[SQUEAKING]

[RUSTLING]

[CLICKING]

PROFESSOR: OK. Why don't we get started? The end of the term approacheth. So please do get to work on the design projects if you're not already doing that.

The homework lengths are being tapered down to open up room to do that. So please don't leave it to the last moment. And I know this is project season so I know many people have a lot of them going on. So try to start early.

Everything I'm going to talk about today is in *Principles of Power Electronics,* chapter 26. Just as a review of what we talked about last time, we said if I thought about a power converter and its filter, if I have a filter like an Lc filter, I have some Cf and Lf, which I'm looking back into from the power converter.

And the problem is if I'm driving current into this filter, if I don't worry about the voltage source but just think about maybe the source impedance is a short circuit, Cf and Lf are in parallel, so I'll get a real-- a peak and impedance and a lot of circulating current if I have any drive at the cutoff frequency of the filter. And we said both this very lightly damped system and the output impedance can be modified by adding a damping leg of one kind or another.

So maybe what I do is I take an additional C damp and R damp so that, at the cutoff, C damp's a short circuit or close to it so R damp is in parallel with Lf and Cf. And I reduce the output impedance of the filter. So right. So maybe this z out looks something like this versus omega on a log scale. Maybe at low frequencies, it rises as omega L. At high frequency, it falls as 1 over omega C. And I'll get some peaking in here, which is limited by the magnitude of z out max is related to the damping resistor here. And if the damping resistors were actually in parallel, it would be exactly the damping resistance.

Now the reason we care about that is both because we don't want a lot of peaking and undamped behavior in this filter, but it's also true that if I look in the other direction into the power converter and say what's the input impedance looking into the power converter incrementally, if I have some V in and then some I in to the converter and the converter is regulating, it's going to maintain a constant voltage across its load or, equivalently, it's going to draw ideally constant power to maintain its load. That means its IV characteristic V in I in looks like this because V in is proportional to 1 over I in.

And so if we're sitting at some operating point, say this is I in and this is V in, incrementally, this slope is dV in dI in evaluated at V in I in is equal to a negative resistor because this slope is negative. So it turns out to be minus p out over I in squared. And so basically, if I'm looking into the converter from the filter, I'm effectively seeing a negative resistor here. And that negative resistor can make this whole thing oscillate.

So we always want to make the output impedance of my filter very small compared to the magnitude of my negative input resistance here in order to make sure that this whole system won't oscillate. So that was what I hoped you took away from last class. Are there any questions about that?

So today I want to talk about something a little bit different. We've kind of brushed lightly over one topic or neglected one kind of effect that you often have to contend with in EMI filter designs. And just to illustrate how important this general topic is, what this is is this is a power factor corrected laptop power supply which somebody gave me. And that's what happens to power supplies people give me.

And if you look at this, here is the twice line frequency energy buffer over here. Here's the power stage. There's a rectifier up front. But a whole good chunk of this converter right over here is the EMI filter for plugging into the wall. And we're going to talk about how you would structure things in a line interface application but also in a bunch of other applications. And there's one kind of aspect we haven't really focused on yet. And to set that up, let me just give you instead of an AC application, let me talk about a DC application.

So suppose I wanted to connect a power converter in a vehicle. And this could be a regular vehicle or an electrical vehicle. Here's my battery. And this is-- let me call this ground. This is like the chassis of the vehicle. And that's where the battery might be tied. I'm going to plug a power converter into this. I'm going to have some cabling to carry the ground and the battery voltage over to whatever I'm powering. OK.

All right. So here's my cabling. And that cabling in the real world doesn't have zero impedance but let's not worry about that too much. Now I'm going to go dutifully put in my EMI filter. OK. So maybe I have Lf, Cf, and I'll be really smart. Maybe I'll say, OK, let me put in a damping resistor. So here I have RD and CD So I've done my damping job here. That's my filter.

Now I'll connect up my converter. And maybe my converter is a boost converter. So here's my boost converter. Has an inductor. Has a transistor, diode, output cap. And here's my load resistor. And I won't worry about the details of the load too much. And keep in mind, this whole thing is indeed referenced to ground, but there's some cabling. So let me just worry about this. I'll call this V source because the source of my transistor with reference to ground.

OK. So what do I intend to happen in this converter? What I intend to happen is I draw a current from my battery. It goes through the cable, goes through the filter, enters the converter, and it might go down through the switch at some times or it might go down through the diode and the output sometimes. But basically, it goes through there and then it returns in this loop. So this is the current path. I'm really using to power this converter. And I filtered that current path. Here's my filter.

OK. Well, that's good. But if I think about it, I've got a heat sink, the switch in the diode. So let's just think about the transistor. And let's remember how we do that. So maybe here I have my transistor. Here's my transistor. And then I'm going to put down a thermal pad. And then I'm going to connect that thermal pad. On the other side of that thermal pad will be whatever I'm heat sinking the device to. OK. What I'm often heat sinking the device to is either the case of the power supply and that case of the power supply is basically often connected back to ground. In fact, sometimes you'll use the case of the whole thing to be ground.

And if I think about a transistor, in fact, what's the package of the transistor if you have a TO-247 or TO-220 or something, that's actually the drain node of this thing. So what I have is essentially a piece of metal here, a thin insulator for electrical insulation, and then a ground. So what is that? That's a capacitor.

So it turns out that in most power supplies like this, there's going to be a significant parasitic capacitance-- I'll just call it Cp, parasitic capacitance-- that gets back to ground because ground is the chassis of the vehicle. Even if you didn't have a heatsink, you have a node flapping up and down. There's stuff around it. And so there is going to be some capacitance back to ground. Everybody buy that?

And so you have this opportunity to have another current path that goes something like this. Current can flow through this lead. It could flow maybe even here up to here and back to ground, or it could flow up through this capacitor and through this inductor back to ground. But nonetheless, there is a path, at least one path, that's not going through a filter inductor.

So I really, to the extent that this node is slapping up and down with respect to something very close to the ground, I'm going to get a bunch of current through this parasitic capacitance at high frequency, not DC current, just AC current. And if this lead is kind of long, that looks just like an antenna. Right? And I'm right next to my radio so I run into electromagnetic interference that I'm causing not necessarily through this lead but current coming through the other power lead.

OK. And this is a problem. And in fact, I mentioned earlier in the class when we set up our line impedance stabilization network to measure everything, usually you actually have one LISN for measuring the noise on the hot line and another LISN for measuring the noise on the return line. So you really have to keep the EMI in both of these leads small.

So what I want to do today is just talk about how we represent noise in these situations and then how do we design filters that deal with those that noise. So before I go on, are there any questions about what the issue is?

OK. So let me think about maybe another example where this comes up. OK. And this would be something like that power supply that I'm passing around would be plugged into. So maybe what I have is at home, what do you have? You have an AC supply. So here's my AC supply and I have the hot terminal. That's the black wire running around your house. Black is for death. Don't get near that.

You have the neutral wire, which is usually white. And you're going to carry some cabling inside your walls, hot and neutral. And I should say that neutral, back at the service entrance somewhere, is actually tends to be tied to ground. So the neutral. Is going to be near ground. But it doesn't actually have to be precisely at ground. And it'll be close somewhere.

And very often, if I think about what wires are going out to the boxes, usually there will also be a ground wire that's connected to ground. And that's usually the green or the uninsulated wire. And if you have a three-terminal plug, one of those goes to the ground, one goes to neutral, one goes to hot. If you have a two-terminal plug, they get rid of this and they just don't have an explicit ground going. Make sense, everybody?

So what happens again-- this is going to plug into whatever my device is. And I'll have terminal one, terminal two for hot and neutral, and then I may have some parasitic path. Why might I have a parasitic path? One reason is in a lot of equipment, we tend to ground the case of the equipment.

So if it has a three-terminal plug, you plug it into the wall. That ground connection coming out of that third terminal is going to the case of the device. Why? Because suppose there's some fault inside the equipment and that fault shorts the hot terminal to the case. You don't want somebody walking up and touching the surface of that thing, getting electrocuted. Right?

So if they ground the case, and some fault happens inside, huge current will flow, it'll blow the breaker, and then things will be disconnected and you'll be safe. So very often, there's an explicit connection between the case of the device and ground. And since the case happens to surround whatever the device is, like the power supply, it could be, in fact, if I had a boost PFC circuit, it looks exactly like the structure I just drew except that instead of being powered by DC, it's powered by AC and I essentially insert a rectifier here. That's what a boost rectifier looks like, the front end of a lot of power supplies.

So this structure can very much represent what would happen in the AC case, too, except that somewhere I put a usually a full bridge to rectify an AC voltage, which I'd have over here to DC that my converter then processes. So the consequence of that is, is even though I don't intend it to be there, there's going to be some virtual third terminal which is connected by some parasitic capacitance again back to ground. OK. Even if the case isn't connected to ground, ground is around you. There's going to be some flow possibly through that. Any questions about that?

I should have noted, by the way-- and I'll come back to this. It's a little bit easier to see in this case of the DC case. If I've done this and now I have very peaky currents coming through this parasitic capacitance, I have high frequency currents flowing on this lead, if this if this pathway has some parasitic resistance and maybe a little parasitic inductance from all the wiring, I can develop a voltage drop across here.

And so this voltage is non-zero. I'll see what's called ground bounce. And maybe you've experienced this when you've tried to measure just ground on some circuit you're building. And it looks like it's got a bunch of high frequency junk on it. That's exactly due to this kind of phenomenon.

So we can see, even though I intend this node to be-- in an ideal world, this would be a zero resistance, zero inductance wire and I intended there to be no voltage there, because it's not an ideal wire, it's a real one, there will be ground bounce here that I have to contend with. So when I go to think about this network, maybe I will think about a current into terminal one that I'm going to call i1. I'm going to think about a current into terminal two that I'm going to call i2.

Again, I could talk about the voltage at terminal one with respect to ground. I'm going to call that v1. And I can think about the voltage at terminal two with respect to ground that I'm going to call that v2. And I will recognize that, yeah, v2 should be close to ground because back through a bunch of wiring, it is tied to ground. But that's a DC. And even a DC there's some resistance there. So I can think about v1, v2, i1, and i2 as being the net currents flowing into my device. Any questions about that?

So what do I intend to happen in this device. I didn't really want this parasitic capacitance. I'm just getting it. Right. So the ideal path that, I'm thinking, OK, this is how my converter should work, is I should have current that's coming from the power, the voltage source, into terminal 1, coming back out terminal 2, and doing this kind of loop around like this. And that's fine but because of this parasitic, there can be some other path that I might want to think about. And if I didn't have this other path, what would I have? I'd have i1 is equal to minus i2. That's the ideal case when this other path doesn't exist.

All right. If the other path does exist, we get what we would call a common mode signal that I'm going to call ICM. Common mode current. Common mode because I think of it as coming through somehow the two leads together into the device and then out through the device through some third path. Does that make sense to everybody?

And this common mode current maybe I would think of as flowing like this. Half of it's coming in this terminal so I'm going to call this 1/2 icm. Half of it's coming through this terminal. This is 1/2 ICM. And then it comes out the other side of the device and returns to ground like this. So this is what I'm thinking of as my common mode current. The current that I was thinking of flowing around the loop, which I'd have in the ideal case, we would call this the differential mode current.

So how would I represent the common mode and differential mode current? Well, by definition, by what I've told you, icm is equal to I 1 plus I two right by. If I basically make this a supernode, icm is coming out, but I'm calling that icm, so it must be equal to I 1 plus I two everybody by that.

Now I got to define what I think about this differential mode current. In the case when I didn't have icm, the differential mode current would be, you know, i1 would equal idm and i2 would be equal to minus idm. The way we tend to define the differential mode current, idm, is simply as being the average of the currents I thought I was going to get. So I would call it i1 minus i2 over 2.

So this is sort of-- and the reason I'm emphasizing it this way is just because these are the definitions of the common mode and differential mode components. OK. If I went and said, OK, if I apply those two definitions, what I get for i1 and i2, if I recombine this, is I get i1 is equal to idm plus 1/2 icm. And i2 is equal to minus idm plus 1/2 icm. So by choosing things this way, what I'm really saying is, OK, if I had no common mode current, I'd have idm in terminal 1 and minus idm in terminal 2-- going to terminal 2. That's what I'd expect. And then I'm saying that each of these two terminals is carrying half the common mode current. That's essentially what the definition says. OK. Does that make sense to everybody?

What about voltages? I focused on the currents here, but I said I have a voltage at terminal 1 and a voltage at terminal 2. And I can assume that the voltage at terminal 2 is ground because of this ground bounce kind of stuff going on and the fact that there's a bunch of cabling here, whether it's switching ground bounce or not. There's some difference between that and ground.

So we can also come up with definitions of voltage. OK. The common mode voltage, if I'm going to look at the input point-- so I'm going to look at this point here. I could define the common mode voltage at the input of the device as being vcm is equal to v1 plus v2 over 2. So basically, the common mode voltage is the average of the two voltages driving node 1 and node 2.

The differential mode voltage, vdm, is simply equal to v1 minus v2. OK. If I thought about it, v1 with respect to ground minus v2 with respect to ground is this voltage vdm. That's the voltage into which I was intending to apply to my device. It's the difference between the two terminals. It's my input of my device. So that is the differential mode voltage.

The common mode voltage I'm just defining as the average. And if I put those two things together, what I get is that v1 is equal to vcm plus 1/2 vdm and v2 is equal to vcm minus 1/2 vdm. So I'm issuing a decomposition of voltage 1 and voltage 2 with respect to ground and current 1 and current 2 into common mode and differential mode components. So this is just a decomposition.

By the way, it's kind of funny because you notice that icm is i1 plus i2 and the vcm is the average. And the differential mode is defined the other way around. One of the reasons why you define it this way is because if I said what's the total power flowing here, I could say it was p I could write as being equal to v1 times i1. That's the power into this port with respect to ground plus v2 i2. And if I work that out, that works out to be precisely equal to vcm icm plus vdm idm. All right. So whether I decompose-- if I take my voltage and currents and I decompose it into common differential mode, it preserves the notion of power.

OK. So that's just kind of a convenient, handy fact. It's not important from the perspective of we're trying to use common mode and differential mode to deliver power. I'm really trying to deliver my power into this thing through differential mode. That's the notion of how this thing is supposed to work. I really don't want any current flowing in my ground path.

But the other reason why people think about this decomposition of voltages and currents is because I tend to use different techniques to fix common mode noise and differential mode noise. And so decomposing it that way tells you what techniques should I use to make a better filter.

OK. So let's think about this for a second. What might I do in a filter design? Well, let's go design a filter for this thing now. And keep in mind, we're going to have to put some kind of filtering to deal with the fact that I can't allow lots of high frequency currents through this path. So I can't just say do what I did before and just have a single-ended kind of filter that filters one path. I'm going to have to do something that filters both leads going to my converter.

OK. Now in some cases, you can get away with a single-ended filter. If this whole thing were built on top of a ground plane and there was no wires going anywhere, and there's just one big ground plane, well, then sure, you only need to filter one lead because everything else is traveling in the big ground plane. But if you have a device that's connected over some cabling, you better think twice because there could be some unintended path back. OK.

All right. So let's go think about how I would design a filter to deal with this. So here I go. Here is my device again. And here's one, two, and my unintended terminal three. And if I thought of it-- let me just think about-- and it's not quite true, but let me just think about, for simplicity, as my converter being a source of drawing common and differential mode currents.

So I might think of it this way. I might think of this coming in here and drawing a differential mode current IBM. And that would include the power current plus any switching noise or something coming between these two terminals. And then if I thought, well, I might be driving some common mode currents, what would that be? I'd have 1/2 icm being drawn this way out here and 1/2 icm being drawn this way to the output. And then this would be icm to ground through my parasitic capacitance back to ground. Does that make sense to everybody?

So let's just-- let me pretend for a moment idm is zero. Let's just think I have a common mode currents that are being drawn together through pins and ones and twos and going back through ground. All right. What would I do to filter it?

Well, they said the first thing I usually put in my filter is a capacitor between the two leads. And I'm going to call this-- for reasons we'll discuss, I'm going to call this c sub x. OK. Does this capacitor really do anything? If I thought about if the currents are kind of equally coming this way, this capacitor is like an open circuit to those currents. All right. Or if v1 and v2, the voltages, are going up and down together, it has a common mode component to the voltages, c sub x is drawing no current. So for the common mode case, I mean c sub x might as well not be there.

So what could I do to deal with c sub x? Well, one thing I could do is put in what's known as a common mode choke. What is a common mode choke? A common mode choke is essentially a transformer that's wound like this. It has equal numbers of turns on each side. And it's wound with its dots like this. So if this were an ideal transformer and I said, OK, let's pretend that cx is an open circuit here, how much current can flow together through these two ideal transformer windings?

Can I get a common mode component through an ideal transformer? Nobody's willing to bet on that? It's got to be zero because, in an ideal transformer, whatever comes into this dot comes out of that dot. It's an end to end transformer or a 1 to 1 transformer. So an ideal transformer only allows differential mode current. So that's why it's called a common mode choke. It chokes off the common mode current.

OK. Well, what would I do in my filter design? This thing makes like a perfect inductor against common mode currents in some sense if I wanted to think about that, if I could go out and buy myself an ideal transformer.

Now I can't go buy myself an ideal transformer. Why? Because they don't sell them at Digikey. What do I have to think of in terms of parasitics in my transformer? Well, one thing is I said I could put a magnetizing inductance L mu on one side of-- if this is the ideal transformer part, I can put a magnetizing L mu across one of the terminals. Now they have the same winding so they'd have the same inductance whichever place I put it right.

But I could also represent L mu as 2L mu in parallel with 2L mu. So another way I could write this is I could put 2L mu on this side and, to make it symmetric, I could put 2L mu on the other side of the transformer. So I have some magnetizing on each side. And maybe I should have-- I'm intending to draw this in pink although I'm not sure you can see the difference just to illustrate that these are parasitic components.

OK. What else do I have? I also have leakage inductance. And if this is symmetrically wound, I would have L leakage here and an equal L leakage here. And that would represent a model for a real transformer. So in principle, if this is an ungapped transformer, common mode current could come, go through the 2L mu, the magnetizing inductance on each side through the leakage, and then in here. So it does pose a path for common mode current in the real world, but it's a very high impedance path because if this transformer is ungapped, L mu is a pretty big number.

OK. That's inductive choking. What would I do to get rid of the-- what would I do to get rid of the-- help filter these common mode currents? Maybe what I would do is I would go in and I'd put in a capacitor. And I'm going to call this cy to ground here and another cy to ground here.

So I hope what you'll see is half cm could come through here, come up through this capacitor, and happily circulate there. That's a low impedance capacitive path to high frequency. Same thing here. It can circulate this way because these guys are connected. And so the current at high frequency wants to go through the cy's but doesn't want to go this way because of the high magnetizing inductance. Does that make sense to everybody?

This is actually very convenient because if we think about it, we have common mode currents, but we also have differential mode currents. If this is my differential mode current here, idm, idm is coming this way, where would the differential mode current flow?

Let me ignore cx and cy. Let's pretend they're not there for the moment. Where would the differential mode current flow? Well, it could go through L mu. But think about it this way. Differential mode current doesn't mind going in this dot and out of this dot. This common mode choke. The ideal one is a perfect short for differential mode currents.

So the differential mode currents don't go through the magnetizing inductance. They just go through the ideal portion of the transformer. And so you don't magnetize the core. And so even if you have high differential mode currents, because this is what you're delivering power to the device through, they don't magnetize the core. And so you don't need a big common mode choke to get a high effective common mode inductance because it doesn't store any energy, at least it doesn't store any differential mode energy. Any questions about that?

So to the extent that the differential mode currents don't go through the magnetizing inductance, I can get very high magnetizing inductance with very few turns by using an ungapped core. And it's not going to be very large. And by the way, in the one I'm passing around here-- may I steal this back? I don't know. Did this make it over to the right hand side of the class? Yeah. So see these guys here?

These are common mode chokes right here. And actually, what you'll see is the two sets of windings are identical. And they're split up on the core. They're split up on the core, actually, to help enhance the amount of leakage inductance that we have from those things. But it's symmetric in ungapped cores. And that's very convenient. Why? Well, I said if I wanted to kill the common mode component of current, I want it to cycle through cy.

And my filter then, if I were to redraw this, let me just consider the common mode components. So if I just consider the common mode component-- so this is the cm only. I have half cm, 1/2 icm, 1/2 icm. Here I have cy. Here I have see cy. And then these are both going to ground, which is connected back here.

Then I'm going through leakage on each side and 2L mu on each side because the ideal portion of the transformer is now gone. And then this is connected back to my input, which I'll just treat as a short circuit. So the currents here basically form-- and I'm acknowledging that I have ground connected back here, too. So basically, the currents form an lc filter that I could think of if I mirrored this, I could redraw this as this.

So let me just mirror everything that looks like it's in parallel reflected across ground. And what I would get is this. L mu L leakage over 2 icm 2cy And then this is shorter this way. So putting aside damping, which I'm not talking about here, basically, I have a filter comprising 2cy is my capacitor and L mu plus half the leakage as my inductor. OK. Make sense to everybody? And that's handy because this c sub y, if I come back to my real system, it can be connected between the negative terminal and the positive terminal to ground.

It turns out I'm not allowed to use a very big y capacitor. I'm not allowed to connect a big capacitor between, say, hot, my AC voltage coming in, and ground, y, because, first of all, we're not supposed to carry currents in ground. This is actually allowing current to flow in the ground wire. Devices like GFI's-- you might have a GFI in your bathroom, a ground fault interrupter-- what they're really doing is they're looking at the difference between these two currents or, equivalently, they're looking for current going into the ground. And if they see current going to the ground, they think, ah, something's wrong, somebody is being electrocuted and the current's flowing through them. Shut everything off.

So if you allowed your device to put a bunch of current into the ground, it's going to mess things like that up. So they put very strict limits on how much current you're allowed to put in the ground. And for 60 hertz currents, which is what they're really looking at, or 50 hertz in Europe, this y capacitor is very limited in value. Depending upon the application, you might be talking like 5 nanofarad. It's very small capacitors.

So I don't get a very big capacitor value that I'm allowed to use. How do I get all my filtering? Well, I have the magnetizing inductance, which can be huge. So I have a tiny capacitor, but a really big inductor. And that gives me-- I can still get a low cutoff frequency and very good filtering for common mode signals. Does that make sense, everybody? And the reason I get away with that is because the high power currents, the differential mode currents, are not magnetizing the transformer core.

That's common mode only. Let's think about differential mode only for a moment. And you notice when I drew the common mode filter, I completely ignored this x capacitor because he's not doing anything for the common mode component. Let's think about the differential mode only.

So suppose here's my device. If I'm only thinking about the differential mode components, I have idm. I'm pretending common mode 0 now. I have an x capacitor, c sub x, which is sitting between terminal one and two. So this provides-- if I have a high frequency component to idm, it provides a low impedance path for it to flow through at high frequencies.

If I look back into this-- for filter purposes, let me just ignore the source voltage. The ideal transformer portion of my transformer carries all the differential mode current so I don't magnetize the core. So basically, the differential mode, the magnetizing inductance is essentially shorted out. But the leakage inductance is not.

So what I'm really going to see at differential mode is the following. I'm going to see-- I'm going to see the leakage inductance here and the leakage inductance on this side because there's two leakage inductance to the transformer. And then if I connect this at the bottom, that's fine. I should say we also have the y capacitors connected to ground. From a differential mode perspective, what that looks like is a y capacitor here and a y capacitor here. And the ground is like a virtual open. Nothing's flowing in ground. So these guys just look in series.

So maybe what I could think of if I thought about this is net controlling the current flow around this loop. What I really have is idm. I have c sub x plus 1/2 c sub y. And c sub x, by the way, can be very big. There's no actual limit on it. I mean I don't want to carry too much 60 hertz current in it, but it's not going to be tiny like the y capacitor does because it's not connected to ground. And then I effectively have-- if I consider these two paths together, I have a net 2L leakage here and this forms my lc filter.

Now c sub x can be pretty big so this capacitor can be relatively big. The leakage. Inductance is small. It's just the leakage inductance of my transformer. And that actually stores energy. If I'm passing differential mode currents to deliver power and those currents are amps or tens of amps, that's storing energy in the net leakage. But still, the leakage is relatively small compared to the magnetizing, a few percent maybe. So I can still keep my transformer pretty small. And now for differential mode, I get a big capacitor dominated by the x capacitor and then the leakage of my common mode choke. Are there questions about that?

So what do I want to know when I'm designing a filter? Right. If my problem is common mode noise, beefing up the x capacitor here is going to do zippo because the common current doesn't even flow through that. It's a virtual open. Increasing my leakage inductance, well, I could, but it's not going to help much because at common mode, this guy is what's dominating the impedance, the magnetized dominating impedance.

So if I have common mode noise, what I really need to do is increase the magnetizing inductance component. That's what would help me or maybe have another pair of y capacitors over here and make a higher order filter. But I want to focus on the elements, the magnetizing inductance, and the y capacitors that dominate my common mode filtering.

If the thing that's killing me is differential mode noise, then I might as well not worry about the magnetizing inductance because it's not helping me. And I ought to focus on the x capacitor and the leakage components or adding in another filter stage and worrying about the leakage components. So we can really think about the strategy used to design these filters in terms of the common mode and differential mode components. And I'm using different elements to help me build the filter and pass the specifications.

Now in the final analysis when I go to measure this stuff and I'm doing my EMI testing, what I'm really coming back and doing is setting up a LISN on this lead and looking, from the source's perspective, looking in the ripple in i2 and looking in the ripple in i1 or, equivalently, the voltage on the LISN for this lead and the voltage on the LISN for this lead. So my EMI measurements aren't done in terms of common mode and differential mode, but there will be common mode and differential modes components to those that I can go think about. And we often figure out ways to separate those because I'm going to do different things in my filter to fix them. OK.

What might I do if I wanted-- like if I just had this device and I wanted to go figure out the common mode current going into it, how do you think I'd do that? I could go get a current probe and grab both of this lead and this lead together through the current probe. So only the sum of the currents is what I measured, which is precisely the common mode current. So I could grab a current probe and say, oh, do I have common mode current? Oh, I do. I better think about fixing the common mode. Or if I grab this lead through the probe in one direction and I flipped i2 and I measured i1 plus minus i2, i1 plus minus i2 is precisely twice the differential mode current.

So I can separate out common mode and differential mode currents. I can do the same thing with voltages. If I look at the average of the voltages at terminal 1 and 2, if they're bouncing up together and down together, that's common mode. If they're doing this, that's differential mode. So I can use differential probes or sometimes what you can do is you look at how much your ground's bouncing and say, yeah, that's related to my common mode. But I'll think differently about how I will deal with those. And even when you're making measurements, you tend to do this.

Actually, if you look at this cord, you see this kind of cylinder on this cord? All that cylinder is is basically a ring, a toroidal ring of ferrite through which both leads are slipped. So this is just a one-turn common mode choke. It's helping keep common mode noise out. And it's very high impedance to common mode. Gives you almost no impedance to differential mode. And that's why you can get a lot of filtering with a very small core.

So that's just a notion that everything I've said about filtering is true. And sometimes you only need differential filtering. If you're building something over a ground plane and currents can return wherever they may in the ground plane, that's not a problem. But if you're going to build something with some pair of wires going out to the wall, or to your car battery, or to something else, you better start thinking in terms of common mode and differential mode, voltages and currents for noise. Any questions? Yeah.

AUDIENCE: So common mode and differential mode, do they both occur simultaneously or do they just-- are they situations that occur separately?

PROFESSOR: Well, different things might drive common mode and differential mode noise, but, typically, they're occurring together. And it's just a question of what you're seeing on pin one and what you're seeing on pin two in terms of voltage and current. So they occur together but what's dominant may depend upon the situation.

So if I suddenly increase the parasitic capacitance of my transistor to ground, suddenly I'd probably see a bunch of common mode noise there too, even if I have a differential mode component. OK. So if I'm making this third terminal current path easier, that's probably going to lead to common mode noise, for example. But no, they occur together. You've got to filter both at the same time. Other questions?

OK. Next class, we're going to take up an entirely new class of converter but we will do that tomorrow. Have a great day.