[SQUEAKING]

[RUSTLING]

[CLICKING]

XIN ZAN: So I think we can start. So welcome to my lecture. Today, we are going to learn about the switching loss and snubbers. So before that, I would like to have a quick review about our devices.

So one of the thing power electronics deal with is about the circuits. And nowadays, these circuits play with the transistors. And the transistors can be a bipolar transistor or the field effect transistors. So we use transistors as switches, which is on and off. And other analog circuits, or advanced analog circuits, they use transistors as a current source. And for the switches, we are focusing on there could be ideal switches or practical switches.

For ideal switches, we assume the switches will instantaneously turn on and turn off. And also, during the switch-on state, there is no voltage drop, or the resistor is 0. And it can carry both positive and negative current.

And when the switch is off, we said there will be an infinite resistor, and there is no leakage current. And it can also block positive voltage and negative voltage. And also, for parasitics, we assume the ideal switch has no parasitics. And because of these characteristics, we said that there is no loss if we use the ideal switches.

However, for reality, mostly, we use practical switches. So I list some practical switches in the lecture notes, that is like BJT, IGBT, thyristor, which is also called CSR or a diode. These days, we use mostly about the MOSFET or the wide bandgap gallium nitride FET.

And for these practical switches, they need some finite time to turn on and turn off. And also, when the switch is during its on state, there is a finite voltage drop, or a finite small resistor. And the current it can carry has some polarity.

So let's say, for the BJT, it can only carry the positive current. But for most FET, it can carry both positive and negative current. And also, when the switch is off, the off resistor will be very big. So there could be some leakage current.

And also, the blocking voltage also has a polarity. And because of this, and also for parasitics, we usually have a parallel capacitance in parallel with the switch. And also, some switches will have a antiparallel diode inside of them.

And because of these non-ideality factors, there will be some non-zero losses. And the losses could be conduction loss during the on state or the switching loss when the switch turn on and turn off. And also, we could have some gating loss and some other loss.

So this is a quick review about our transistor. And today, we will focusing on the switching loss and the corresponding method to improve the switching loss that we call snubbers.

So let's take the most basic circuit block converter as an example. So we have a input voltage source. And we can have a practical switch that is a MOSFET. And we can have a diode here. And usually, we will have a low-pass filter, L and a C, and also a resistor here.

So if we assume that the current flow through this inductor is constant, which is there is no ripple here, and this inductor is pretty big, then we can model our circuit, as we still have an input voltage source, and we have a MOSFET, and we have a diode here. And now our load will be a constant current source.

So we already know the switching pattern of the buck converter. So let's see. For a given switching period that is from 0 to Ts, from 0 to DTs, which is a duty cycle, the active switch, or the MOSFET, will turn on this load current. So the switch current will be a square wave like this. So this will be isw.

And for the diode, when the switch is off during the DTs to Ts, this diode will flow through this load current. So that will be a current waveform like this. And this is the diode current.

So when we considering the conduction loss, what is the power? Conduction loss is still a power. So what is power? Power is v times i. So for MOSFET, the conduction loss will be something like i rms squared times the on-state resistance, which I said before, for a switch, for a practical switch, when it's during that on state, either it can be a resistor or a voltage drop. And for a MOSFET, it will be a Rds on resistor.

And we can calculate the rms current for the MOSFET. So that will be the duty cycle times the IL squared times the Rds on. So this will be the IL for its amplitude.

And a photodiode, its conduction loss will be the average current of the diode times the voltage drop. So still, the loss is a power. Power is v times i, just like, for the MOSFET, the v will be i times the r. So it will be the irms squared times the Rds on. But for the diode, it will be the average current times the voltage drop. So that will be the 1 minus D times IL times the voltage drop of the diode.

So I also list, during its on state, the MOSFET looks like the resistor. And during its on state, a diode looks like a voltage drop. And for the BJT or IGBT or the SCR during its on state, it still looks like a voltage drop.

So when you calculate the conduction loss for a BJT, IGBT, or a diode or a thyristor, you use the average current times the voltage drop. And when you calculate the conduction loss for MOSFET or gallium nitride FET, you use the rms squared times the Rds on. So this is about the conduction loss.

And also, today, the semiconductor loss is back-of-envelope. So if you do more research, we can model this conduction loss more precisely. But generally speaking, this can be a rule of thumb for a rough calculation, and it is enough good for our design.

And for the conduction loss and for the switching loss, it occurs during the turn-on and the turn-off. And we need to imagine what will be the waveform for the switch current and the switch voltage during the turn-on and turn-off.

Here, we have assumption. Our assumption is we assume the vsw and the isw will be linear during the transient. And here, we also assume our diode is ideal. So what do I mean by an ideal diode? It is from the characteristic I-V curve. This is vd. This is id.

So a diode can conduct any amount of current during its on state with a zero-voltage drop. And the diode can block any amount of the voltage during its off state. So this is the ideal diode.

And if we notice, this term reference as this is vsw. This is isw. And this is id. And this is vd. We can simply have the KCL and KVL equation for this. The KCL equation at this node will be IL is equal to isw plus the id. And for the KVL equation, that will be the v in is equal to the vsw minus the vd.

So let's imagine what will be the current and voltage waveform. So for turning off, I would first say that it will be the voltage increase first. And when the voltage increase to its maximum amplitude for the buck converter, it's v in. And then the current will drop.

Why it's like this? Because from this KCL and KVL equation, the diode cannot turn on or carry current until it has the zero-voltage drop. So to have the zero-voltage drop, you need to have the switch voltage vsw to increase to its maximum.

And when it's increased to its maximum, which is v in, then the vd can become 0. And later, the diode can conduct the current. And then, if the diode conducts the current, then the isw will decrease. So that is during the turn-off. The switch voltage increase first, and then the switch current decrease later.

And similarly, during the turn-on, we can also see that it will be the switch current increase first and when the switch current go to its maximum, which is IL. And then the switch voltage will decrease.

And why is that? It is also because of the characteristics of the style because the diode cannot be turned off or block voltage until it has 0 current. And to have the diode to have the 0 current, it means the isw should flow through all the load current, which means the load current should increase first.

And at this time, the current in the diode will become 0, and the diode can be turned off and block the voltage. And once the diode blocks the voltage, the vsw can decrease.

So this is switching waveforms for the switch during the turn-on and the turn-off. And usually, we notate this time interval as the t fall during this turn-off. And we have this time interval as t rise during its turn-on.

For ideal switch, because this will be 0 and this will be 0, the current and the voltage will have no overlap. So the ideal switch, the switching loss will be 0. But for a practical switch, because we have the tf and the tr, the switch current and the switch voltage will have some overlap. So we will have some switching loss.

And what is loss? Loss is a kind of power. So that will still be the voltage times the current. So if we draw the power loss curve, that will be the P dissipate equals the vsw times the isw. So during the time interval beside the tr and the tf, it will become 0, or it will become a pretty small number. And during this, the loss will be triangular.

And a similar follows tr, follows the turn-on. It will also be triangular. It is just simply the switch voltage times the switch current. And we will find this will be the switching loss. And this part of area, which is the power integrated by the time, will be the energy. So this area will be the turn-off energy-- let's say E off. And this area will be the turn-on energy-- let's say the e on.

So that is if we switch this device in one period-- we switch off and we switch on-- we will lose part of this energy. And as we said, the switching our power converters, they switch frequently. There is a switching frequency definition.

So then when we think about the switching loss, that will be this triangular area, which will be 1/2 tf times the V in times the IL, which is the turn-off energy plus the turn-on energy, which is the time times the peak value V in times the IL and times by the switching frequency. That will be our switching loss.

And you can also consider with times the switching frequency is equivalent to divided by the switching period. And if you divide it by the switching period, that will be an average power of it. So it's still the same definition, but you can look it in two aspect.

And also, for the switching loss, this is killing us in our current converters. So to decrease the switching loss, we can decrease the switching frequency. However, if we're decreasing the switching frequency, our passive components, like the inductor or the capacitor, will be very big, which limits our power density and our valve volume of our converter. So we usually want to increase our switching frequency. But the switching loss will limit us, how large or how fast can we switch.

So another thing to reduce the switching frequency is, Can we decrease the tf or the tr, or we decrease the turn-off energy or the turn-on energy? So that comes with our snubber.

So before that, let's have a demo of the switching loss. So Rafa will do a demo. And before we start the demo, do you have any questions?

RAFA ISLAM: So I have a circuit here that's designed to help us look at the voltage and the current of a MOSFET when we're turning it on or off. So here, you can see two transitions, the purple or pink. The pink waveform is the voltage waveform. And the yellow waveform is the current waveform.

So on the left, the yellow waveform rises, and the voltage is falling, which means there's no voltage across the switch, and the switch turns on. On the right, the current, the yellow waveform, is falling, and the pink waveform is rising again, which means the switch is turning off.

Now let me zoom on in one transition. Let me zoom in on the turn-on transition. So as you can notice, the yellow waveform is rising pretty quickly. But the pink one, which is the voltage waveform, takes some time to completely hit 0, which is the rise time and fall time Xin was talking about.

And what will this do? This means that there is a overlap time between the pink and the yellow waveform crossing. And that's the overlap time creating the overlap loss. Now there's another loss here. Notice when that switch is turning on, the voltage is non-zero, which means if the switch's capacitance is storing energy in it. Now, let me also show you the power loss.

XIN ZAN: So you can see, the yellow curve will be the current, and the purple curve will be the voltage. And you can see that, for hard switching, it is a voltage increase first, and then the current will decrease, which match with our theory.

And you can also observe that, for the yellow curve, which is the voltage-- sorry, the purple curve, which is the voltage. And during its on state, it has a very small value. So that will be on-state voltage drop. It could be the rms current times the Rds up.

RAFA ISLAM: Yeah. It's really hard to see, but the purplish waveform, the zigzag waveform, is the power loss. You can also see that, in here, in the off state, the line is almost to 0 because there is no voltage-- because there is no current in the switch. In the other hand, whenever you are seeing all those ripples, that's because when the switch is on, it acts like a resistor. So it has some Rds on and non-zero current, i square r, which makes the loss.

XIN ZAN: Yeah. The math shows the time of the multiple of the voltage and the current. And you can observe there is a triangular of that.

RAFA ISLAM: Yeah. So we turn on and off our switch how many times-- 10 million times or 100,000 times per second. It can seem trivial for one time. But if we keep doing it this many times, we cannot neglect this anymore.

XIN ZAN: Thank you. So another thing I want to-- I'm not sure if you observed. So during the switch turn-off, we do observe the voltage, it have some resonance here. So this is because, as I said, we want to decrease the tr and the tf. But we have some limitations.

So the first limitations will be the parasitics. So the parasitics is some unwanted parameters inside of the circuit. So for example, the parasitics could come from-- there may be a parallel capacitance in parallel with the switch. And also, there could be some stray inductance. And when the switch is turned off, this parallel capacitance can resonate with this stray inductance. And that will cause an overshoot during the switch turn-off. And this overshoot can kill the switch. So this is one thing like we have the limitation for the tr and tf.

And the second is about during the transient, if we have pretty low, we have pretty small, tf and the tr, our di/dt or the dv/dt could be very large. So what do I mean by the di/dt and dv/dt? So that will be the slope for the rising voltage or the falling current or the slope for the rising current and the falling voltage.

And this di/dt and the dv/dt, they can have some coupling inductor or coupling capacitor. So imagine if we have a coupling inductor, which is L, this L di/dt will cause some voltage. And if we have a coupling capacitance, which is C this C dv/dt will cause some current.

So previously, if we have our di/dt or dv/dt pretty small and our parasitic is pretty small, these things will not match our control circuit. But either if we have a large inductance or a large capacitance together with a large di/dt or dv/dt, this voltage or current, they are unexpected. They can cause some errors for our control circuit. So this is the second limitation.

And for the third limitation, for the device itself, we sometimes have the di/dt or the dv/dt requirement. So the second one is for the EMI issues. But for this, this is bad for the device itself. It has nothing to do with the control circuits.

So for example, if we have a large current rating device-- let's say the IGBT or the SCR, if the di/dt is pretty large, in a short time, the current cannot spread for the parallel diode or the multiple wave bound. So maybe one diode or maybe one wave bound will blow up. So that will destroy our device.

And for the dv/dt, if we have a high dv/dt inside of the thyristor, it can trigger the thyristor back to on. So usually, what we want to turn off the device. But because of this high dv/dt inside of the thyristor, it can trigger the thyristor back on. So this is the third limitations for the tr and tf.

And usually, the fourth one, we said every device has a safe operating area. So let's draw the vi curve of a device if this is v, this is i. So for a normal device, we have a maximum current rating. And we also have a maximum off-voltage rating.

But this is not like a square because we also have some power limitation or some thermal limitation. So this is a safe operating area for a device. And we cannot have our switch voltage or switch current exceed this safe operating area for steady-state operation or for an instantaneous operation.

And here, for the snubbers, we care about the instantaneous operation. And the next lecture, when we learn about the thermal, we care about the static operation. That is, the rms voltage or the rms current cannot exceed. But here, we care the instantaneous one.

So if we think about this hard switching during the turn-on and turn-off, let's say for during the turn-off, the current will hold constant until the voltage increase. And then the current will drop. And if it's hard switching, we can find that our instantaneous current or voltage will exceed the safe operating area. And this is not good, and this can destroy our device.

So that's why we want the snubber. We want the snubber to manipulate with this switching locus of the iv curves. And also, for snubbers, we want to decrease this turn-off energy or the turn-on energy of the switches, inside of the switches. So that's the motivation of our snubbers. So before we start snubbers, do you have any questions? Cool.

So for snubbers, we have two kind of motivation. One is we want to maintain the instantaneous current and the voltage of the switch in the safe operating area. That is, also, we want to have low di/dt or dv/dt.

And the second motivation will be we want to decrease the switching loss inside of the switches. So please have attention, What do I mean by the inside? And now let's think about the turn-off snubber first.

So still, we use a spark converter as our example. We have the input voltage source. And we have a MOSFET. And we have a diode. And this will be our constant load current source.

So previously, at this terminal, we said the diode cannot turn on or carry current until its voltage becomes 0. But now we can have a capacitor that is in parallel with a switch. And previously at this node, we will have the KCL equation as IL is equal to id plus the isw. But now, we have an extra term, which is the ic.

So previously, the diode cannot conduct the current. But now the capacitance can flow through the current. And now we can have instantaneously the small voltage on a current during the turn-off at the same time.

So if we draw the I-v curve for the switch current. We still see like it will we still assume that will be a linear transitions and when the switch current decrease from the ill the capacitor current can conduct.

And pay attention at this time. The id of the diode is still in the off state. So when the switch has a linear ramp of the current, the capacitor will, similarly, have the linear ramp of the current. And at this, this will be the IL.

And the full capacitor voltage, we know that the capacitance current will be c times the dv/dt. And correspondingly, the voltage of a capacitor will be the integral of the capacitance current.

And here, if we have a linear of the switch of the capacitance current, we will have the quadratic of the capacitor voltage. And that capacitor voltage will be the switch voltage at the same time. Maybe I should change another color.

So if we draw it, the waveform, this will be the capacitance current. If we draw the capacitance voltage, because this is linear, the integral of the linear will be quadratic. So at this time, the switch current will be off. And after that, the capacitance current will fully conduct the load current.

And when the capacitance current is a constant, the capacitance voltage will become linear. But we don't care about this part anymore because we care the switching loss. I mean, for this time, we don't care. We only care the switching current and voltage during this time interval, from 0 to tf. So we only care the energy loss during this.

So actually, we can have a calculation about this energy. So let's see. Our switch current is IL 1 minus t over tf. And the corresponding layer, our capacitance current, will be IL times t times tf.

And correspondingly, our capacitance voltage, which is also the switch voltage, will be the integral of this. That will be the IL times the t over tf dt. So that will be IL tf times C t squared. So let me check if I do my algebra correct. Oh, sorry. So I should plug into the switch current. Oh, sorry. My bad. This is correct.

So that will be IL t squared C times the tf. So that will be the switch voltage expression. And similarly, if we calculate the switching loss, what is loss? Loss is a, still, kind of power. That will be the v switch times the i switch.

So we have v switch as this. That will be IC times t squared over the capacitance value times the tf times the switch current, which is this expression. That will be the IL 1 minus t over tf. So that will be the instantaneous power expression.

And if we integrate this instantaneous power, we will have the turn-off energy. That is like we integrate this PSW during the time interval from 0 to the tf. And if you do the algebra by yourself, we will find the result, which is IL squared times the tf squared over the 24 times the capacitance. So do you have any questions about this part? Yeah, go ahead.

AUDIENCE: ic is just equal to IL 1 minus t over tf, is that coming from that IL is equal to id plus x plus xt?

XIN ZAN: Yes. So here, we have assumption. So even if we have a snubber, we still assume the transient for the switch current is linear. And we know that the current will decrease during the turn-off. So we have assumption like this will be a linear current. So that's why we have it start as a part.

And sure. And previously, because we don't have another alternate path for current to flow, so we need to wait until this id. But id is still 0 at this time.

AUDIENCE: OK, it makes sense.

XIN ZAN: Yeah, cool. So then we can calculate this turn-off energy. And what we can observe from this is we can have a control handle, which is our capacitance. So if we want to decrease our turn-off energy, we can increase our capacitance value. So we can do this.

However, nothing is free. We have to pay for something. So imagine if we have a capacitance in parallel with a switch, every time when the switch is off, we will store the energy inside of the capacitance. That will be 1/2 cv squared.

So we reduce the energy loss in the inside of the switch. But outside the switch, we need to dissipate this part of energy. So that's what do I mean by we decrease the switching loss inside of the switches, but we also have to pay for something. That is the energy stored in this snubber capacitance.

So during the turn-on, if we do nothing, this energy will be dumped into these switches. So it will still loss. And this part of energy could be very large. It can still destroy our devices. So this is not a practical snubber as the turn-off snubber.

So a practical one, we need to do something else. So let's still take this circuit. We have the input voltage. And we have the MOSFET. We have the diode. And we have the ideal current source.

So we use two other components. One is the diode in parallel with a resistor and then the [INAUDIBLE] with this capacitance. So during its-- well, we want to turn off the switch. The current will still flow through this, through this diode and the capacitance.

And then, when we want to turn on the switch, so then, because of we are charging this capacitance to the v in, this will be positive, this will be negative. And when we turn on the switch, this capacitance will have a current path through this resistor and through this MOSFET.

And most of the energy we can control. We can dump it into this resistor instead of this MOSFET. And also, we can use this resistor to limit the current that flow through this MOSFET. And in this way, we kind solve this part of energy that could destroy our device during the turn-on.

But again, we are not recover this part of energy. This part of energy is still dissipated, mostly on this resistor and the small part of amount in this MOSFET. But we can improve this. So do you have any questions for a practical turn-off snubber?

OK. So then let's go to the turn-on snubber. So the beauty of the circuit is that sometimes we can have a dual circuit of the original circuit. So a turn-on snubber is the real-- the dual, circuit of the turn-off snubber. So let's draw the buck converter again.

So we have a voltage source. We have a transistor. And we have a diode. And we have the constant current load source, a load, constant current load. And now I insert a inductor in series with this transistor, with this MOSFET.

So previously, we have the KVL equation, which is v in is equal to the vsw minus the vd. And now we have an extra voltage, extra components, that can sustain the voltage, which is vL. So previously, we are limited by the vi curve of this diode.

And now we have a second component to sustain this input voltage, which means when we turn on the switch, we can have simultaneously small current and voltage at the same time. We don't need to sustain the linear one during the overlap as the triangular.

So if we draw the waveform of the turn-on, that is still like we have the input. We have the switch voltage, which is vsw. They will have a linear decrease. This is our assumption. And also, because we have a linear decrease of our switch voltage, we will have a linear increase of our inductor voltage. So the inductor voltage will increase linearly.

And the most basic equation for an inductor, that will be vL is L di/dt. So correspondingly, if we want to find the inductor current, we can just do the integral, which is 1 over L times the vL times the dt. So if we know that the inductor voltage will be a linear increase, then the inductor current-- and if you pay attention, this inductor current will be same as the switch current because they are in series.

And now, this switch current will increase as quadratical. And during this, this is the quadratical of the switch current. And after this tr, the switch is fully on. So the inductor current-- sorry. The switch is fully on. This will be 0. And this is still 0. And this vL will fully take the input voltage. So this will be a constant value. And if it's a constant value for inductor voltage, then the current will be linear.

But again, we don't care this part for the switches. Because it is after the tr. The switch has already passed the transient. And we can still calculate what will be the turn-on energy during this part and compare it to the original hard switching. We can see that we have small overlap at the same time for the high voltage and high current. So we can improve the turn-on energy during this.

And also, the same problem will be we still store the energy. That is 1/2 Li squared in this inductor. We need to dissipate this part of energy somewhere. And for practical use, we still have a resistor in series with a diode.

And if we want to dissipate the energy of this inductor, we will have a current flow like this when the switch is turned off. So that's the beauty of the circuit. So for a concept, we need a turn-off parallel capacitance. And for the concept, we need a series turn-on inductor.

And for a more practical use, we need a diode in parallel with a resistor, then in series with this capacitor. And for the practical turn-off snubber, we need a diode in series with a resistor, then in parallel with this inductor. So this is the fully dual of the circuit.

So this is a practical, one of the practical, turn-on snubber. And this is the practical turn-off snubber. So do you have any questions? Yeah, go ahead.

AUDIENCE: Would you use both at once?

XIN ZAN: Yeah. That's, actually, a very good question. So this is only we care about the turn-off. This is what we care about the turn-on. And also, again, we dissipate this amount of energy fully. So in the practical, we can design some snubber that can both deal with the turn-on and turn-off.

And we can imagine, some semiconductor devices, we may care more about the turn-on, or we may care about the turn-off. So we can select a trade-off, like we want to mitigate the turn-on loss more, or we want to mitigate the turn-off loss more.

And also, here, we are dissipating the energy of the half cv squared and the half Li squared. In the practical, we can still design some recovery circuit. We can recycle this part of energy. So what's your question?

AUDIENCE: In the [INAUDIBLE], we have a [INAUDIBLE], can you just mention what vd is doing during all of that?

XIN ZAN: You mean this diode?

AUDIENCE: Yeah.

XIN ZAN: So after this, when the-- let's say this is the inductor current, which also the switch current. So when the switch current is going to the IL, and, also, similar here, when the capacitor voltage, or the switch voltage, is fully go to the v in, then the diode will make a row in here. That will be similar in this case. So the diode will play a role after this time interval.

AUDIENCE: Why is dv not changing at all to the left of that time interval?

XIN ZAN: Oh. That will be the same reason of this. Because we still assume this is an ideal diode. So the diode cannot turn on or carry current until it has zero-voltage drop. And similarly, a diode cannot turn off or block the voltage until the current becomes 0. Cool. So do you have any questions about those numbers? Yeah, go ahead.

AUDIENCE: Does [INAUDIBLE] capacitor or conductor make the resonance problem worse?

XIN ZAN: Yeah. That's, actually, a very good question. So let's say, because we have a parallel-- we have a series inductance here. And during some transient, we still have this parallel capacitance. And for this diode, there also could be some parallel capacitance. They're still resonant. That is something we cannot avoid.

So in the textbook, there's a chapter talk about how we choose this inductor value and how we choose this resistor value. And similarly, we still have the parasitic stray inductance here. And during some case, this capacitor will still resonate with this.

So this is something we cannot avoid. But we can have some circuits, or elements, like how we choose this capacitance and how we choose this resistor to improve this.

And also, if you imagine a second-order system, we can have critical damped. We can have overdamped. Or we can have underdamped. So we can selectively purposely put some small resistor to dampen that out. But this is something we need to pay off about that. That's, actually, a very good question.

And here, I want to still mention about the snubber is we improve the switching loss or the turn-on and the turn-off energy inside of the switch itself. But we lose energy here. And we lose energy here. And the total energy we lost may be even more.

But why we want to do this? Because we want to keep the switch iv curves inside of the safe operating area. We want to have a safe di/dt or dv/dt. So that's the motivation.

And as I said before, like for the snubbers, we use it for IGBT. We use it for thyristor. We use it for the BJT. And currently for the MOSFET, we generally don't use snubber for the MOSFET.

But from this, we still introduce this part of the content because you can learn the beauty of a capacitor. You can learn the beauty of a diode. So the diode is only one directional device. So you can imagine, for future, when you design a circuit, how to use a diode to control your current flow paths.

So another thing I want to say, because we still have some time, is I want to introduce the gate drive. As we said before, for this tr and tf-- where is that? For this tf or tr, what do they depend on? They depend on the devices, or they depend on the drivers.

So imagine we have a huge, or a big, device. It may take longer time to finish the turn-on and the turn-off transient. But if we have a powerful driver, maybe we can reduce that time. So I want to introduce a small bit of the gate driver is like sometimes when we want to drive a MOSFET.

So this is the voltage source, which is a gate drive. So we can have different paths to turn on and to turn off of the MOSFET. So during the turn-on, we can select a relatively bigger resistor to charge this capacitor. For turn-off, we really want it to be fast, so we can have a small resistor here.

So do you have any further questions about today's lecture? We still have some time. So if not, that will be end for today's lecture. Thank you.