Digital Control in Switched Mode Power Converters and FPGA-based Prototyping
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Module - 06
Digital Control Implementation and FPGA-based Prototyping
Lecture - 52
High-Frequency Current Sensing Techniques in Digitally Controlled SMPCs

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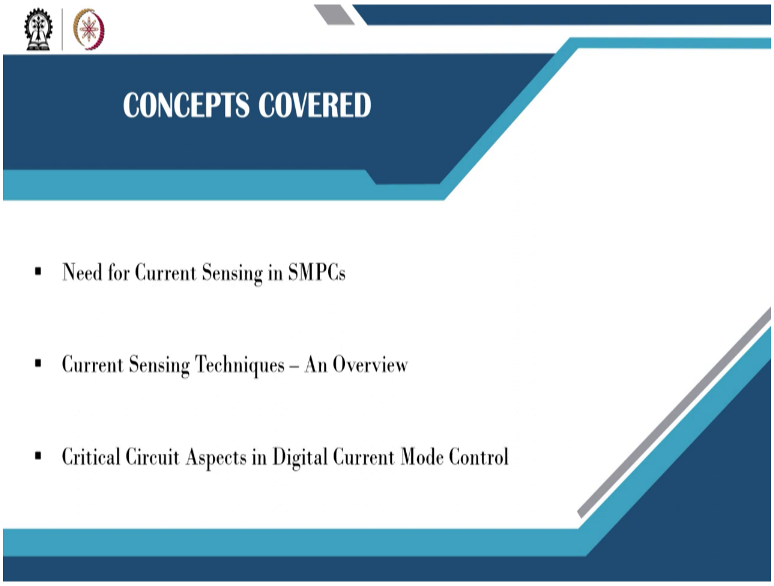

In this lecture, we are going to talk about some High-Frequency Current Sensing Techniques in Digitally Controlled Converter. So, first, we will talk about the need for current sensing in Switch Mode Power Converter, then-current sensing techniques, and overview and critical circuit aspects in digital current mode control.

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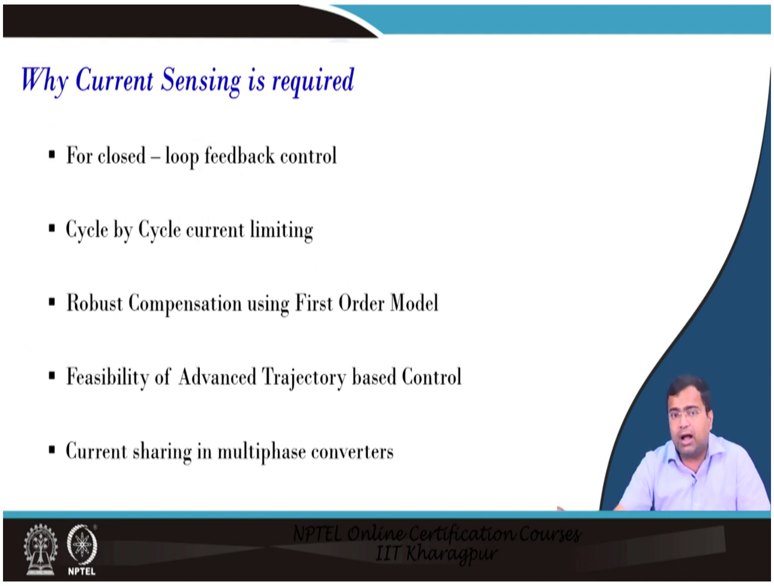

So, why current sensing is required? For the closed loop you know the feedback control cycle by cycle current limit because we know about the current mode control you know cycle by cycle current limit. Then we also have robust compensation because, if you use a current mode control, then we can virtually represent that the converter like you know you can inductor will become virtually a control current source.

So, in that way we can very easily design a robust compensation is possible. And also we can implement very advanced control logic non-linear control like trajectory-based, charge-based control, and various non-linear control can be implemented and finally, current sharing like in the case of a multi-phase converter those are necessary.

So, the current mode control needs to be very useful you know to achieve a very fast transient response and so on. But it is equally challenging if you are going for high frequency the current sensing itself poses a challenge, how to sense the inductor current.

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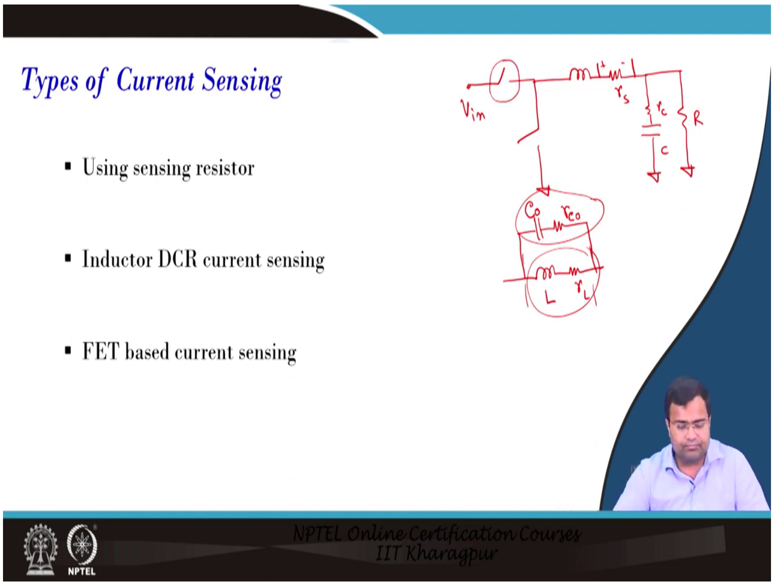

So, typically the current sensing technique that you have is a sensing resistance, right? You know if we take an inverter like an inductor suppose we are talking about a buck converter. So, suppose this is our buck converter and this is our input voltage, now we have this inductor right. So, one way we can put a sense resistance here and then we have a capacitor and this is our inductor I register load resistance.

Now, you can put a sense resistance plus-minus, and this sense resistance if you put the issue will be it will add your incorporative resistance in the path of the inductor. So, your equivalent resistance effective equivalent resistance will increase. So, as a result, your conduction will say increase, and also you have voltage gain will get reduced, as we have discussed in our earlier NPTEL course. But this can be useful to sense the inductor current you know almost the full inductor current can be sensed, one is an inductor DCR current sensing. How does it work?

So, suppose you have an inductor, the inductor has it is own r L which is not accessible it is a part of the inductor, and suppose you are putting a capacitor and an external resistance which is let us say capacitance you know I would say compensating network, this is your capacitor compensation capacitor you know and this is your L. So, in this case, DCR sensing we want to match the time constant of this block and this block I will discuss and the FET base or we can sense the current through the FET, either high side FET or the low side FET.

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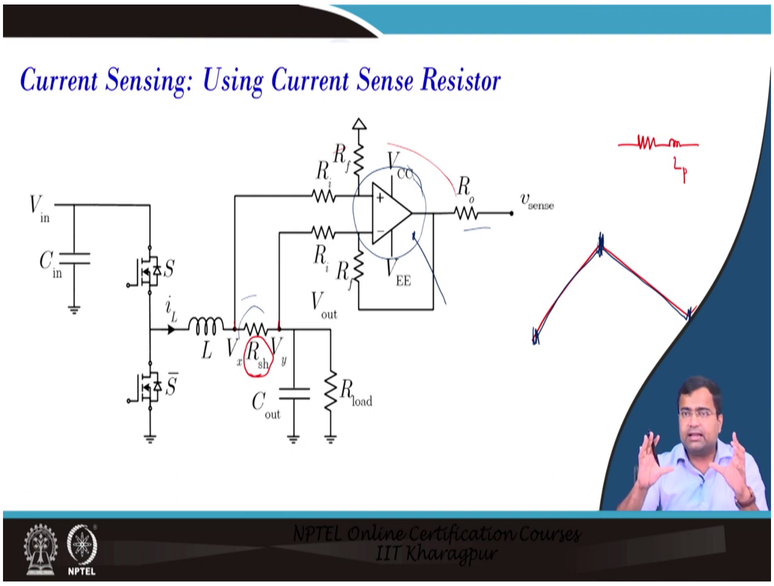

So, current sensing: using a current sense resistor, so this is the one where we can put a resistance this is a shunt like a current resistance and then across that we can use and you can use a differential amplifier and that way we can get the sense voltage. In this case, you know the problem might be you have to be careful, if you are going for a very high power high voltage application then your terminal may be exposed to this. So, you have to be careful about the selection, but you can also use a resistive divider.

So, you have to be very careful about this also in this sensing since you are tapping the 2 terminal voltage and you are putting a separate current resistor sense resistance, each resistance will also have some parasitic inductance. So, this is a parasitic inductance and this may introduce some spike in the inductor current.

So, if this is your actual inductor current, then the sense inductor current can have some spike here. So, it can have some spike here and this spike may be due to this parasitic inductance. So, you have to be very careful about this. So, we are talking about the current sense resistance-based approach.

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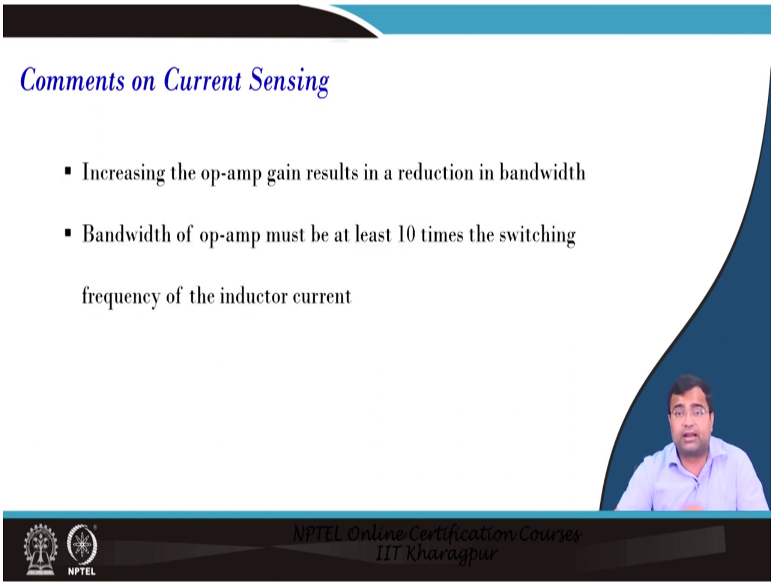

Then it is increasing the op-amp gain result in a reduction in bandwidth. That means, what way is the best? If we put a large resistance then the losses will be more and that is not acceptable because it is in the power part. But if you take a very small resistance then you need to use a high gain of the op-amp. So, you can get sufficient voltage corresponding to the current and high gain if you increase the gain of the op-amp then the bandwidth can reduce, so you have to be very careful.

Even for a small resistance you have to be very careful about the op-amp design should it should have a very high signal-to-noise ratio ok. Then bandwidth of the op-amp must be at least 10 times the switching frequency because we need to provide sufficient harmonics to represent the actual triangular shape current waveform.

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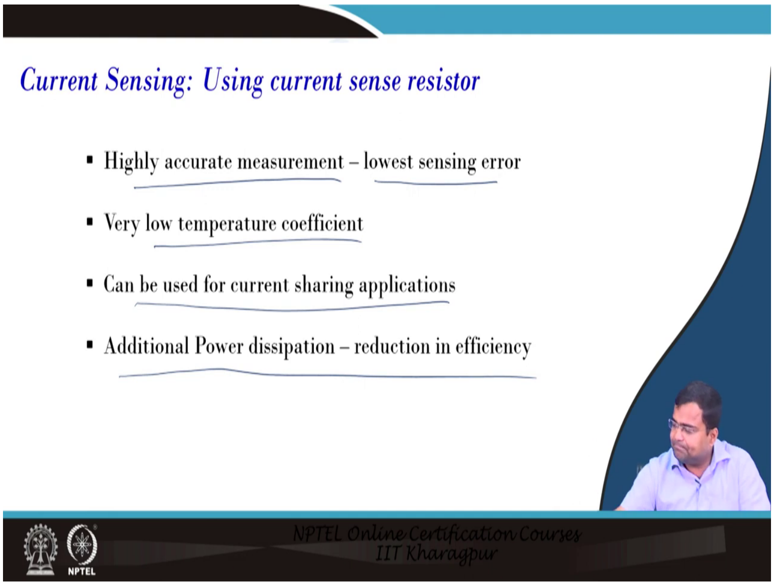

Then using current sense resistance the accuracy because very highly accurate with a lower in the lowest sensing error. But a very low-temperature coefficient, but it can be used for various applications it has an additional power loss and you also need a separate differential op-amp and all this arrangement.

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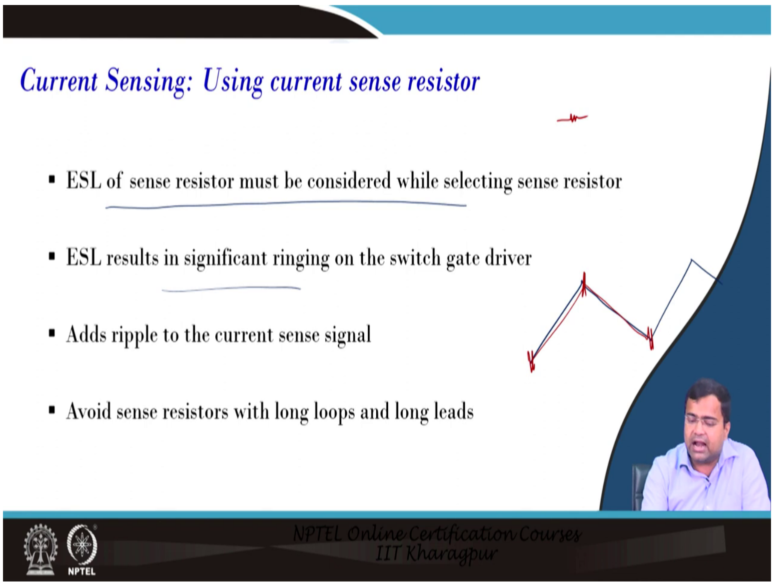

Now, in current sensing using sense resistance the ESL effect must be considered as we have discussed because it will introduce spikes. ESL can result in ringing at the switch node particularly when there is a turnover; that means if you have this kind of thing. So, it can introduce spikes here, the kind of spikes that we have discussed, and add ripple to the current sense signal ok and avoid sense resistor with long loop. So, you have to be very careful; that means, you should not even if you put a resistance the suitable packet should be selected, you should not use a large lead resistance as that will introduce more inductance.

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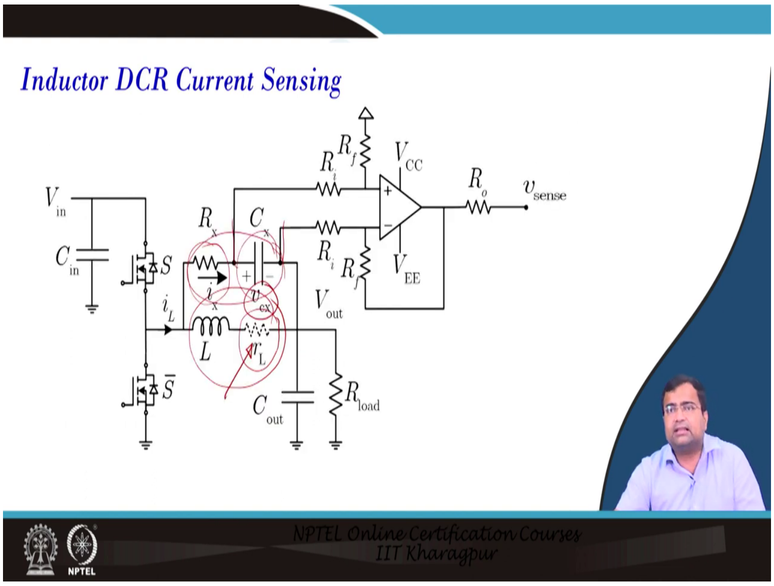

Then the DCR sense we have discussed because the inductor has it is own internal DC resistance and we are putting an external resistance as well as a capacitor. So, here the time constant of this branch should match the time constant of this branch, and then we have to take the differential voltage across the capacitor and that will correspond give you the sense voltage, which corresponds to the inductor current.

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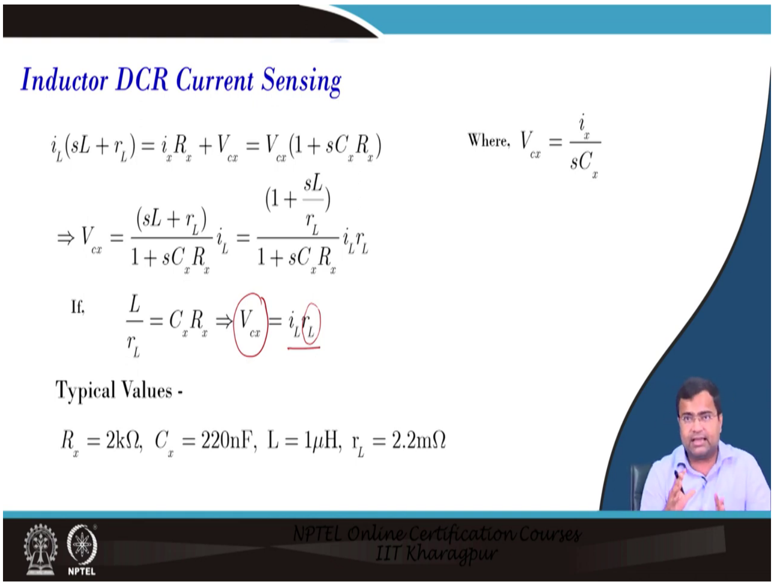

How does it work? So, if you obtain this you know all this calculation it turns out that the actual inductor is the voltage across the capacitor which is a V cx this voltage across the capacitor will virtually become i L into r L, where r L is the DC resistance of the inductor if you can match the time constant ok.

But this method is nice there is no physical resistance placed in the inductive path, but it may be difficult to actually estimate the right value of the wire. That is one thing or even if you are using an inductor with a very low DCR, then this can be affected by noise because matching time constant can be very sensitive it can be very sensitive because, and if you take a larger this here then the loss it will be lossy. So, this way this technique is good, but you have to be very careful because it can be a sensitive technique.

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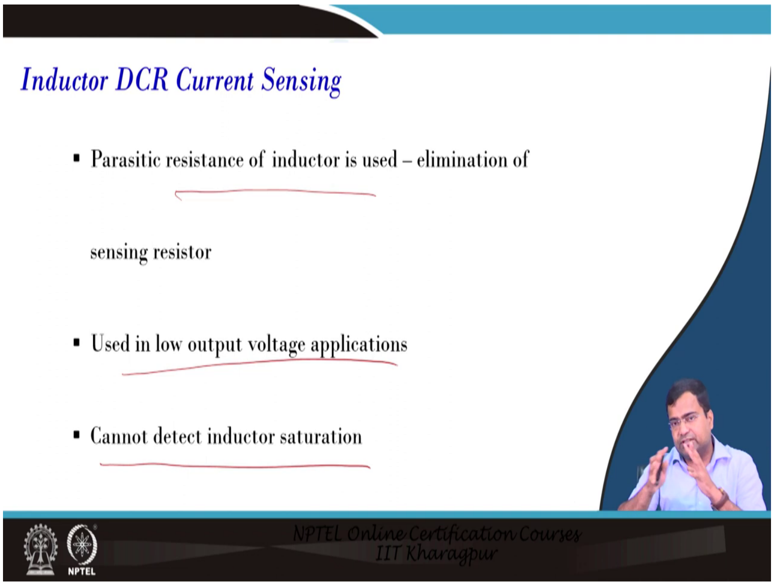

So, the parasite resistance of the inductor is used and there is physical resistance is not needed it can be low voltage high current applications that are very useful. But this cannot detect saturation inductor saturation cannot be detected because this assumes inherently that the inductor is in the linear region and that is why you are using all the time constant calculation. But once it enters into saturation the mathematical equation which is the representation there is no longer valid, so it cannot detect ok.

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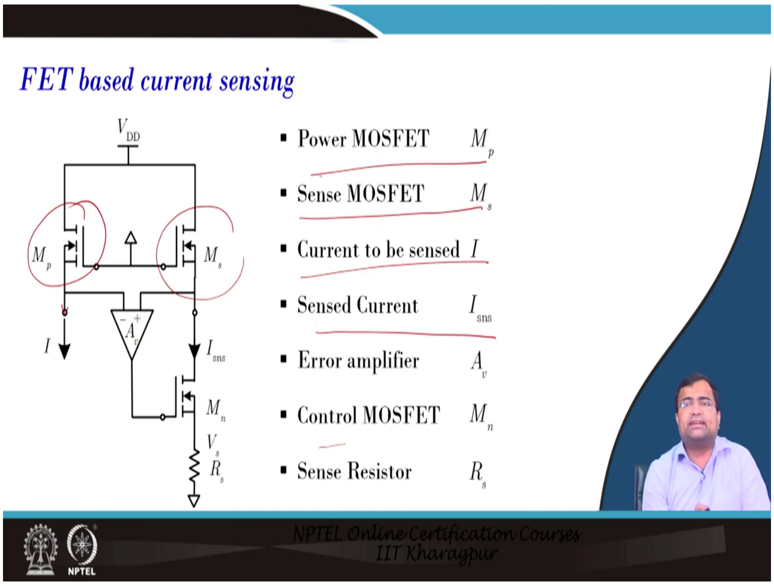

Another way is a FET-based implementor; which means your switch. So, if you use a power switch then you can use you know this is the power switch, but you can use a mirror of the power switch; that means, you know these are the power switch is M p, the sense MOSFET is M s, then current to be sensed that is I, but you can create a mirror that senses current error amplifier control.

So that means, it can be a current mirror approach can be used and that can give you a measure; that means, information of the current that is going to the actual power FET. So, you are not putting any resistance in the power stage, but you are because this can be used in the IC-Integrated Circuit implementation these techniques are useful.

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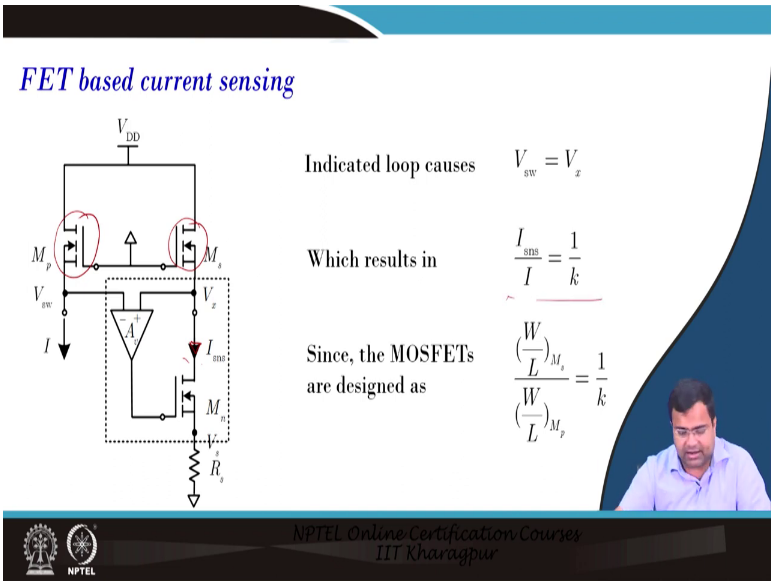

Now, another way you know in this case is when you are using this; that means, the current sensing FET based we have to be careful about the ratio of current. That means, what is the ratio of the sense current with respect to the original current and that depends on the W by L ratio of these 2 transistors; that means, your M s and M p. So, the selection of this transistor their ratio of W by L is very important and that means, they are highly sensitive to their W by L ratio. So, you have to be very careful about this particular factor.

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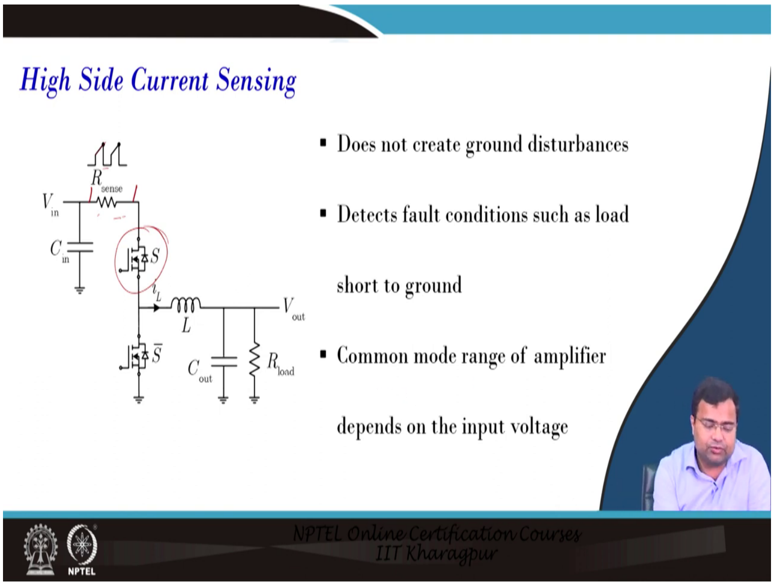

Now, once you use the sense resistance-based approach then either you can sense or you can also, but it is generally not recommended to use resistance in the switch path, because any parasitic inductance can create a loop. So, that can be L it can be very high and it can damage the switch. But if you want to use the switch you know we can use a FET current, if you want to use a physical switch it might be possible but you have to be very careful and typically it can be used in an integrated circuit.

So, high-side current sensing is good in analog peak current mode control because you are sensing the all-check current. But if you want to do digital peak current mode control. So, this is a high current sensing I am telling about. Now so it does not require the good thing is that the ground is not referred to as the physical ground.

So that means, the ground-bound issue may not arise that it can detect the fault, because if there is any fault from the load side to input voltage this current can be. That means, the fault current can be detected from the high side switch; that means, the load to you know the common mode range amplifier depends on the input voltage. So, you have to be careful about this.

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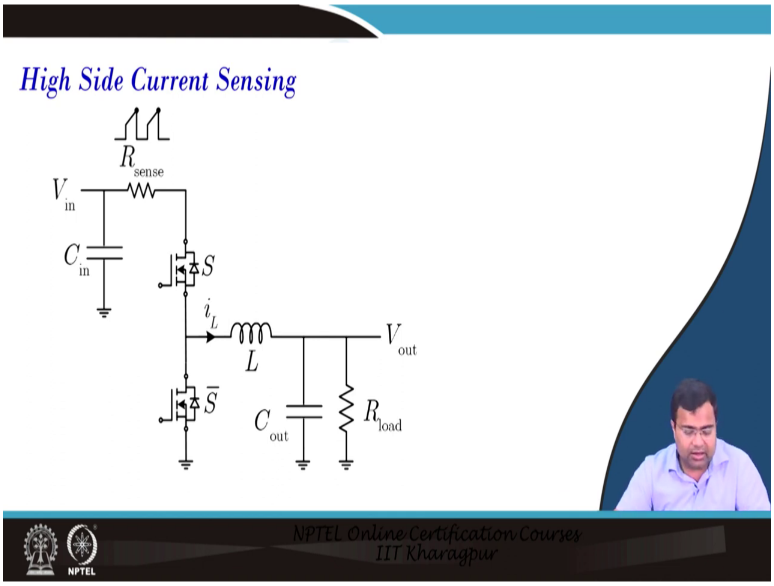

High side current sensing here if we consider then if we want to implement peak current mode control in analog it is possible, but if we want to implement digital peak current mode control can you use valley current?

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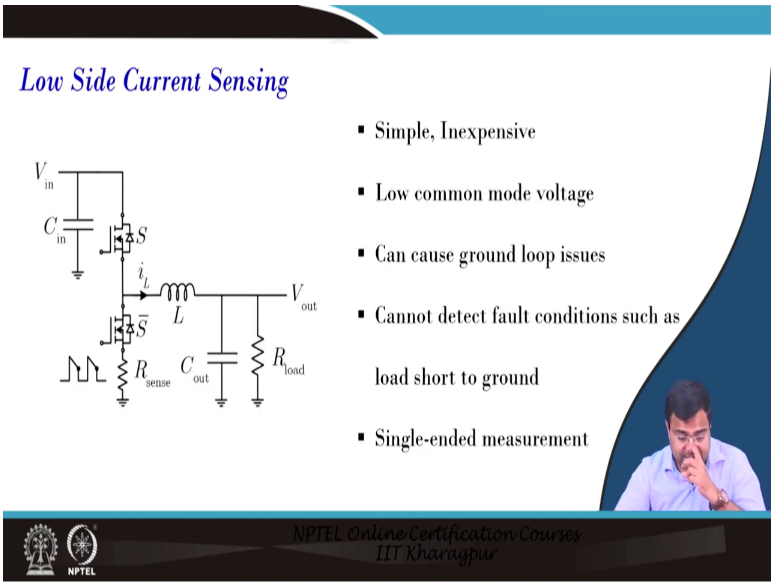

Like low-side current sensing in low side, you can put a resistance just below the low-side switch and you can simply take it as a ground reference. So, it is a low side sensing; which means, low common mode voltage it is very inexpensive in many applications you use but again you have to be very careful about the parasitic of the resistance.

The packet selection is important otherwise it will introduce inductance in the switch path ok. But it cannot detect the fault condition such as load short to ground ok and a single-ended measurement, so it is easy to do the single-ended measurement.

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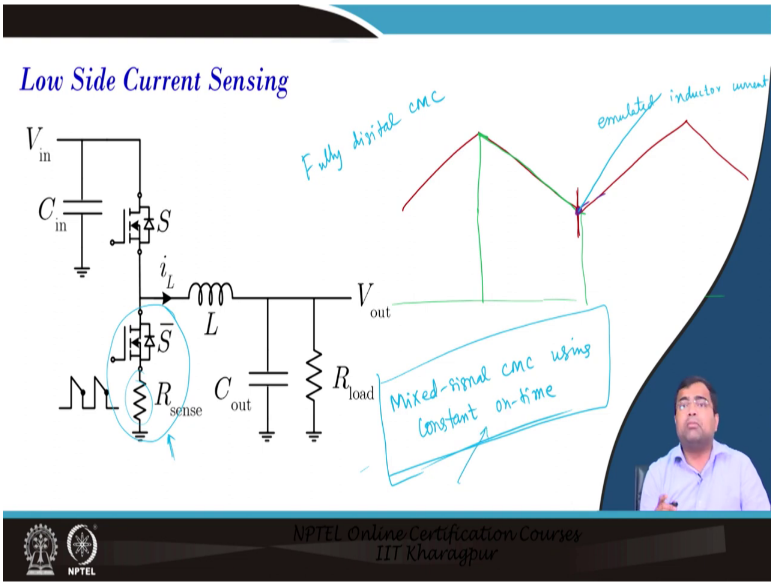

Now, in the case of digital peak current mode control, suppose this is my actual inductor current. Let us say I am using I am sensing the low side current I am just sensing my sensor has like I am just using let us say this is my axis again this, so I am sensing this. Now if I take the sample here this point if I take the sample; means let me use a different color. If I take the sample where then I can emulate it in the digital controller I can emulate the inductor slope.

So, typically this emulation slope has to be that means we are talking about the fully digital current mode control. So, I can emulate the slope inside the digital control. So, this is like an emulated inductor current and this can be realized used to realize a peak current mode control using fully digital current mode control, we can use a low side current sensing also.

And if we go for mixed-signal current mode control mixed-signal, where the current loop is analog using constant on-time and this is a very popular product technique in the commercial product. So, you can use simply the valley current mode control using constant on time and the current loop is inherently stable, but you cannot you should not use a fixed frequency valley current mode control, which is unstable for duty ratio low duty ratio operation ok.

So, that is why this mixed signal with analog current loop mixed signal current mode control with constant on time is very popular, which requires only low-side current sensing. I have discussed in lecture 3 some examples of multi-phase (Refer Time: 14:37) power stages; that means, if there are multi-phase converters there are many such phases and each phase has its intelligent power stage where it has a hub-based switch with a driver and it also has a current sensor, which senses the low side current sensor ok.

And it emulates the high current; that means, it emulates the rising slope, but it senses the falling slope. So, these techniques are important and that is why you know these currents are very accurate and constant on time and are a very preferred choice for multi-phase converter control.

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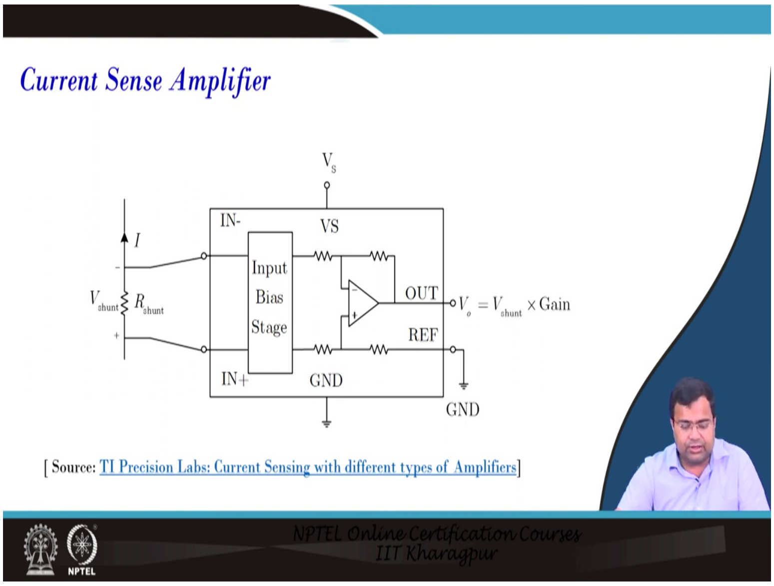

So, for the current sense amplifier typically we can use a dedicated current sense amplifier with proper biasing and all.

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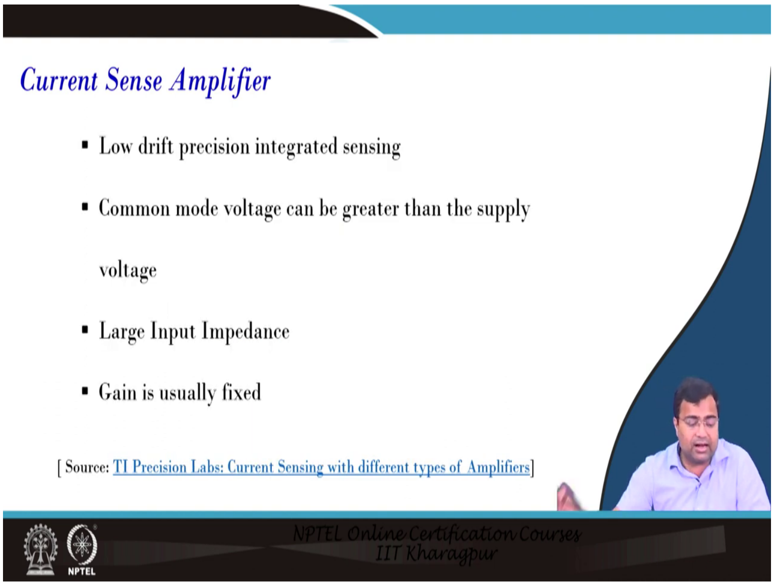

Or current sense amplifier generally has a low drift precision integrated circuit; the common mode voltage can be greater than the supply voltage. Large input impedance and it can have a fixed gain, it is unlike that you know a regular amplifier where the gain can be adjusted here it is a gain is fixed.

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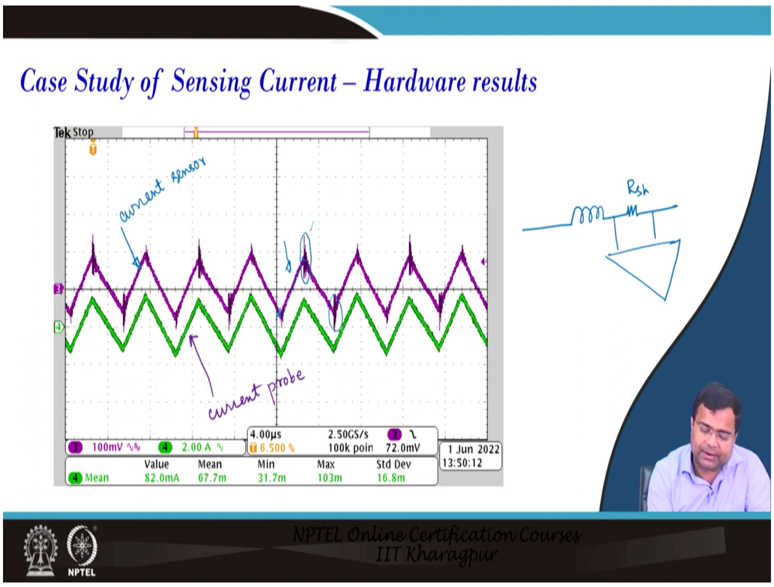

And this is the waveform of the board that we will be you know showing our NPTEL course harder case where the blue one I mean. So, green one here the green one this is the probe current probe this is from current probe sorry current probe, it is coming from the current probe and this is coming from the sensor current sensor and we are using this is the inductor current.

So, we are using the shunt resistor base; that means, we are putting a resistance in series with the inductor for this course and we are using them we are using instrumentation amplifier to do that we will discuss when we will talk about our PCB design aspect.

But in this course, we will be using sense current and this is to show how the sense current look compared to the actual current, which is using the probe they are quite representative. So, we can go ahead with the various improvement, but you can see there are still some spikes at every switch node point.

But if we go for peak current mode control mixed signal since we will be using it after the latch operation. That means once the switch is turned off then only the noise is coming, so means this noise will not affect the operation and if you go for we are not going to show full digital implementation in hardware. But in hardware, if you go for full digital we can take this sample clean sample here and emulate the current slope this is also possible.

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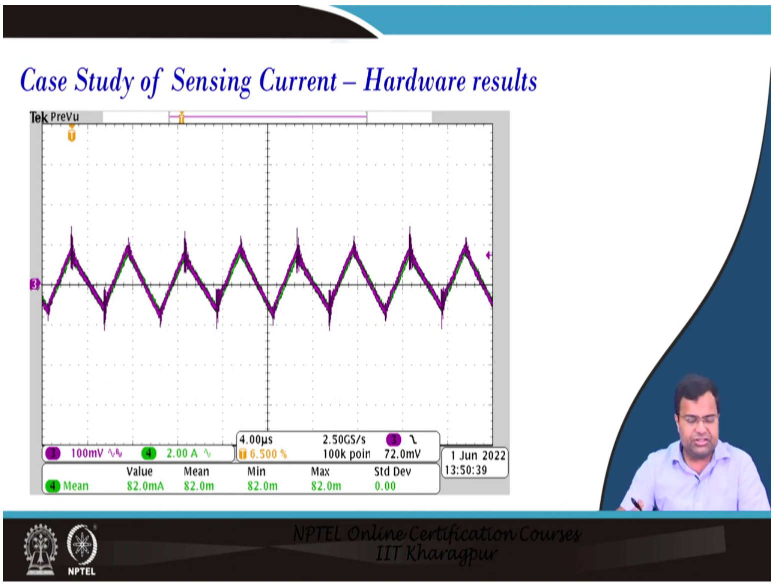

So, this shows you know apple to apple comparison between the current sense resistance followed by the amplifier, compared to the current which is obtained by the current probe high bandwidth current probe and they are reasonably well and this will be used for our closed-loop control.

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So, in summary, we have discussed what is the need for current sensing, then what is the current sensing technique like different types of DCR current sensing, resistance-based current sensing, and also the FET current sensing.

And we have discussed some critical aspects of digital current mode control design and then in the subsequent lecture we will be talking about you know others like a mixed signal circuit then PCB design aspect some aspects with a schematic and finally what are the steps for FPGA prototyping and implementation that is it for today.

Thank you very much.