast-- it's more or less an open circuit. You want to break down the gases, the voltage of the gases to make it strike, you can use the resonant gain of your network to get voltages that are much bigger than your drive voltage.

And, in fact, at resonance, the voltage on that capacitor in this network-- and I don't think-- I'm not sure if I exactly showed you this, but it's easy to show. If I go right to resonance, the voltage on this capacitor is precisely Q0 times the source voltage at the resonant frequency.

So maybe I would want some situation where I can generate large voltages. Well, the resonance helps me do that. But to get a large voltage relative to the input, I need a higher Q0. On the other hand, I'm only going to get that over a narrower and narrower frequency range.

On the other hand-- so on the one hand, maybe I want high Q because I get large voltage gain. Or because I get large frequency selectivity, like higher Q means I don't have to move very much in frequency to modulate power.

But at the same time, what did we say that meant? That means when we're getting towards resonance, that means I'm storing-- the proportion of energy I'm storing compared to that amount I'm putting into the resistor, it gets bigger. So if my if my network Q is too high, that means I get big voltage and current stresses on my capacitor and my inductor respectively. And it means I have to store a lot of energy in the circuit for the amount I'm delivering into the resistor.

So we have-- what we're going to see is as we start talking about power converters that use this characteristic, low Q means, eh, maybe I don't get the frequency selectivity I want, and I can't use frequency to modulate things very well.

If Q is too high, I get large stresses on my inductor and capacitor, or I have to store a large amount of energy for the amount of energy I put into the resistor. That's not so good. And in the medium, maybe I get something where I get nice ability to modulate the amplitude with frequency over a reasonable frequency range without putting too much energy storage in my network. Questions about that?

So what I want you to take away from today, and this is just done in the example of a series resonant circuit, first of all, when you're handed a circuit like this, and you're thinking about sinusoidal drive, you want to calculate characteristic impedance and natural resonant frequency. And the next thing you want to get after that is quality factor-- Q0, quality factor of the circuit. Because those are going to tell you essentially how peaky or sharp this whole thing is.

And then the second thing we can take away from that is what kind of bandwidths do I need to operate to modulate power? And what kind of stress ranges am I going to get compared to my input drive in the network?

We will take this up next class. Go out and have a beautiful day. Nice day out.