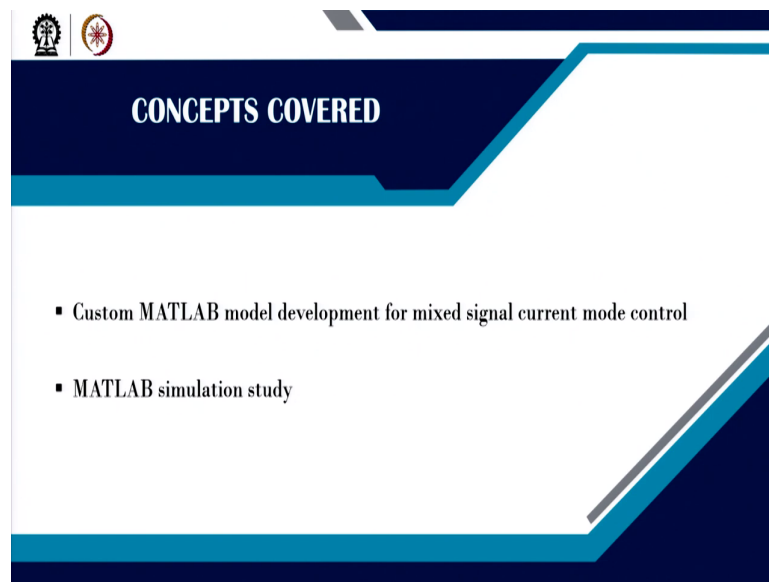


Digital Control in Switched Mode Power Converters and FPGA-based Prototyping
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Department of Electrical Engineering
Indian Institute of Technology, Kharagpur

Module - 03
MATLAB Custom Model Development under Digital Control
Lecture - 26
MATLAB Model Development for Mixed-Signal Current Mode Control

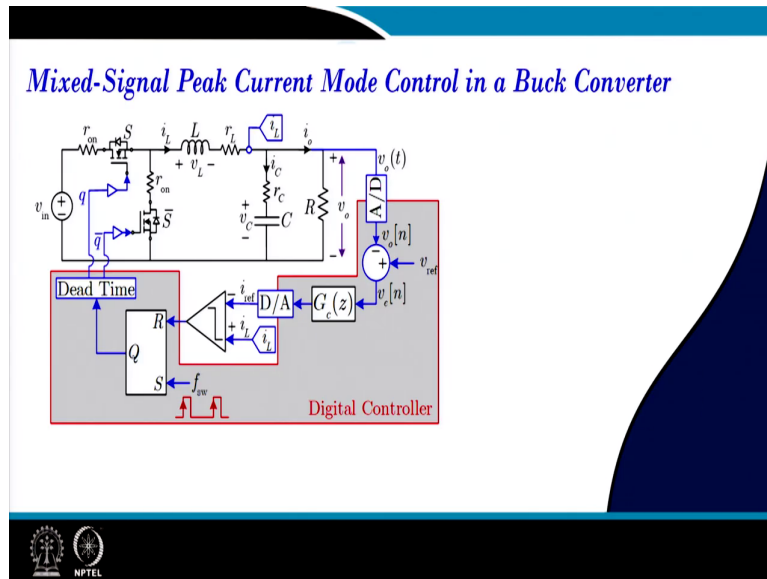
Welcome. So, in this lecture, we are going to talk about MATLAB Model Development for Mixed Signal Current Mode Control.

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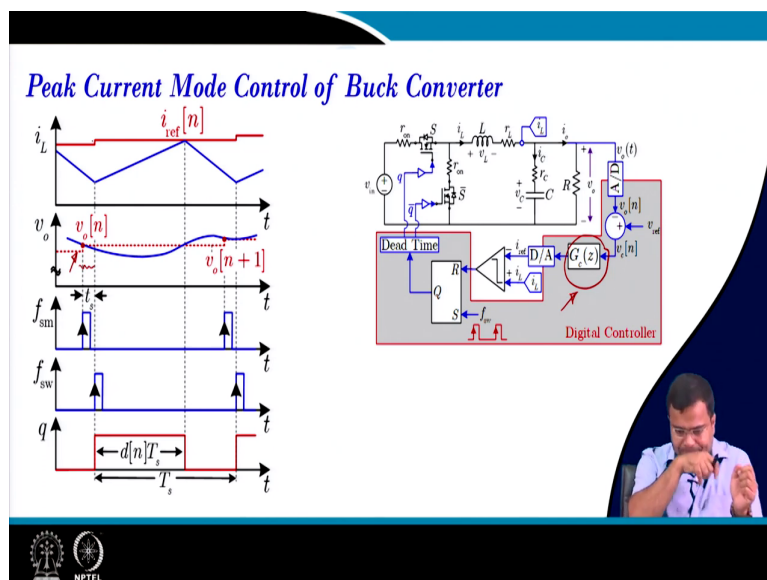
So, we will first talk about custom MATLAB model development and then we will take a few simulation case studies.

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So, this is the architecture that we have discussed in detail in the previous you know week and we are taking starting from this known mixed-signal control architecture where the current loop is in analog and then you have a voltage loop which is in digital.

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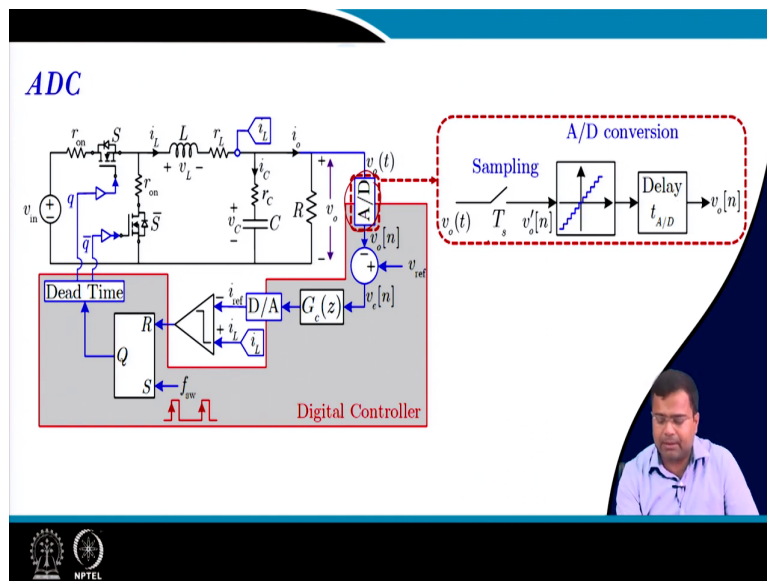


So, the first thing we need to understand is the waveform here. So, here we know that if we take the sample here and we know it requires some time for the conversion and computation and then the peak current will be ready and at that time we will start the switching process; that means, the switching clock and the sampling clock there is a delay and to implement that

we have understood particularly this clock compensators have to be clock synchronized, it should not be a simple transfer function.

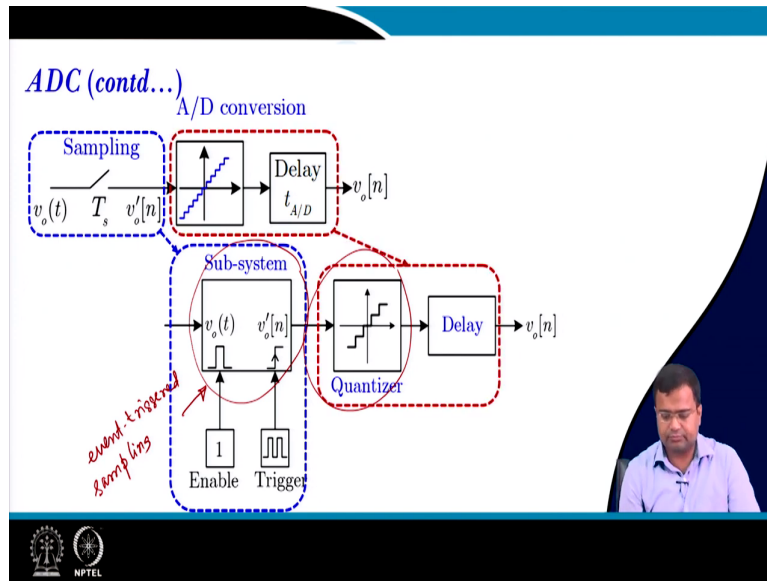
So, we need to use a difference equation that we have discussed in the previous two classes ok. So, we want to use the same approach, but now in this case we will use a PI controller rather than PID controller because it is a current mode control and we need to implement this.

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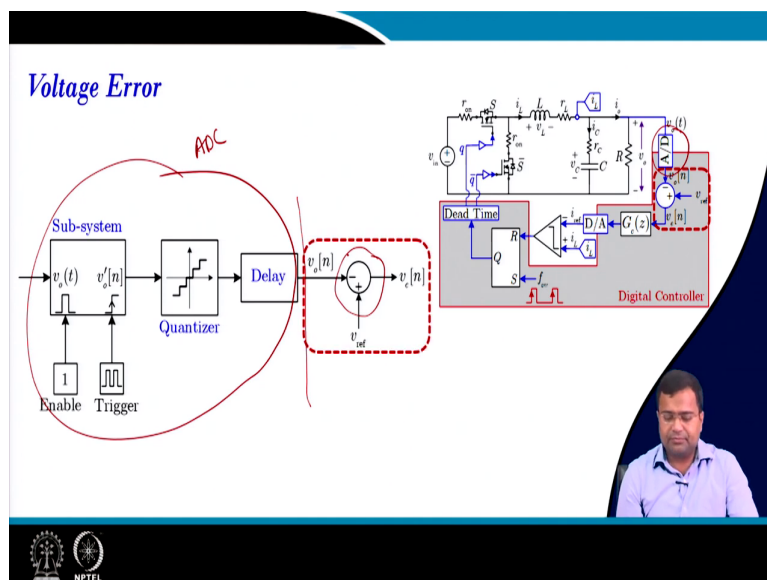
Now, we will have A to D converter and we have already discussed the implementation of the A-to-D converter which is a quantizer block and then you know sampling block; the sampling block is we can make even trigger sampling that we have discussed earlier.

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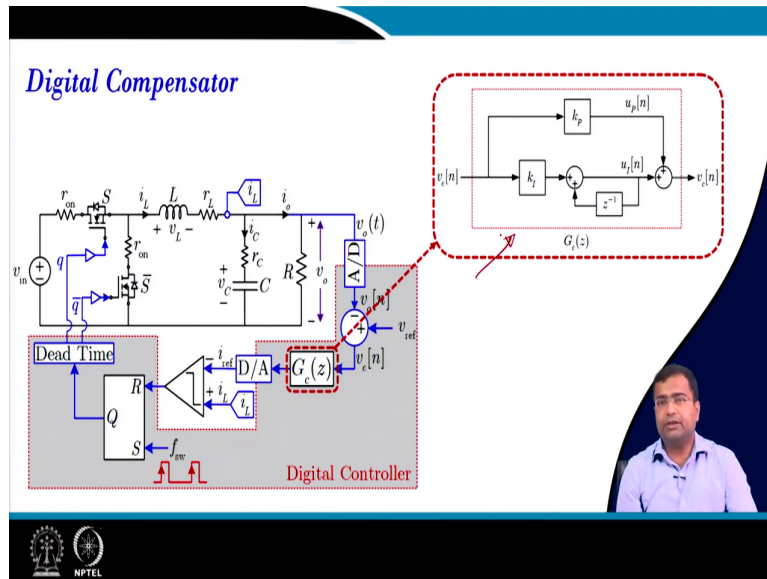


Then you can use a quantizer block and we can add a delay. So, this is event-triggered sampling we know it is an event-triggered sampling and we can use it with respect to any clock event can be a clock or you can create a virtual an event.

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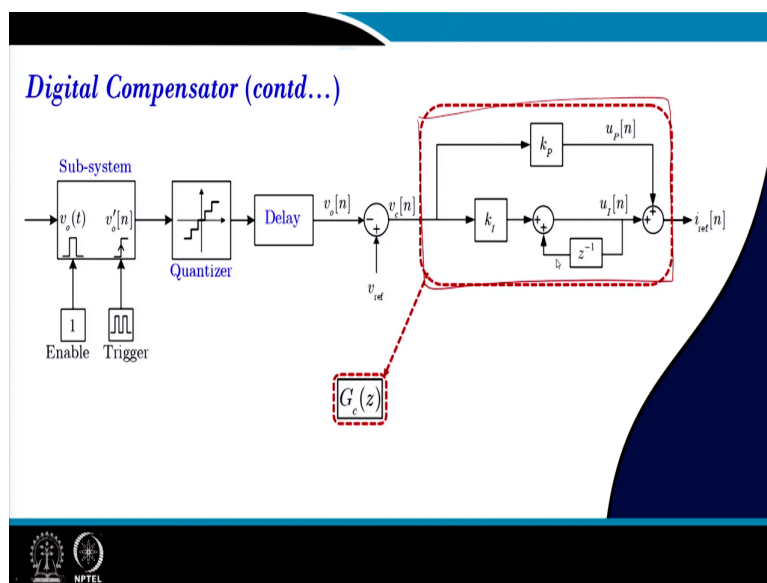


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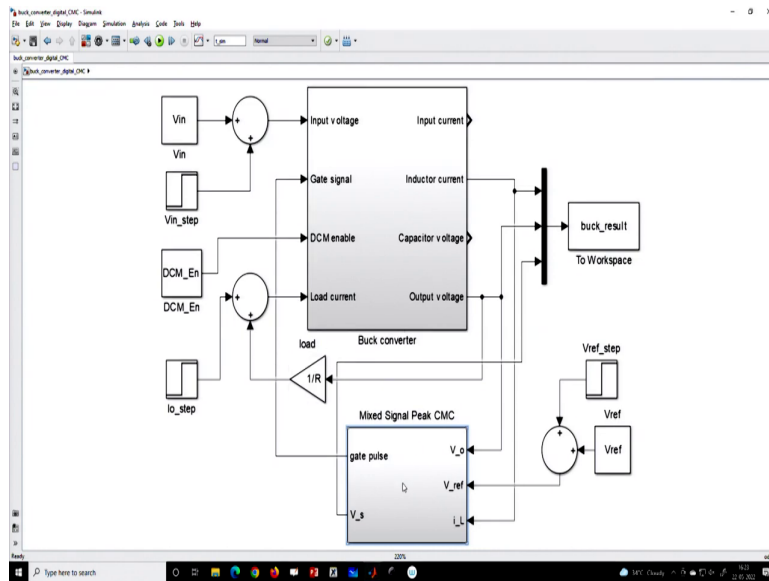


Then we can generate the error voltage. So, after this block delayed block; that means, this represents this whole block represents our ADC output of ADC is the visual end which has an error amplifier block, then it goes to the controller and is a PI controller and we have discussed this PI control implementation using a clock synchronized difference equation; that means, here this will be implemented using a clock synchronized block.

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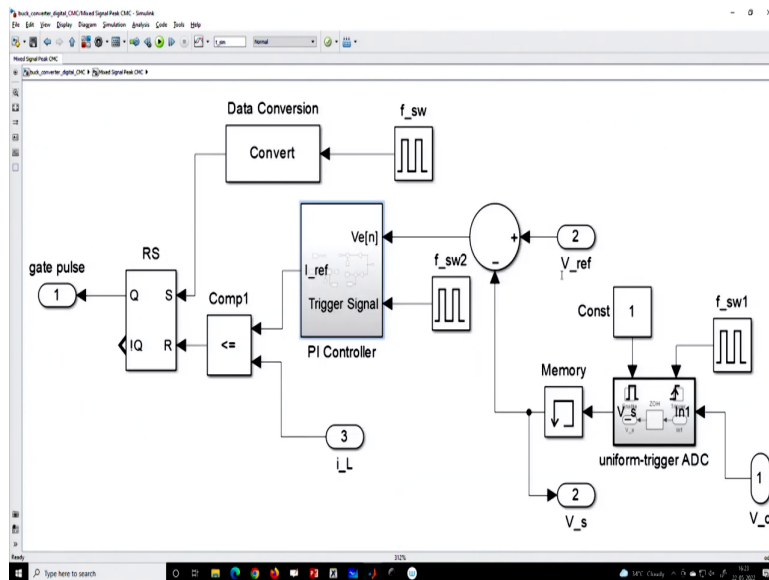


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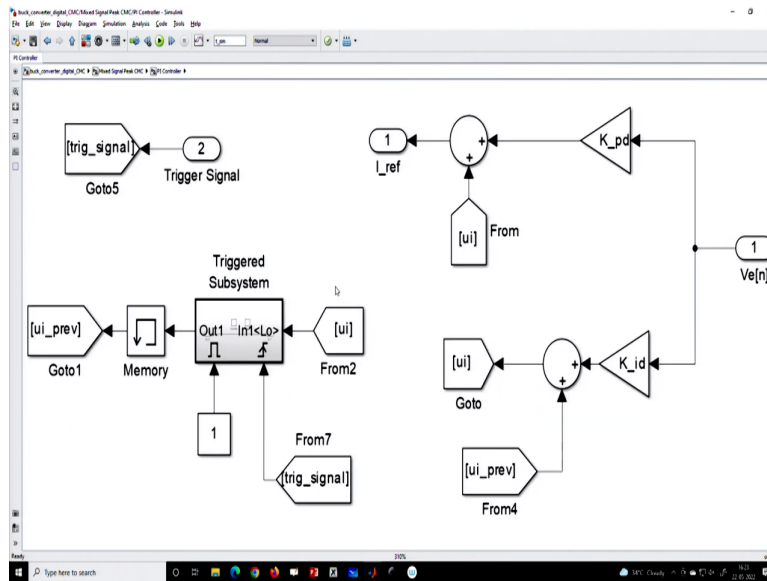


And let us go to the MATLAB block I will just show this is mixed signal architecture here the past remains the same, but the controller is different.

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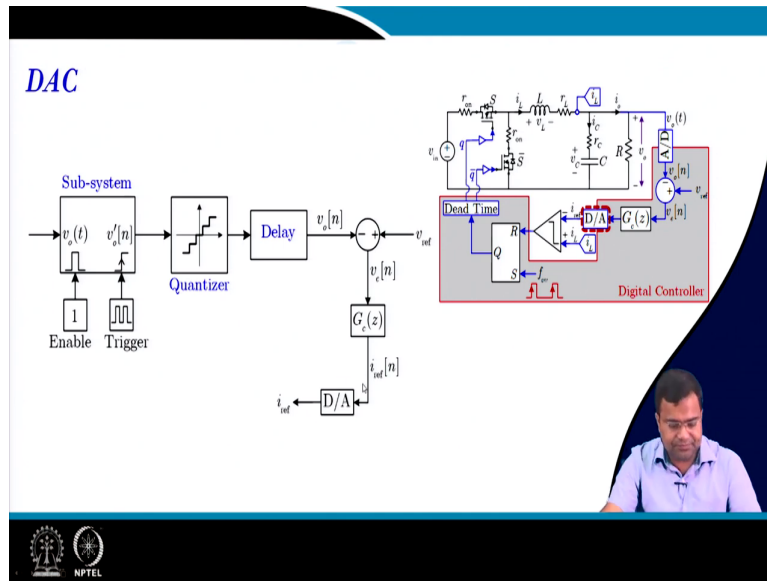


And if you go to this block this is our A to D converter, then here is the pi controller if you go inside the pi controller then what we will see? That this will generate. So, this is the overall error voltage this is simply the proportional controller part plus the integral controller part. So, this is a K_p into error voltage plus integral u_i of n .

How do you generate u_i of n ? u_i of n will be generated from; that means, it is nothing but $K_i u_i$ of n minus 1 plus K_d into error voltage $K_i d$ that is a K_i is a discrete-time integral gain and this go to a go to block. So, this block creates a delay; that means, this block input to this block is u_i of n , and the output of this block is u_i of n minus 1 and that is used here ok this is used here u_i and u_i of n , and this delay is created with respect to this clock; that means, this clock will synchronize with the delayed error I mean the integrated output.

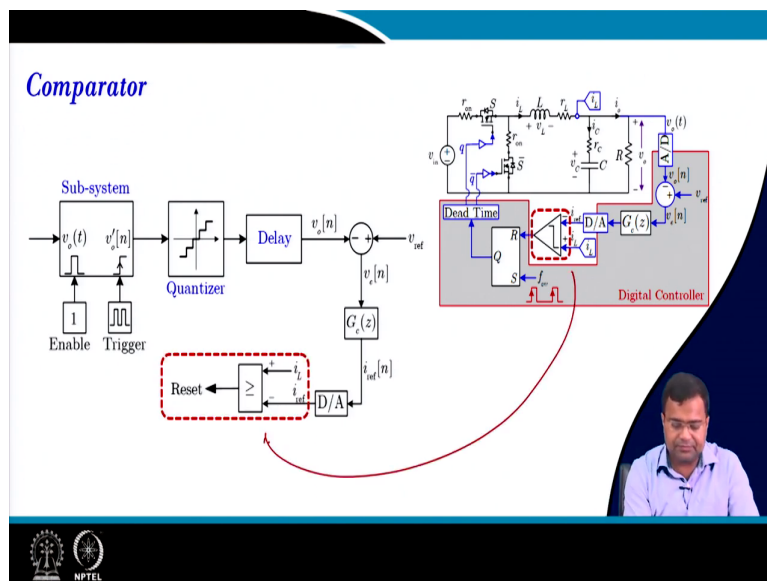
And if you go up a controller and the rest of the blocks like your typical current sense then this is a reference current peak current so; that means, this is the block that we are we have discussed G of z .

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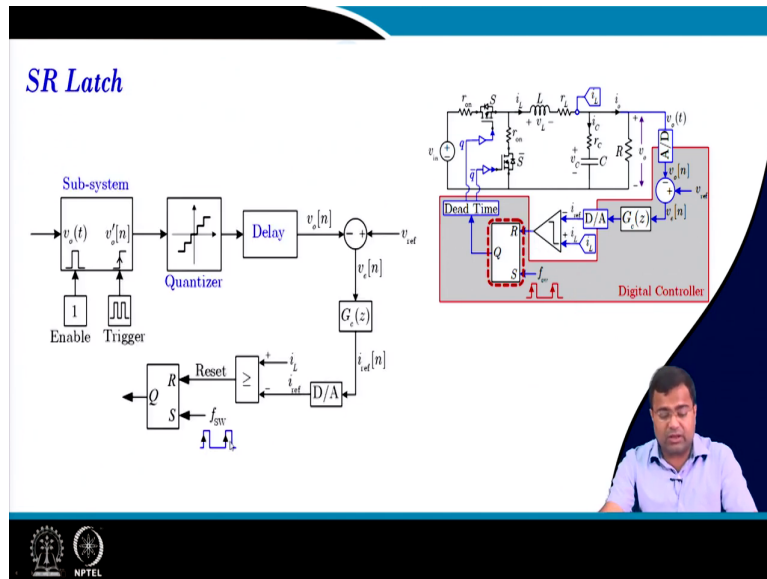


Then that means, it is you can also put a delay if you want to additionally consider the controller delay, then that is simply you can add a quantized block here, and in fact, this digital control is quantized itself. So, DAC may not need another quantization. So, only the DAC bit size should match the quantized level that we are sending, but if you say a lower resolution DAC then you may have to create another quantization block here.

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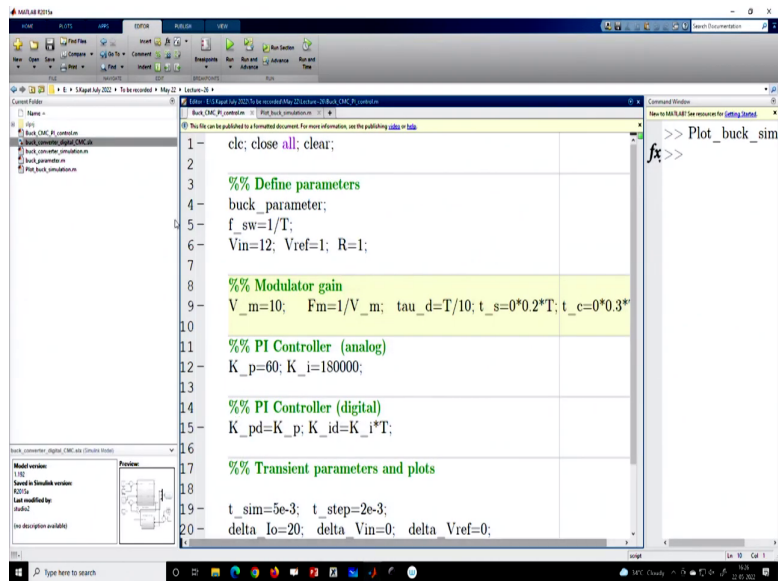
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Then it goes to the reference current, the reference current is compared with the inductor current this is the comparator ok. So, this is the comparator, this comparator is here and the output of this comparator goes to the SR latch and the SR latch it will be set by the switching frequency clock and will reset by the comparator output and this is under trailing edge modulation that we have discussed.

So, if we just look at the current mode control implementation if you remove this digital part then it is the same as analog current mode control because it is an analog current loop and we are just creating and generating the reference current through a digital controller where this is the reference current generated from the output PI controller output digital PI controller and we need an A to D converter ok.

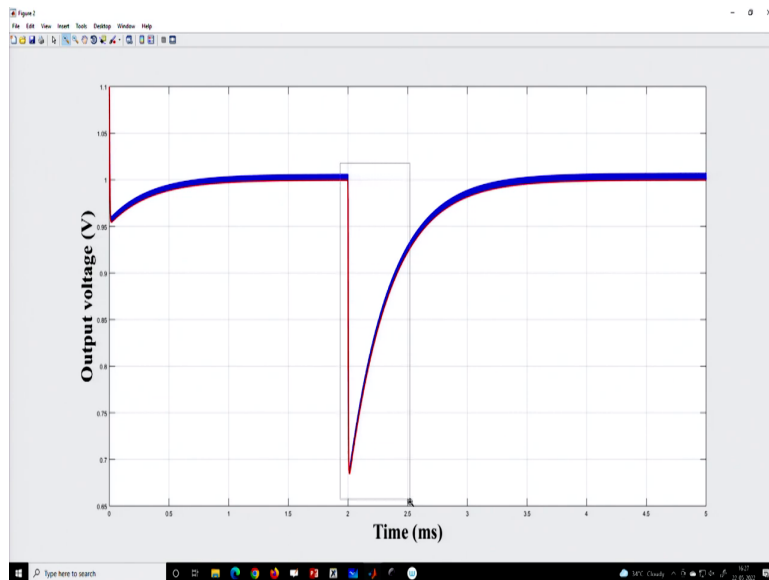
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```
1- clc; close all; clear;
2-
3- %% Define parameters
4- buck_parameter;
5- f_sw=1/T;
6- Vin=12; Vref=1; R=1;
7-
8- %% Modulator gain
9- V_m=10; Fm=1/V_m; tau_d=T/10; t_s=0*0.2*T; t_c=0*0.3*
10-
11- %% PI Controller (analog)
12- K_p=60; K_i=180000;
13-
14- %% PI Controller (digital)
15- K_pd=K_p; K_id=K_i*T;
16-
17- %% Transient parameters and plots
18-
19- t_sim=5e-3; t_step=2e-3;
20- delta Io=20; delta Vin=0; delta Vref=0;
```

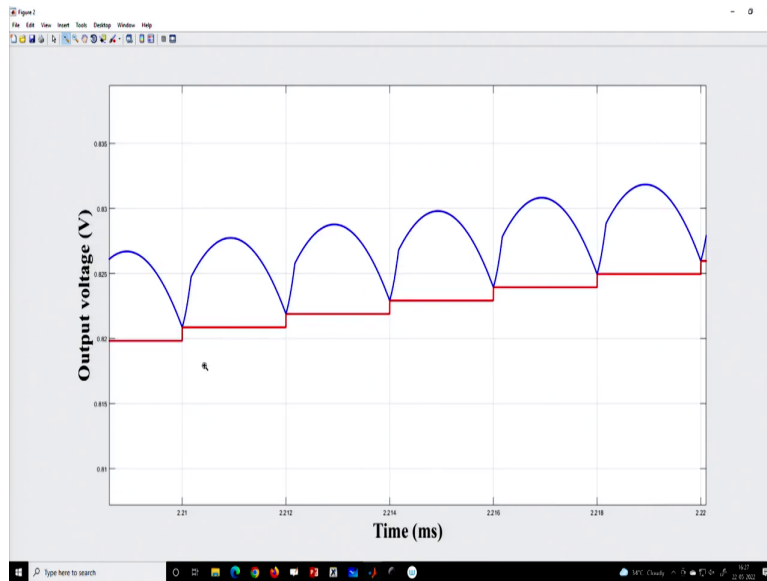
So, now we want to run the simulation case study, now we want to first use a load step size of 20-ampere load step. So, we can again change whatever we want to change.

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So, here I am showing the load transient response, we have not yet discussed the design of the current mode controller this is just with an arbitrary set of PI controllers.

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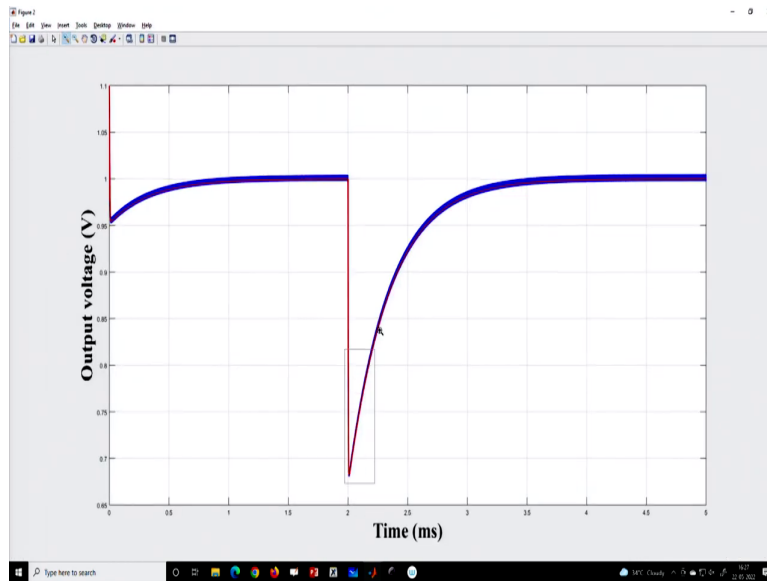
And you can see that this is the sample voltage here we are using the sample point the same as the switching point, but suppose we want to adjust this. So, we have to just delay this clock; that means we can use this block to be let us say 0.9.

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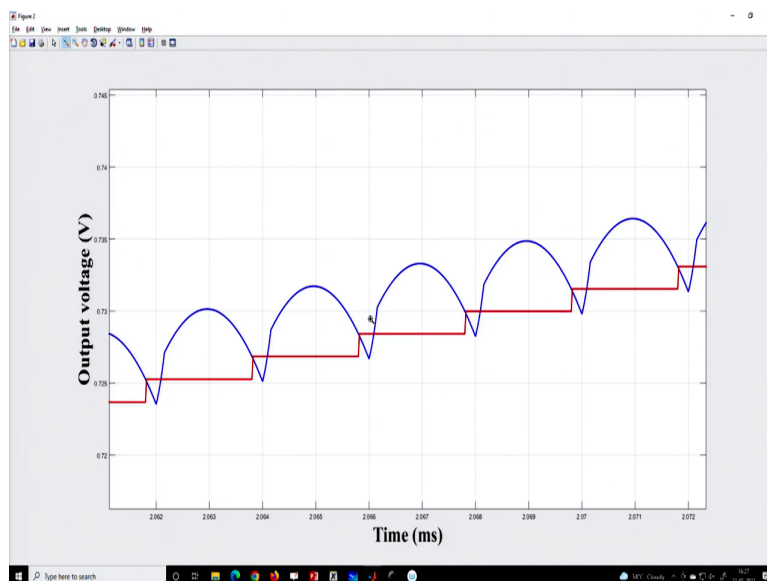
```
5- f_sw=1/T;
6- Vin=12; Vref=1; R=1;
7
8 %% Modulator gain
9- V_m=10; Fm=1/V_m; tau_d=T/10; t_s=0.9*T; t_c=0*0.3*T;
10
11 %% PI Controller (analog)
12- K_p=60; K_i=180000;
13
14 %% PI Controller (digital)
15- K_pd=K_p; K_id=K_i*T;
16
17 %% Transient parameters and plots
18
19- t_sim=5e-3; t_step=2e-3;
20- delta_io=20; delta_Vin=0; delta_Vref=0;
21
22- buck_converter_simulation;
23
24
```

WINDOW: I/O
eliminate this message, set the Algebraic loop option in the Diagnostics page of the Simulation Parameters Dialog to "None"
> In buck_convert
In Buck_CMC_1
Found algebraic lo
'buck_converter_
'buck_converter_
'buck_converter_
'buck_converter_
'buck_converter_
fx

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And I will show you that the clock will be delayed. So, I just want to show that now the sampling is happening fast before switching so; which means, you can customize the sampling process and this will help to accommodate the conversion time and computation time.

So, you can implement current mode control very effectively using MATLAB simulation block so; which means, A to D converter. So, everything; that means, is all set. So, you can implement any mixed signal current mode control architecture.

So, we have discussed custom MATLAB model development for mixed-signal current mode control then we have considered a few MATLAB case studies.

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```

5- f_sw=1/T;
6- Vin=12; Vref=1; R=1;
7
8- %% Modulator gain
9- V_m=10; Fm=1/V_m; tau_d=T/10; t_s=0.9*T; t_c=0*0.3*T;
10
11- %% PI Controller (analog)
12- K_p=60; K_i=180000;
13
14- %% PI Controller (digital)
15- K_pd=K_p; K_id=K_i*T;
16
17- %% Transient parameters and plots
18
19- t_sim=5e-3; t_step=2e-3;
20- delta_Io=0; delta_Vin=-5; delta_Vref=0;
21
22- buck_converter_simulation;
23
24

```

Command Window:

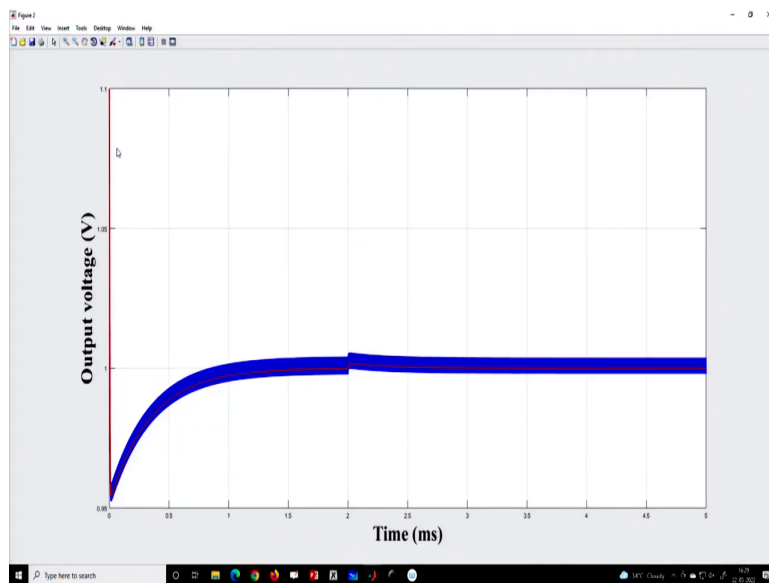
```

> In buck_convert
In Buck_CMC_1
Found algebraic lo
'buck_converter_
'buck_converter_
'buck_converter_
'buck_converter_
'buck_converter_

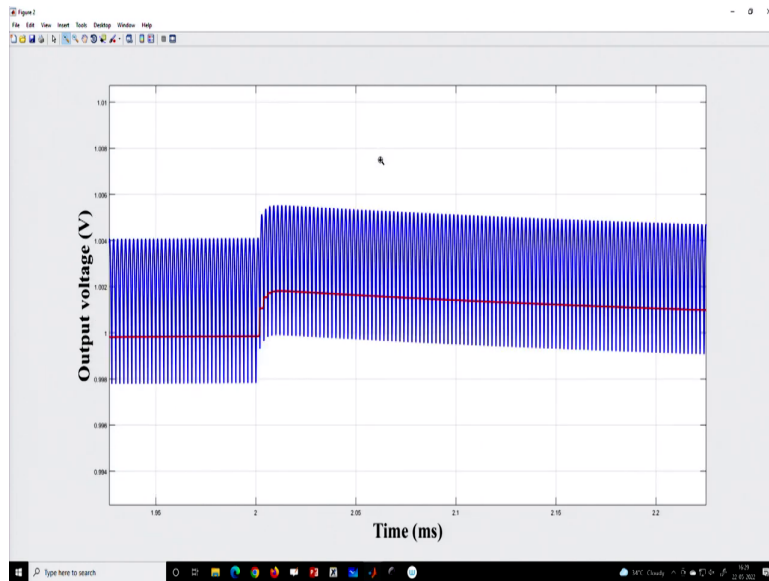
```

So, I want to show one more thing here I forgot because in current mode control has excellent line regulation; that means if you take about the supply transient we want to see what happened with the supply transient. That means I am just making a 5-volt step down; that means, the supply is changing from 12 to 5 volt.

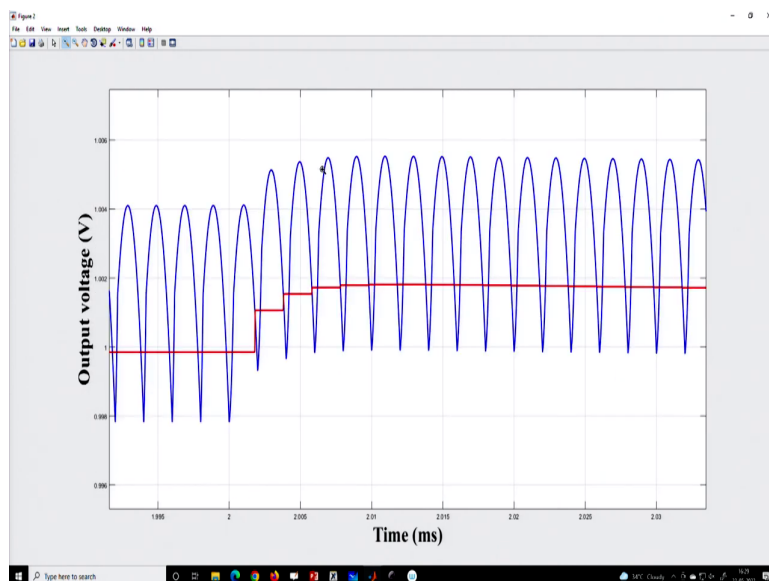
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And see what happened you can see unlike in voltage mode control here almost the effect is negligible there is almost no effect because current mode control has excellent audio susceptibility as well as line regulation and that is why you can hardly see any transient effect here.

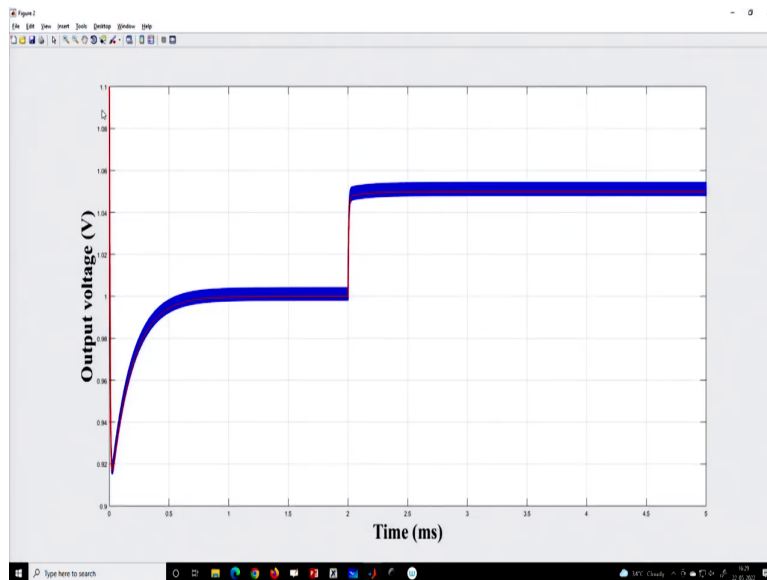
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```
5 f_sw=1/T;
6 Vin=12; Vref=1; R=1;
7
8 %% Modulator gain
9 V_m=10; Fm=1/V_m; tau_d=T/10; t_s=0.9*T; t_c=0*0.3*T;
10
11 %% PI Controller (analog)
12 K_p=30; K_i=180000;
13
14 %% PI Controller (digital)
15 K_pd=K_p; K_id=K_i*T;
16
17 %% Transient parameters and plots
18
19 t_sim=5e-3; t_step=2e-3;
20 delta_Io=0; delta_Vin=0; delta_Vref=0.05;
21
22 buck_converter_simulation;
23
24
```

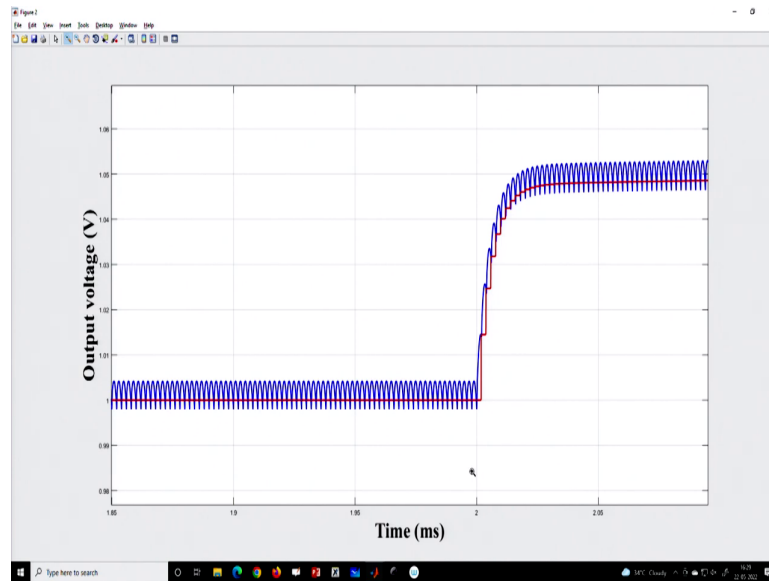
WINDOW: I/O
eliminate this message, set the Algebraic loop option in the Diagnostics page of the Simulation Parameters Dialog to "None"
> In buck_convert
In Buck_CMC_1
Found algebraic loop
'buck_converter'
'buck_converter'
'buck_converter'
'buck_converter'
'buck_converter'
fx

Similarly, if you want to do reference voltage transient; that means, I can use simply 0.05, but I can reduce the gain controller gain. So, we have not yet discussed the design.

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So, here yeah this is the reference voltage transient. So, you can say the output voltage is changing from 1 to 1.05 ok. And here we have used continuous-time integral gain and continuous-time proportional gain and have converted them into discrete-time proportional gain will remain the same integral gain there will be a multiplication of T , and the discrete-time integral gain is a sampling time into the continuous-time integral gain.

So; that means, we have discussed a few case studies; that means, we have considered a few case studies using mixed-signal current mode control. So, we will consider fully digital current mode control in the next lecture. So, I want to finish it here.

Thank you very much.