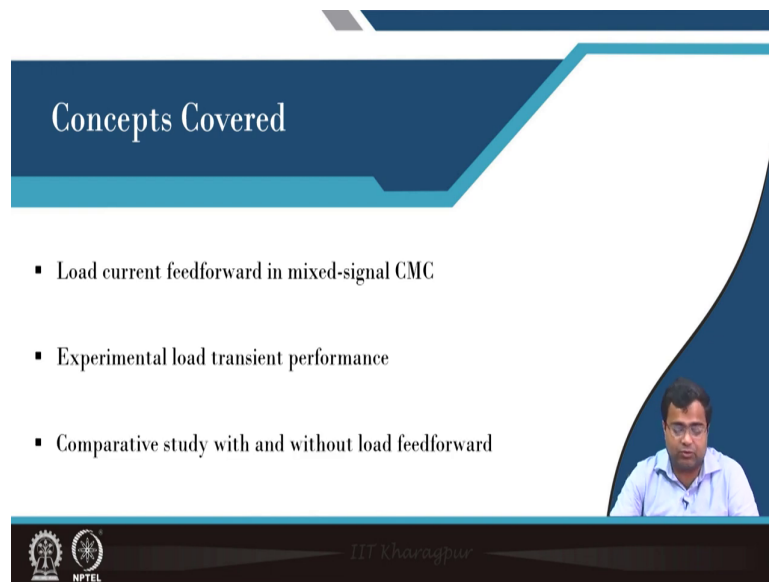


**Digital Control in Switched Mode Power Converters and FPGA-based Prototyping**  
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**Module - 11**  
**Design and Validation Case Studies using Digital Voltage and Current Mode Control**  
**Lecture - 109**  
**Load Current Feedforward in Digital CMC Buck Converter: Experimental Results**

Welcome to this lecture we are going to discuss the Experimental Case Study with and without Load Current Feedforward. And in the previous lecture, we have seen some analytical aspects of output impedance with and without load current feedforward.

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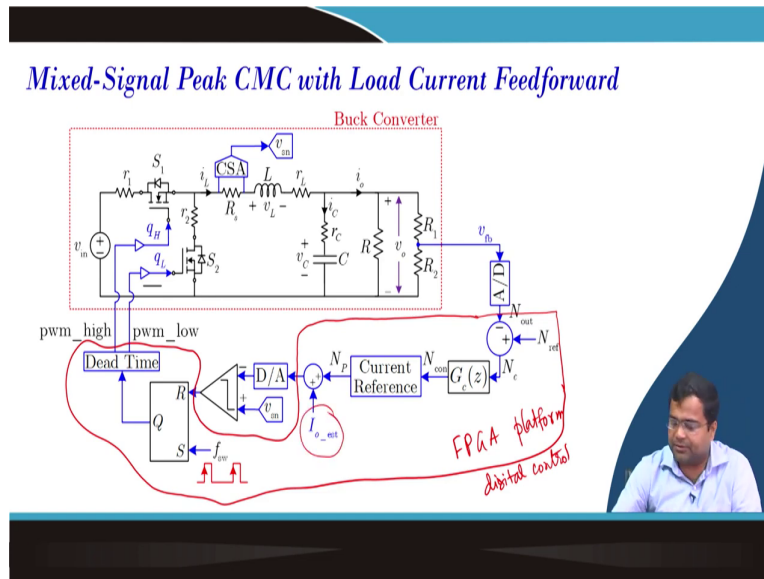
**Concepts Covered**

- Load current feedforward in mixed-signal CMC
- Experimental load transient performance
- Comparative study with and without load feedforward

The slide features a dark blue header with the title 'Concepts Covered' in white. Below the header is a white area containing a bulleted list of three items. In the bottom right corner of the slide, there is a small video inset showing a man in a light blue shirt speaking. At the bottom of the slide, there is a dark blue footer containing the logos of IIT Kharagpur and NPTEL, and the text 'IIT Kharagpur'.

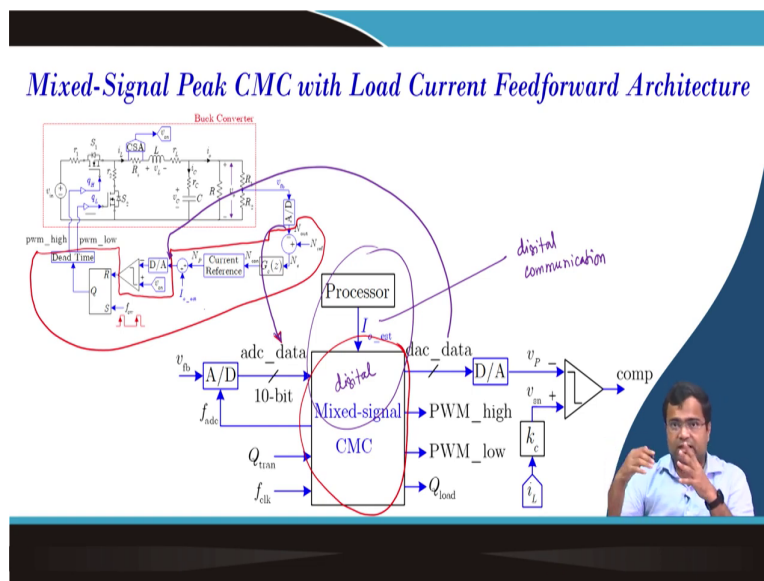
So, first, we will talk about load current feed-forward in mixed signal current mode controlling some implementation aspects. Then experimental load transient performance and comparative study with and without load feedforward.

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So, if we talk about this mixed signal current mode control we have discussed it multiple times and you know from this part if you consider this part. So, this part this whole part will be we have to synthesize inside the FPGA. So, this is an FPGA platform, so this can be claimed or any other platform, but we are going to do these are the digital you know control the other part of analog. So, here we are using this estimated load current.

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Now, the question is since this part is digital; that means, we are talking about this part, we are talking about this part, so this part is digital. Now we can actually; that means, we have to

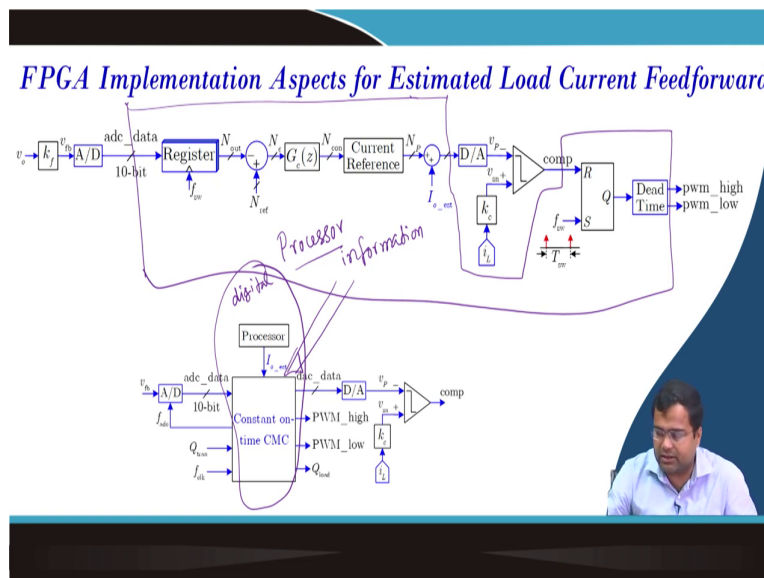
synthesize this block and this is your mixed-signal block where the data is out to the ADC we have discussed. It is the ADC data and we can use a different color.

So, this data going out is ADC data, then the DAC data is nothing, but which is here coming out. Then naturally the comparator output will be from here like that we know all this aspect ok. So, we can now since this whole thing is digital since the whole thing. So, this is digital we can use FPGA we can use digital I C whatever it depends on the implementation platform, but this thing is digital.

So, inside digital, if you communicate with the processor; that means, I will say here we are talking about digital communication. So, if your power management unit the controller can communicate with the processor then the processor knows what task is going to come and that gives you an estimate of the load current.

And that is why we are using this load estimation inside the digital platform and we will be considering if the load step size is perfectly known or if there is some variation then how the output voltage is going to get affected. And if you do not consider load feed-forward and if you consider load feed-forward what is the response in the output voltage?

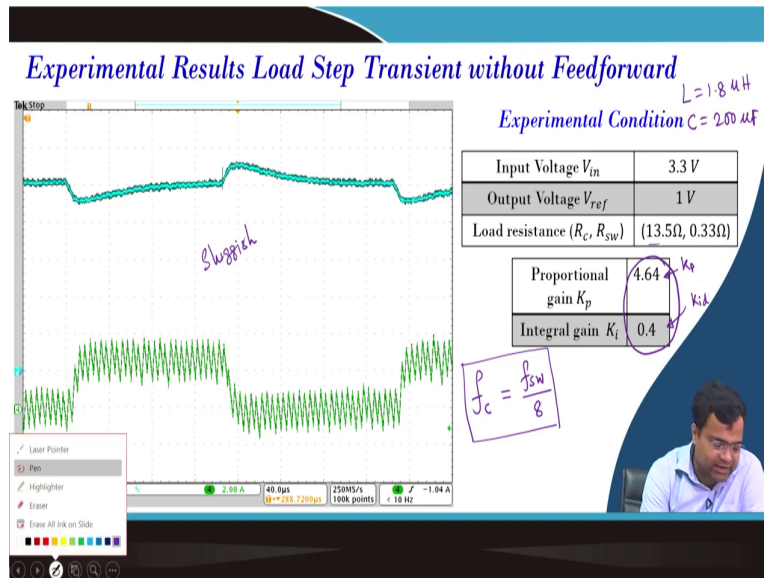
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So, here is the implementation aspect we have discussed this is where the ADC data is going and this is where our DAC data is going out then again we have to discuss and this block is nothing, but even this and as if we have included the processor is part of the information is

available. So, it is a part of digital communication. So, this is also part of digital, so these are all digital. So, this is the estimate of the load current.

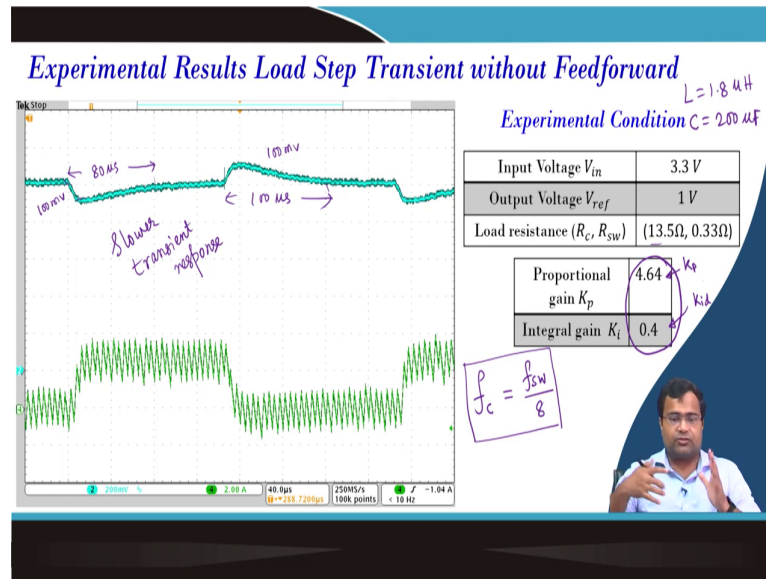
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Now, we are going to consider an experimental case study. First, we already have discussed multiple time about the power stage. So, what was the inductor? 1.8 microhenry capacitor is 200 microfarad and we are changing the load resistance from 13.5 to 0.33.

And we have considered the simulation whatever we made simulation this is our  $K_p$ , all discrete-time this is our  $K_i$  that is the discrete-time integral gain and we are considering 1 volt. Now we are making a load step. So, these are load step transient which is designed; that means, our cross wave frequency is designed by considering switching frequency by 8 and since it is current mode control, it is a sluggish response.

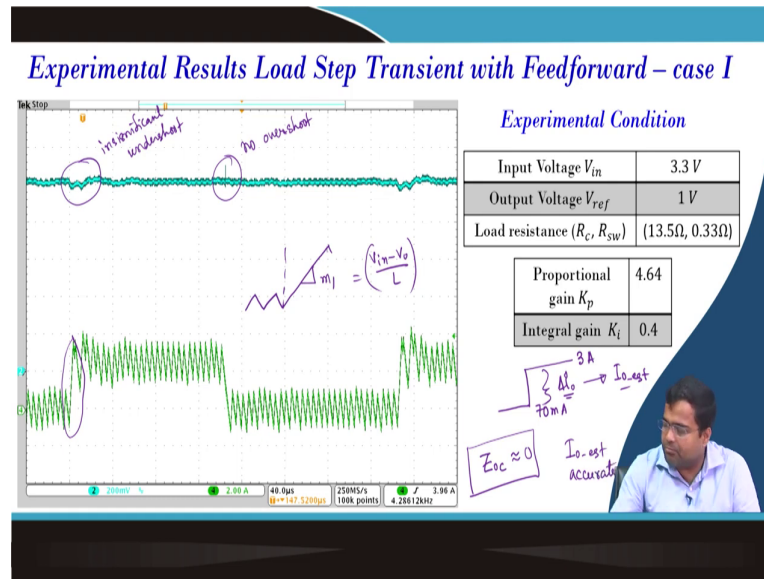
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You can see the response is sluggish I can say the slower response, I can say it is a slower transient response, but it is a well-damped, slower transient response. Because what is the undershoot? Undershoot is coming to be this undershoot is coming around 100 millivolt, but this is coming to be around 80 microsecond which is pretty large and that is the problem.

In fact, in voltage mode control we got around 30 micro second. Because if you use an alternative design approach we can get an indirect load feedforward action. So, that is why it was coming to be much smaller, but here it is large. And if you see the step here also it is like 100 microseconds something like that nearly 100 microsecond and the overshoot is also roughly around 100 millivolt, millivolt overshoot and this is a typical current mode control slower response looks like something similar to a fast order system.

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Now, we are considering load step feed-forward where assuming the load step because we are making one load current to the other load current. So, here it was 70 milliamper, and it is going to be like a 3 ampere. So, this load step size i would say if is perfectly known and we are calling this an  $I_0$  estimate as if it is a digital value that we are giving inside the digital controller platform. You can see overshoot is cut down there is no overshoot, no overshoot, and insignificant undershoot.

That means what we learn is that closed-loop output impedance with load feedforward was approximately 0. If it is 0, perfectly then it should not have any overshoot, or undershoot effect. Overshoot is almost like a vanished undershoot should also be vanished if it is exactly, but because of the practical limit because you know inductor current if you consider this. So, there is a slew-up process right so; that means, the inductor current was like this.

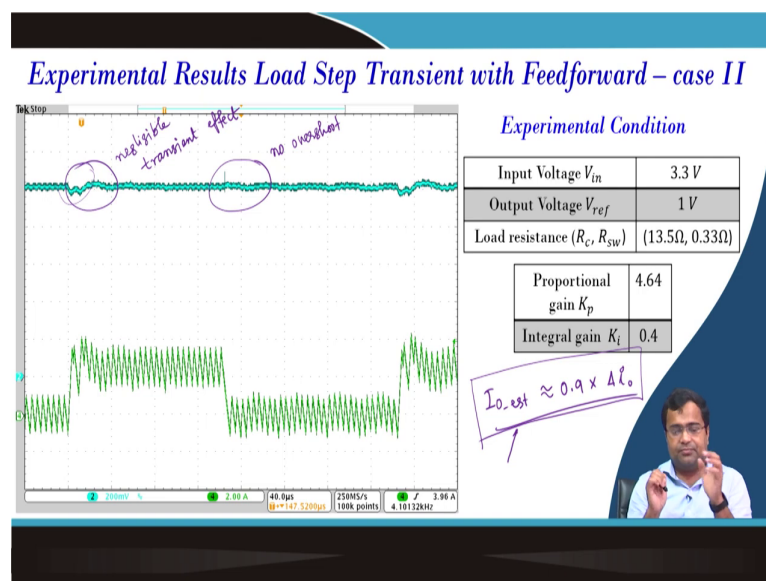
Now, it is slewing up right sorry. So, the inductor current has to be slew upright. So, this slew up depends on the slope  $m_1$ , and what is this it is  $V_{in} - v_0$  by  $L$ . Since it cannot reach immediately if it could have reached like this then there should not have been any undershoot, but since it cannot go this is a physical limit comes from the slew rate limit and that is why slight undershoot will be there bound to be there.

So; that means, practically it will not be exactly 0, but it is nearly 0; that means, the effect can be negligible. This is the case where the load current is perfectly known; that means, we know the  $I_0$ , estimate almost accurate it is like accurate.

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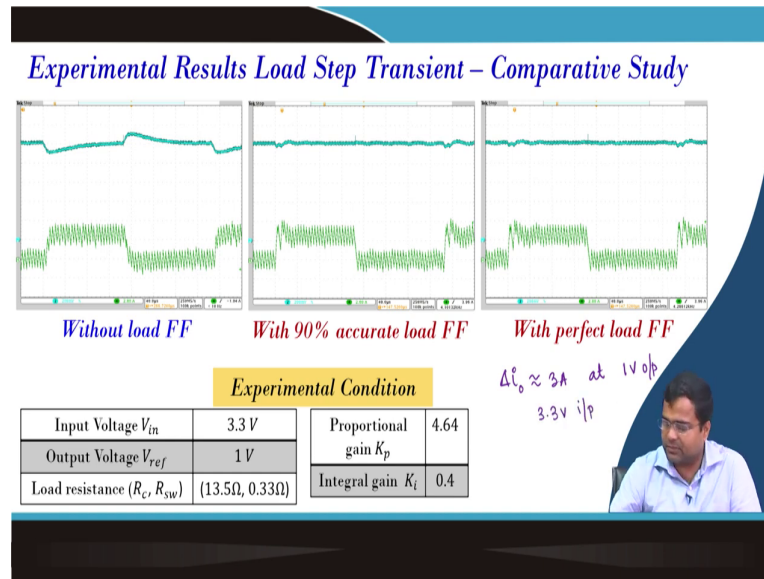
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But what happened in the second case if the same condition if  $I_0$  estimate is about 0.9 times your actual load step size it is a digital number. Then what will happen? Again overshoot is also negligible almost no overshoot again kind of small transient effect, I will say negligible transient effect.

But this is much superior to without load feed forward. That means, even if you get some partial information about the load current. See you can further reduce maybe this will get a little bit more deteriorated, but it will be far better than without load feed forward.

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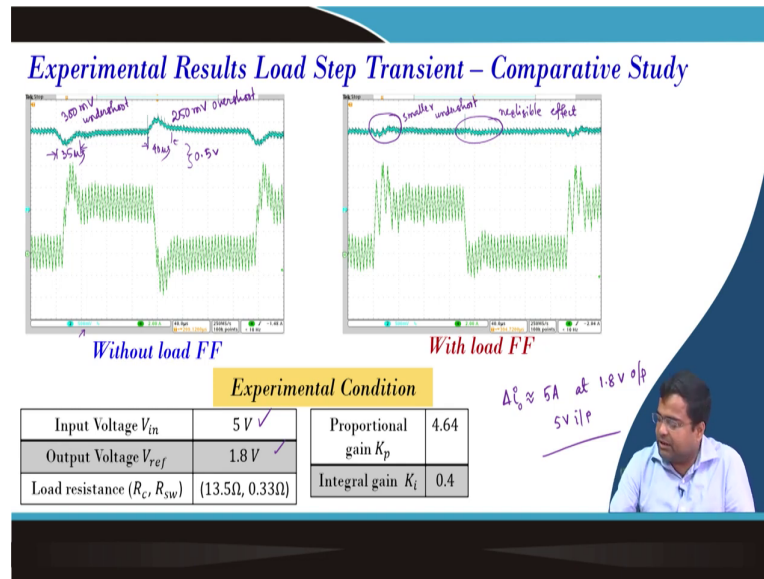


So, in the bottom line if we incorporate this information you will get and if you compare this; that means, this is without load feed forward this is 90 percent accurate load feed-forward and this is like a 100 percent accurate load feed forward. So, this two are more or less identical transient performances you can see they are closely transient identical performances.

So, it is because 90 percent and 100 percents are almost close ok. So, you will get a transient performance of almost 90. So, this is much superior to without load feed forward. Now we want to show the same thing if we have increased the load step size What was the load step size here? Our load step size here was nearly 3 ampere and it was at 1 volt output.



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Now, we want to change the load step size is nearly 5 ampere at 5 volt sorry at 1.8 volt output. Another thing this was input was 3.3 volt input and here input is 5 volt input ok. So, this is here 5 volt input, 1.8 volt output. Now the first thing again the load transient performance here you can see it is in the 5.5. So, this division is 0.5 volt.

So, you can see undershoot is 1.8 around 300 millivolt undershoot, the overshoot is around 250 millivolt, overshoot and the settling time is coming to be it is in 40 microsecond. So, it is roughly around I will say 35 microsecond and here it is around i would say 40 microsecond.

Now, if we add the load feedforward you can see an almost negligible effect here and also a very smaller undershoot. That means, even for a such load transient the effect is almost there is an almost insignificant effect in the output voltage. So, as a result, you can make fast transient performance ok.

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## Summary

- Load current feedforward in mixed-signal CMC
- Experimental load transient performance
- Comparative study with and without load feedforward

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So; that means, what we saw in the summary load current feed-forward in mixed signal current mode control we have discussed. And we have shown experimental transient performance with and without load current and we have made a comparative study with and without load feed forward. And we saw that load current feed forward can significantly cut down the undershoot and overshoot. As a result, we can reduce the output capacitor size because if you go back to the result if the undershoot and overshoot of the output voltage can be reduced.

So, you can decrease the output capacitor size as a result your power supply size will come down. Because the capacitor output takes a significant occupy a significant space and you can reduce that you can reduce the bill of material and this will also help in the reference transient performance.

Because if you use a smaller capacitor in the output you can change very fast output voltage from like a DVS. It will allow a fast DVS slew rate with reduced kind undershoot so; that means, this feed-forward action digitally if you can estimate and you can communicate with the processor you can make the power supply much much faster and superior.

So, in summary, all these points we have discussed and a comparative study shows that this effect can be explored in digital control. And this is how digital control can make a much faster response compared to the analog control counterpart that is for today.

Thank you very much.