Digital Control in Switched Mode Power Converters and FPGA-based Prototyping

Prof. Santanu Kapat
Department of Electrical Engineering
Indian Institute of Technology, Kharagpur

Module - 02
Fixed and Variable Frequency Digital Control Architectures
Lecture - 20
Summary of Digital Current Mode Control Architectures

Welcome back. So, this is the last lecture of week 2. In this lecture, we want to Summarize various Digital Current Mode Control Architectures that we have learned in this week 2.

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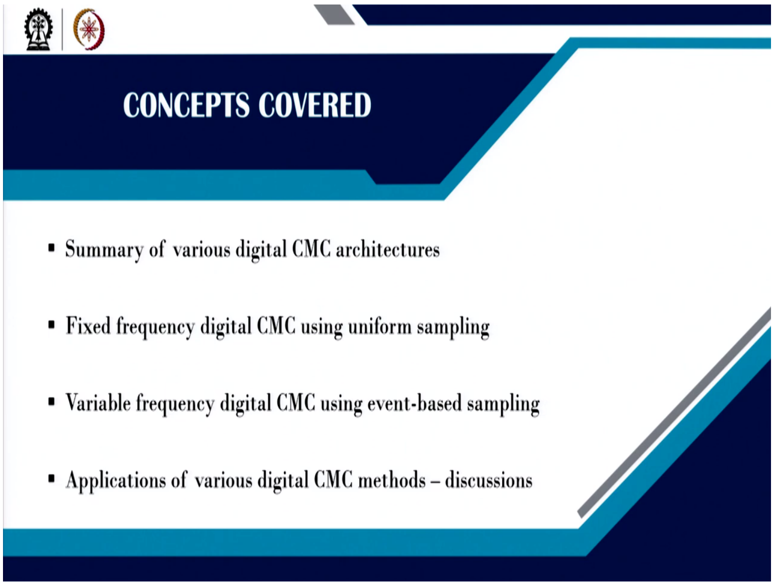

And I will talk first. I will summarize various digital current mode control architectures, then some fixed frequency digital current mode control, variable frequency digital current mode control, and some aspects of the application.

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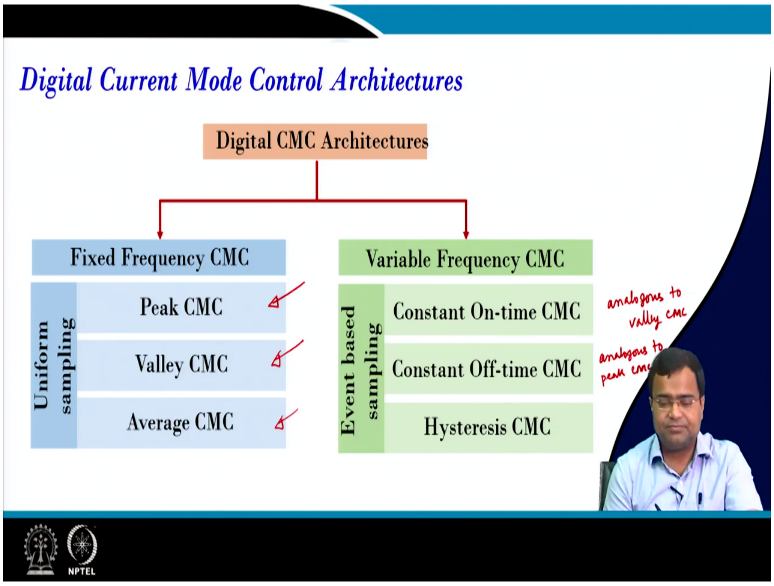

Then, if we take digital current mode control architecture so, this architecture can be classified based on two modulation techniques fundamental modulation; is, fixed frequency current mode control, and another is variable.

So, under fixed frequency, we have peak current mode control that also has fixed signal peak current mode control, full digital peak current mode control, then we can also have valley current mode control and average current mode control architecture and all this architecture since it operates under fixed switching frequency, so we generally use uniform sampling.

Under variable frequency current mode control, the constant on-time current mode control is analogous to valley current mode control.

And the constant obtained is analogous to peak current mode control ok and hysteresis current mode control we can configure to peak valley as well as average and this is a very fast current mode control. So, these are the current mode control basic architecture we have discussed.

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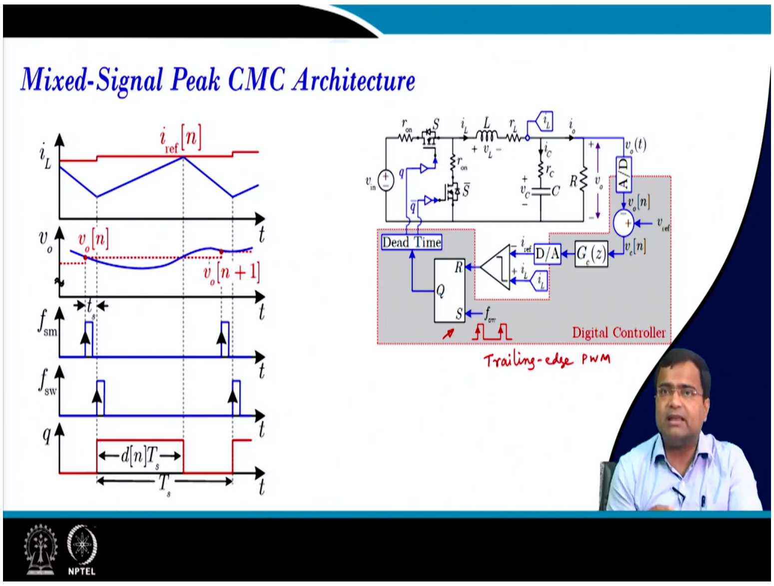

And we just want to summarize that under peak current mode control fixed frequency, we need a fixed frequency call clock and this is under trailing edge modulation trailing edge PWM. Then, it is like a peak current control structure and we know that we need to provide delay for computation and conversion computation.

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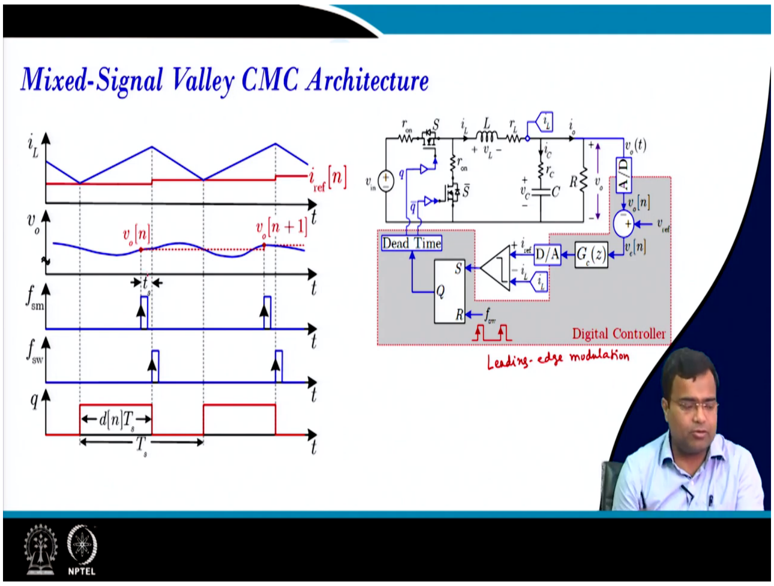

We have also discussed valley current mode control and leading edge modulation, which is leading edge modulation and all are under fixed frequency control this is the waveform where we know that whenever the clock edge comes to the switch turns off, and the switch turns on when the inductor hit the valley currently, and here also you should provide some delay for conversion computation.

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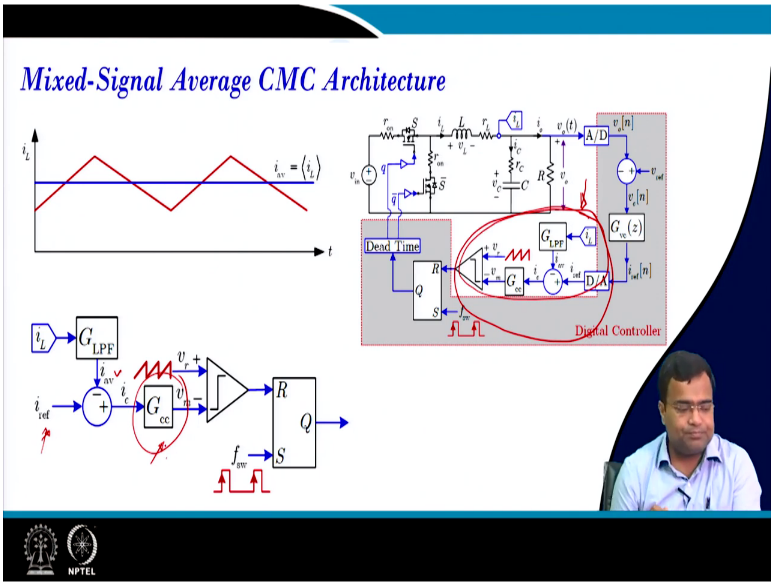

Then, we also know the average current mode control architecture. So, this is quite standard we are only keeping the voltage loop in digital, but there are other architecture advanced architectures where fully digital current mode control.

You can take care of the whole thing in the digital domain, but we are not discussing this in this course because we are first introducing the basic digital control architecture. But anything advanced you know if you can think of or you can refer to a research paper, but we are not discussing you know that advanced technique here.

Here average current mode control is standard; that means, if you take this analog block it is identical to the standard average current mode control technique that we have discussed in our earlier course. Here only difference the reference current is coming through digital. Why it is important? Because, you know if you are talking about, for example, a power factor character circuit may be another controller low bandwidth controller.

So, this current difference should also come from because we need to also track the input voltage profile because we need to achieve unity power factor. So, for this kind of application, this analog-digital voltage loop is very useful to digitize and retain the ripple; which means the line frequency information. So that our inductor current average value can track it ok, and this is very much used in average current mode control is very much used in power factor character network.

But, if we go for the advanced digital average current mode control technique where because, what is the problem with this technique? Because your current loop is in the analog domain and we are using a low pass filter.

So, we have to compromise the current loop bandwidth because of the low bandwidth the low pass filter bandwidth is low, and as a result, the voltage loop bandwidth will also be lower. While these are good for p FC where your outer loop bandwidth requirement is not significantly high if you are going for multi-phase and another converter then you have very very high bandwidth. So, such architectures are not scalable there.

So, there are alternative fully digital solutions, but again these are in the research topic. So, here if we talk about the fully digital sorry and a mixed signal again the average current is compared with the reference current and there is an analog pi controller ok, and if we are tracking you know sinusoids signal, then we may have to use something called a pi controller.

So, it is coming from the internal model control. So, if you track a step I ref current then, the pi controller is good enough but, if you are trying to track a sinusoid current then the controller should have the component if you take the Laplace transform of the sinusoid that particular component should be there in the controller.

But, typically people use a pi controller because this ref if it is a line frequency it is almost very very slow it is so slow; that means, your switching frequency is very high. So, your simple pi controller is good enough; that is why most commercial products simply use a pi controller for the current loop.

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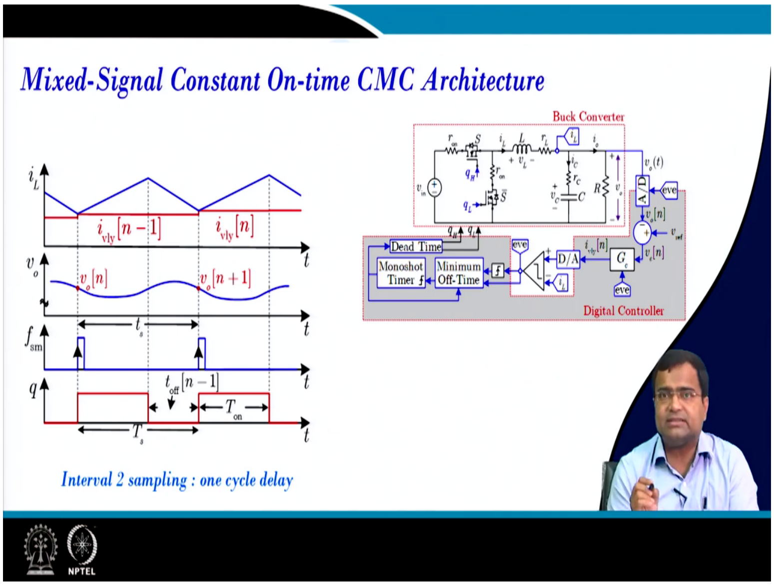

Now, if you are going for mixed-signal constant on-time control again it is analogous to valley current mode control but, here the on-time is fixed. That is the result, there is no problem with the stability in the current loop, but in valley current mode control regular fixed frequency control we know that it is unstable current loop is unstable for less than 0.5, and for k peak current mode control you know, the current loop is unstable for t greater than 0.5.

But in fact, this 50 percent duty ratio range can also get reduced because of the closed outer loop, but in case of this constant on-time or off-time control, there is no problem with the current loop stability. So, we have discussed this architecture.

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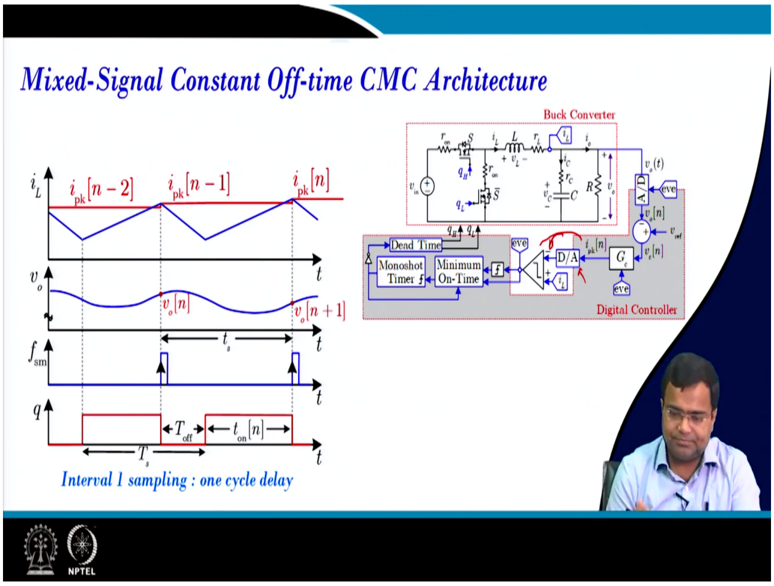

Then we have also discussed the constant off-time current mode control where, we are generating the current reference from the outer loop, and voltage loop and we are converting this that means, where digital peak reference is converted into the analog reference using a D to A converter then, we can do here it one cycle delay we are providing to sufficient provide suffice in delay in the ADC conversion and computational time, ok.

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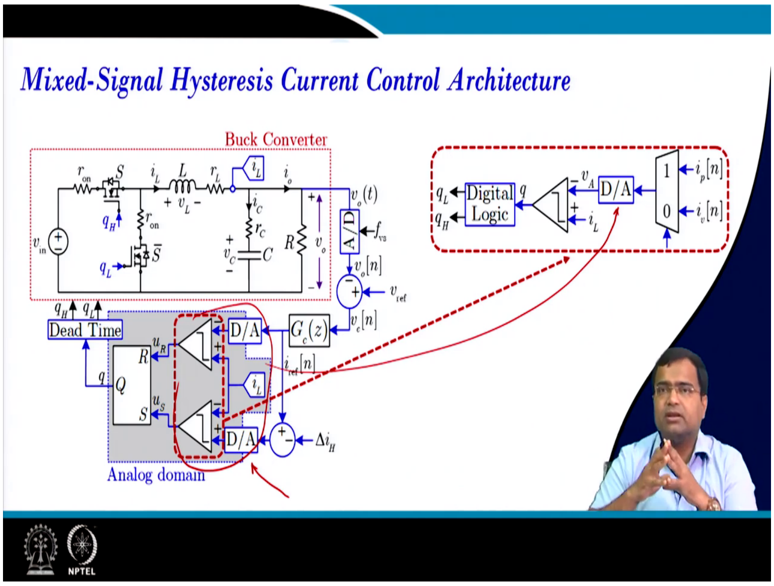

We have also discussed this in the previous lecture previous two lectures about hysteresis control. So, if you straight I use you know a mixed signal hysteresis then, actually it is not effective in terms of utilization of the D to A and A to A, A to D sorry because we cannot use two D to A converter or two comparator.

So, this can be simplified; that means the whole block, this whole block can be replaced by this using a single D to A as well as a single comparator ok and we can reduce that resource requirement and we can make a very fast mixed-signal hysteresis control.

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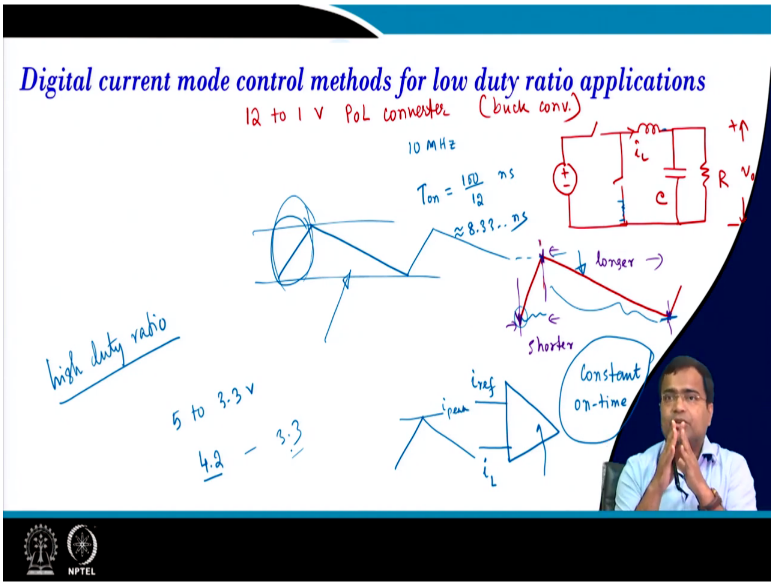

But now the question is if you are going for digital we have you know talked about various digital current mode control. Now, I want to ask, what technique will be suitable for low diffusion operation and this is for let us say we are talking about 12 to 1 volt PoL.

It is a PoL converter, which is a standard buck converter. Why PoL? Because it is called a point of load converter, it is directly supplied to a load ok and the input is a 12 volt. So, here the duty ratio is low for such low duty ratio operation for this kind of example which one will be suitable? To understand if I draw the buck converter it is self.

So, I am just drawing the ideal buck converter, and if we take the inductor current waveform, ok. So, this is the structure and if you take the resistive load and this is our output voltage and this is our inductor current. Now, we need to sense the inductor current, right? So suppose, if I draw the inductor current waveform, ok. So, let me put it because your duty ratio is very low so, it is better to use this like this.

Now, you will see, the interval for on time that means is very very low, this time interval is low this is low or smaller, and here it is longer. So, here I will say it is shorter, instead of low I will say it is shorter, it is very it is shorter and this is longer this duration is longer and this is shorter.

So that means if it is a shorter duration if you want to implement and there will be always a practical noise in the current practical noise will be there. So, if you want to implement peak current mode control logic.

So that means, in case you know if I talk about this current reference right; I am talking of the analog current. So, this is my analog current and let us say I am talking about a reference current. If I do any peak current mode architecture reference current; that means I need to take the action within a shorter duration and that is a very difficult task.

So, as a result of low duty ratio operation such because, if you are talking about let us say you know 10 megahertz switching converter 10 megahertz; that means your time period is 100 nanoseconds and if you take what is mine on time. So, on time will be 100 nanoseconds divided by 12 because it is 1 to 12 that much nanosecond which will be roughly 8 points you know I will say 33 or something like that and that is too small.

Because you need to take comparator action, sensing and all and you need to blank some of this period because of noise. So, we will end up with a very very tough problem and you need a very high-speed comparator that will consume a lot of power, but imagine we have a long duration of the octane.

So that means, if you go by peak current mode control the problem is this, feasibility is a problem. Because we know the peak current mode control is very good I mean, I would say there is no stability problem for low duty ratio, but there is an implementation issue. So, you may not be able to implement it, but if you go for valley current mode architecture it is unstable for a duty ratio of less than 0.5. So, it is not possible.

So, for such an application, we go for constant on-time control. Because constant on-time control is analogous to valley current mode control, we have a long time and since there is no current loop stability problem we consider on time, so most of the commercial product goes for constant on-time control. But, if you talk about a boost converter and also it is easy to sense the low side current of a buck converter because you can put a small resistance here.

So, it is also implementation points of it is easy and that is why the majority of the multi-phase low voltage high current product they go by constant on time because this is easy to sense the low side current and they can you know take the advantage of this current loop stability.

But, it comes with a price because your time period will vary. So, to adjust the switching frequency you can keep some digital loop because anyway the timer can be digital. So, you can just adjust that timing parameter without even having a digital control.

But here is the advantage of using digital control you know this valley current difference, then when it enters into discontinuous conduction mode, you cannot use a valley current because the DCM current will be 0.

So, you need to go for a voltage base approach in light load. Even people go for a current-based approach in light load for PFM; if you keep the peak current fixed and go by this it is analogous to constant on-time control for a particular input voltage condition. So, we will discuss some of these aspects when you go for multi-mode control design, but for the time being, we are only emphasizing for low diffusion operation constant on time is a very very popular solution.

But if you go to hysteresis control, again the hysteresis control you need to sense the full current right, full current. So it is again problematic for this region and anything sensing full current; that means, we have to do something with the inductor path. So, there are many current sensing techniques called DCR sensing, you can put a resistance, but putting a physical resistance will incur losses.

So, full current sensing is not so easy, and sometimes most of the time it may not be practically recommended. So, that means the selection of hysteresis control is something you have to be careful ok. If you are going for very high bandwidth hysteresis, and high-frequency hysteresis control, then the challenges will be the current sensing. But, even if you can implement a high bandwidth current sensor, you still have the problem during the on-time comparator because of the very smaller time.

So, that is why for low-duty ratio operation hysteresis control may not be a very attractive solution and by default, the control on time remains a very popular solution. If you go for wide duty ratio operation; that means, here I am talking about the low duty ratio operation. A similar thing can happen for high duty ratio operation, where constant on time may not be a preferable solution so then you have to go for a constant of time solution.

But, if you are going for wide duty ratio operation, we have to remember, if we are talking about high duty ratio let us say high duty ratio how do you high duty ratio is not desirable for a boost converter because you may not get the acceptable voltage gain? Because boost converter after certain gain it starts falling. Due to the parasitic drop and also the high duty ratio boost converter suffers from a poor bandwidth due to the right-up plane 0.

Because, it comes closer to the imaginary axis, but if you are going for a high-duty ratio buck converter the efficiency will go up because, as the output voltage comes closer to the input voltage the direct power flow will increase and the switching power flow will get reduced.

So, as a result, your efficiency can improve. So, there is a certain application where you may need high duty ratio operation let us say you can talk about 5 to 3.3-volt operation. So, many such applications are possible or your battery voltage is 4.2 and you need to adjust to 3.3 volts the other day because you know when you are talking about your USB you know the driver.

So, what is the voltage level of this or type C charger like type C charger? So, what is the voltage level? So, there are different voltage levels for different applications let us say in a mobile phone. The processor requires some voltage then, your connector type C USB connector requires some other voltage so, different voltage levels are required. So, based on that we have to decide which control strategy is suitable.

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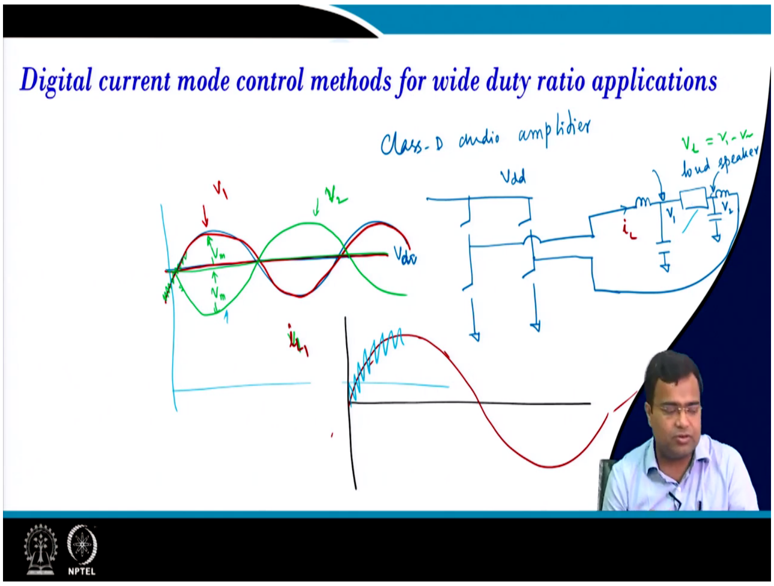

For wide duty ratio operation for example is a class D audio amplifier. This application is quite similar to our full bridge inverter because, if you are talking about a full bridge inverter circuit you know we are talking about a full bridge inverter circuit.

So, this DC link voltage is like V dd and we are tapping from here these two point, right? Now, if we think of suppose you are talking about the load so it may look like you know for class D audio amplifier this will have an inductor, this will have capacitor so, each of this terminal ground and again this side it is the loudspeaker load, again there the inductor sorry here will be a capacitor and this point is connected here.

So, differential connection and this is your loudspeaker. So, in this configuration from either side, it is like a buck operation, where you know if you take the voltage across this point and voltage across this point. So, this is like a V 1 terminal and V 2 terminal. So, at V 1 terminal we need a fixed voltage and on top of that, you have to generate this kind of voltage with the average value of some V dc some average value some V average.

The other terminal you know because this is V 1. So, this is what I am talking about V 1, my V 1 voltage we have to generate like this. My V 2 voltage should have the same DC level so that, it can eliminate that means, this is my red one is this V 1 that is the average value. Now, suppose I take the green waveform and since these two are the different signals across this so that means, the loudspeaker voltage we will see is V 1 minus V 2, right?

So, we need to have a green signal which will be just anti-phase with this and this level also should match. So, they will cancel the DC and their difference will create an AC right because if we take then it will be just twice this the amplitude will be twice this. So, if this is my V m and if this is also V m. So, your differential voltage peak will be just twice that because you will get the differential voltage and this is my V 2 signal V 2 signal.

Now, in between there will be switching which means, I am just not showing the internal waveform. So, the inductor current to achieve a wide duty ratio that means, for one particular voltage level if I take just a V 1 voltage of this of the converter to suppose I want to show the current associated with this I L 1.

So, the current has like a current average will dynamics will look like this; that means, you know actually, the average current should be sinusoids it looks sinusoid sorry, so it should be you know you should erase this point.

So, if I draw this current. The current should look like an average profile like this and on top of that the inductor current has this kind of profile and that can be a wide duty ratio variation. Because the output voltage has to swing in each of this case output voltage has to swing in larger it is both side terminal voltages are positive, but it will swing between a large variation and the DC value.

So, as a result, your duty ratio shall be large and you need to select the suitable control architecture to make the current loop stable. If the current loop becomes unstable then subharmonic will happen and this may cause distortion in you are differential voltage and which will cause the noise you know another signal so, it will distort the audio signal.

So, if such an application-wide duty ratio happens in one of the applications, the suitable selection of this current control technique is very very important.

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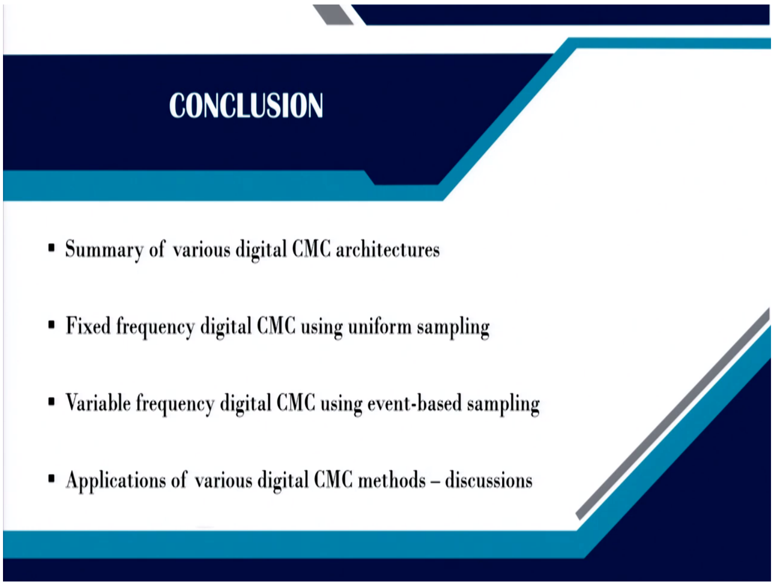

So, in summary, we have discussed various digital current mode control architectures, we talked about fixed frequency digital current mode control using uniform sampling, variable frequency digital current mode control using even-based sampling and we discussed some aspects of the application of digital current mode control method and we have discussed some potential solution.

And in the subsequent lecture, we will be we are going to implement this digital control architecture for both voltage and current mode control using MATLAB. And then, you know you know at the end of this course we will also implement hardware you know we want to implement this control logic in the actual hardware platform. So, with this, I want to finish it here.

Thank you very much.