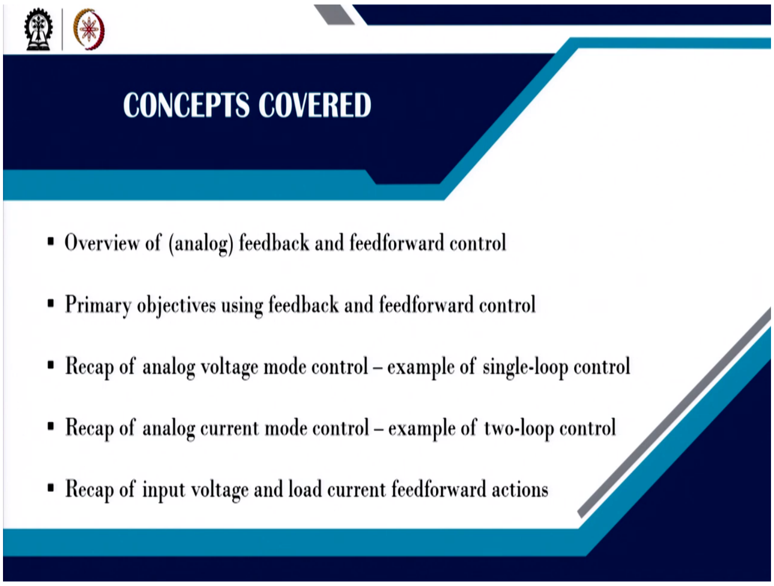
Digital Control in Switched Mode Power Converters and FPGA-based Prototyping
Prof. Santanu Kapat
Department of Electrical Engineering
Indian Institute of Technology, Kharagpur

Module - 01
Introduction to Digital Control in SMPCs
Lecture - 06
Recap of Feedback and Feedforward Control Methods in SMPCs

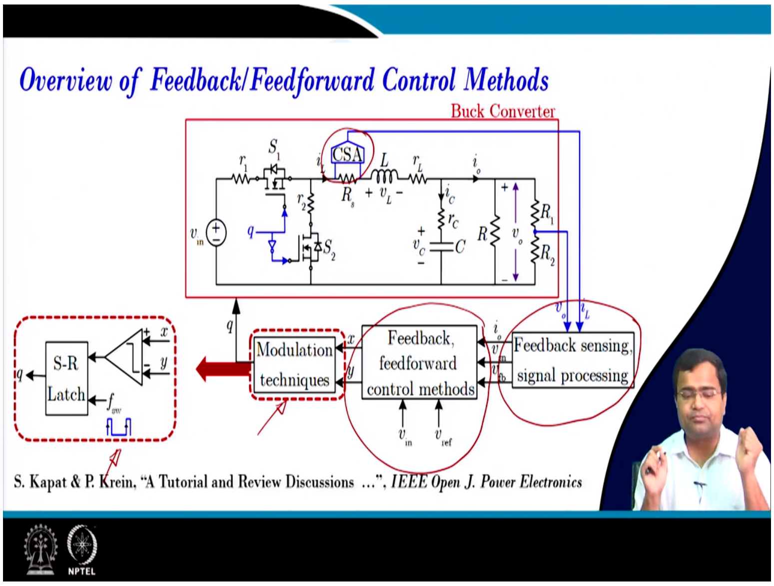
Welcome. In this lecture, we are going to recapitulate some Feedback and Feedforward Control Methods in Switch Mode Power Converter.

(Refer Slide Time: 00:33)



So, here, we first want to you know recapitulate our analog feedback and feedforward control and we want to just you know summarize what are the primary objective using feedback and feedforward control. Then, we will also talk about analog voltage mode control which is an example of single-loop feedback control. Then, we want to recap analog current mode control which is a good example of two-loop control, and then, we want to recap input voltage and load current feedforward actions.

(Refer Slide Time: 01:04)

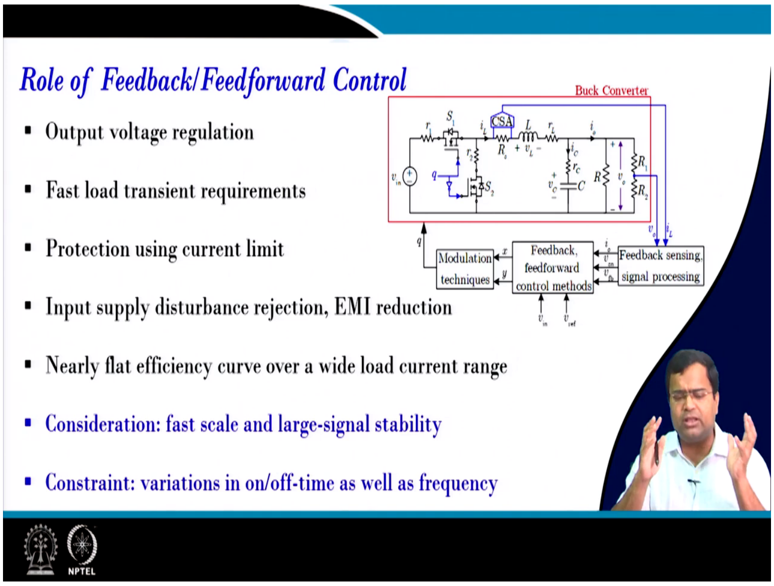


So, in this lecture, we want to have an overview of feedback and the feedforward control methods. Here, I am showing a buck converter example; but there can be any other converter and here, I am showing that you know there is a current sense amplifier. And this current sense as well as the voltage sensor is this block consisting of the sensing circuit as well as the feedback resistive divider and some signal processing like impedance matching and so on.

Then, after output, the output of the sensing block will come to the feedback and feedforward control block. As we have discussed in detail in our earlier NPTEL course, all this detail as well along with MATLAB implementation and ultimately, this particular signal has to be converted into a gate signal. So, you need a modulation technique.

So, here I am showing a simple pulse width modulation by using a latch as a comparator. So, you can synchronize with a fixed frequency clock which is why it is a pulse width modulation, and using a comparator and a latch circuit, you can generate the duty ratio of this converter.

(Refer Slide Time: 02:16)



And the role of feedback control; so, here the feedback control as well as feedforward control, we have a certain objective and their functions. So, first of all, we need to regulate the output voltage. We need to achieve a very fast load transient; that means, we need to meet certain load transient requirements.

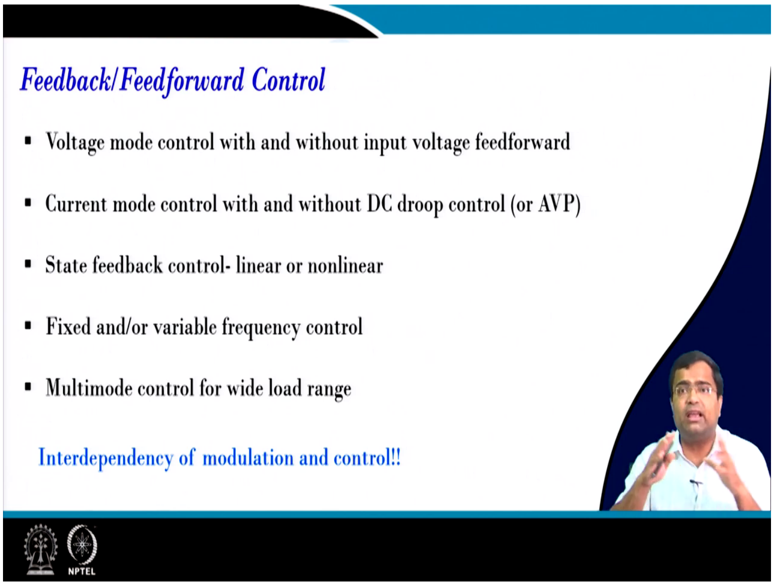
We need to protect the current limit. If you take a boost converter for example, without a current limit, you know your switch can get I mean switch can burn; I mean the whole power converter can collapse. If you do not take the proper current limit ok or it can damage your switches or even it can saturate the inductor.

Then, supply disturbance. Input supply disturbance is also very important and also you need to reduce EMI. So, these are the aspect that is part of you know objectives for designing the feedback control. Then, we need to achieve an almost flat efficiency curve over a wide load current range this is very important and this will be challenging if you are going for a light load and we may have to shift the control technique or modulation technique from one modulation to the other modulation.

And these are the consideration that means, we need to also take care of the fast scale and large signal stability. That means, there should not be any sub-harmonic oscillation or the system should not collapse. That means, on a large scale, the system must be stable and the constant is that the variation in on and off time of this gate signal should have a limit because we will have a limit in terms of switching frequency. After all, the driver may not support.

The switch rise time fault time may be a constant and there can be booster arrangement for the high side circuit. That also requires some time for charging and discharging.

(Refer Slide Time: 04:02)

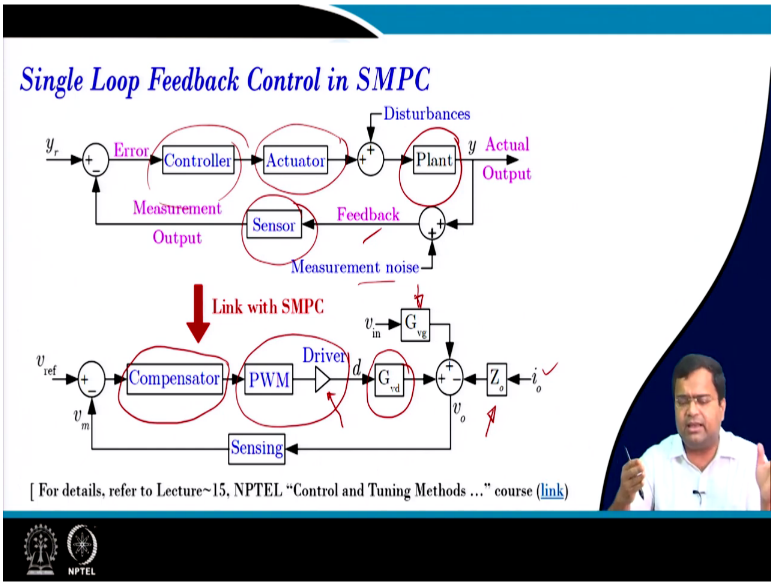


So, all these should have some content on the on-off time. Next, we have discussed in our earlier course; that means, feedback and feedforward control like a voltage mode control with and without input voltage feedforward, current mode control with and without a droop control; then, state feedback control, linear and non-linear control, fixed and variable frequency control, multimode control and all these controls are interdependent.

With the modulation and control, they will go you know they are not independent; like if you take a feedback voltage control, you can use either pulse width modulation and you can also use constant on-time modulation. Similarly, in current mode control, you can have various modulation techniques which will translate your feedback signal into the duty ratio on off time ok.

And all these details have been discussed in the previous you know NPTEL lecture like a control and tuning method in the switch mode power converter course. So, I am not going to discuss know the detail of this; but I just want to take some gist of this analog control before we start the digital control.

(Refer Slide Time: 05:08)



So, if you take a single loop feedback loop control, the general architecture of any feedback control consists of you knowing you need to control the plant, and some output to meet some desired response. And we take generally the feedback control, there can be some measurement noise, and sensor; then, this will be compared with the reference signal and there is a controller right. And finally, the output of the controller will go to the actuator and which will generate the signal and the disturbance can be load disturbance or supply disturbance.

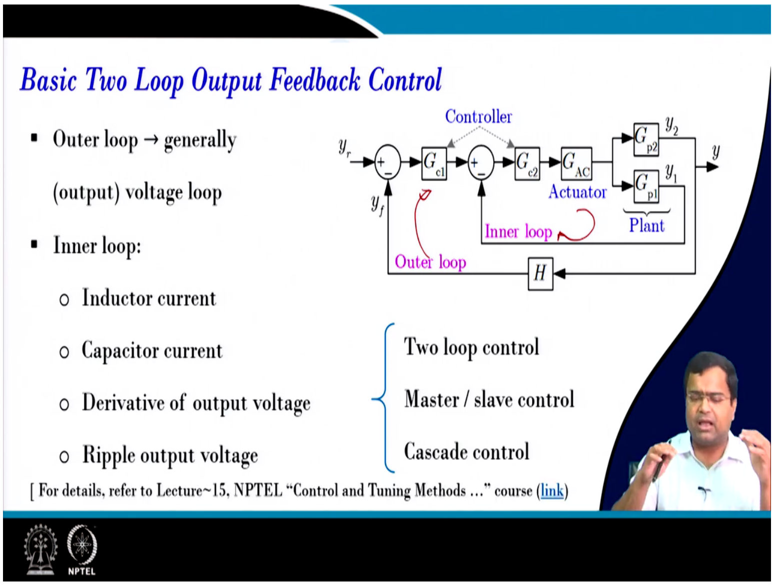
So, if you link with the power converter, then this controller is nothing but the compensator you can use a type 2, or type 3 compensator or even if you use a PID controller. Then, this actuator is nothing but PWM and this is a gate drive circuit, and that PWM will convert the compensator output into some gate signal.

When we say PWM, that means, we are generally assuming that the switching frequency is constant. But it is not necessary, we can have also a concept of time off time or hysteresis control. But ultimately, you need a gate driver to generate the controllable gate signal for the MOSFET.

And then, if we model in the small signal model that we have discussed, so there will be a control to output transfer function and then, we need to control the output voltage and there can be load current variation. So, you need to assess the output impedance. Then, there can be supply variation, so we need to know what is the open loop audio susceptibility and what should be the design objective as well as the control objective to make the output voltage more or less insensitive to supply disturbance or you need to meet certain load transient requirements.

That means, in terms of overshoot undershoot requirement, and so on. And this can be you know you will get detail of this in lecture number 15 in the previous NPTEL course and you can get the link from here.

(Refer Slide Time: 07:03)



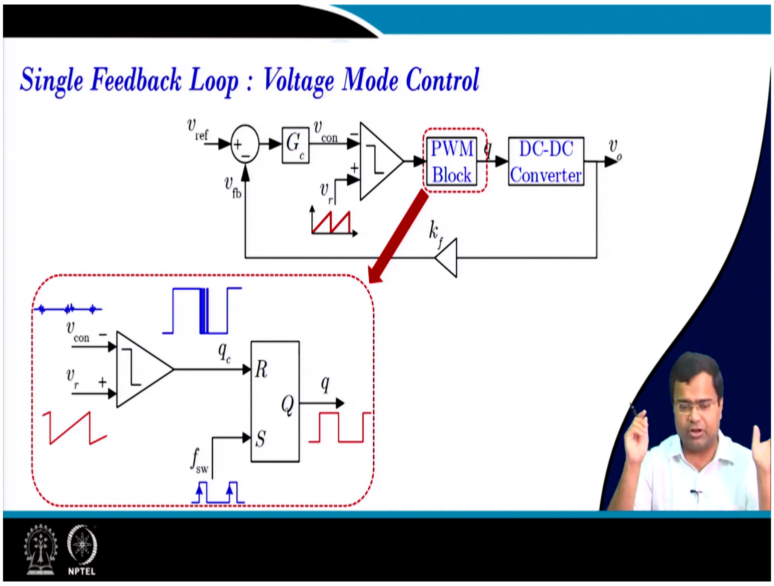
Now, in basic two-loop control, if you consider it, we generally consider an inner loop which is generally the current loop for the DC-DC converter which is considered to be pretty fast. Then, you can have an outer voltage loop which is a slower loop and this kind of control is known as two-loop control.

It can be master-slave control or cascade control and the outer loop is generally kept the output voltage loop and the inner loop can be the inductor current loop. In the case of current mode control, it can be capacitor current; but capacitor current is generally if you want to sense directly the capacitor current, that may not be recommended because if you introduce any additional resistance that will increase the ESR.

So, that can increase the ripple and it can also create a DC droop; when there is a large low step transient that can also impose a large voltage, you know sudden jump. So, that is why sensing capacitor current using a resistive sensor is not recommended and you can also take the derivative of the output voltage. We have discussed in the previous lecture, if you incorporate the derivative of the output voltage, you can have time optimal recovery in voltage mode control by suitably selecting the controller gain.

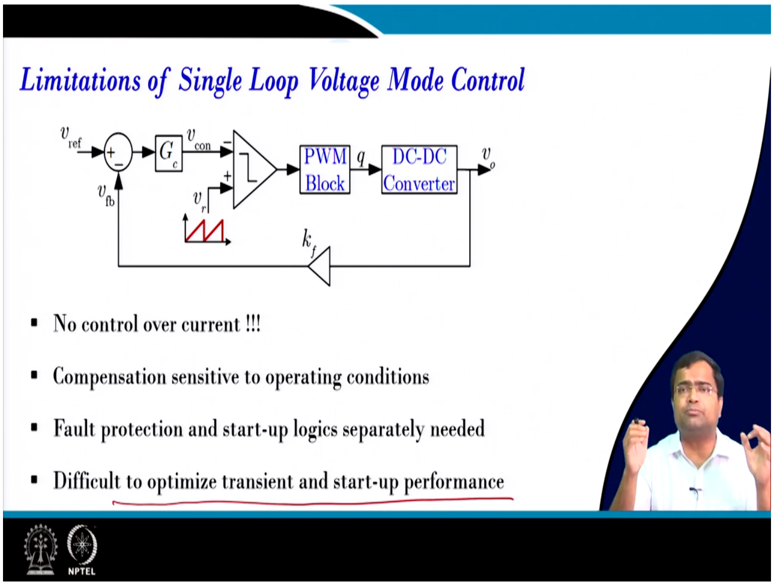
So, we are not going to discuss you know the detail. This has been discussed already and it can also ripple output voltage can also be the outer loop because this is for ripple-based control ok and you can get detail about this in lecture number 15 in the previous course.

(Refer Slide Time: 08:35)



Now, in single loop feedback control, if you take a DC-DC converter which is a voltage mode control we call, here you can have a PWM block and there is a latch circuit we have discussed this is a trailing edge modulation and we have discussed this latch action can introduce some delay and we have also discussed how to design this compensator and we have validated this design using MATLAB switch simulation.

(Refer Slide Time: 09:00)



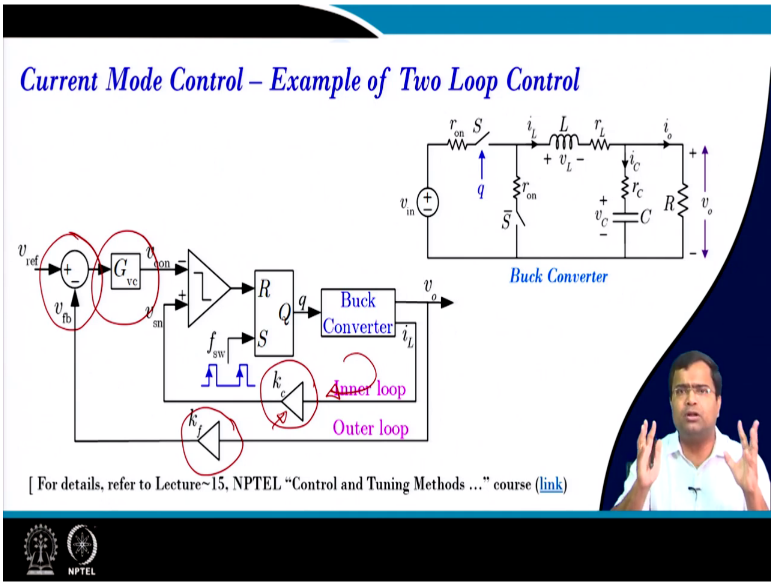
And we have also discussed that what are the limitation of single loop control because in single loop control, there is no control over current in voltage mode. So, you will have a difficulty in terms of limiting the current; particularly for fault protection startup transient.

Then, the compensator design can be sensitive to the operating condition because if you want to design a type 3 compensator, then you need to also take into account the load current variation. You know if you know the inductance capacitor and if there is a variation in the LC also, so your compensator design is very critical when you are talking about the worst-case-based design scenario.

Then, you need to consider the fault protection and the startup logic. These are also very important and this can be slightly difficult in voltage mode. Because if you take a startup in voltage mode startup logic, you need to intentionally keep the process slow because there is no control over the current.

So, you need to make sure the current should not go out of you know the safe limit and this kind of single loop control may be difficult to optimize transient performance; but this statement is applicable for small signals. If you go for a large signal, you can even achieve the fastest responses in single-loop control. So, these are all design perspectives and we are mostly talking about the small signal-based design.

(Refer Slide Time: 10:23)



If you are talking about the current mode control, it is a good example of two-loop control, where you have an inner current loop which is an inductor current feedback loop, and this current loop gain is decided based on how are you sensing the current. Suppose, if you use a resistive sensor, then there is a sense resistance voltage of the sense; voltage will be that resistance into the current.

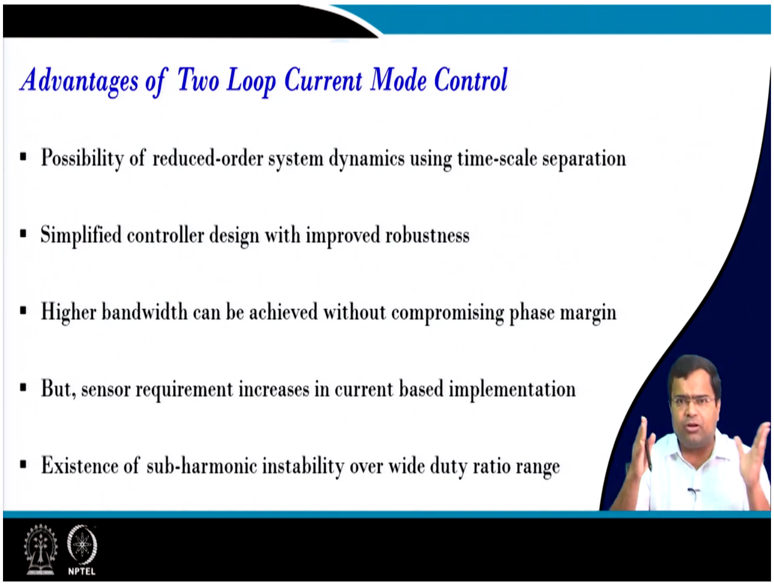
Then, after that you need to put a current sense amplifier; so, the gain of the amplifier. So, this k c is a combination of the sense resistance multiplied by the current sense amplifier gain. So, this whole will appear like a gain which will translate the actual inductor current to a sense voltage and this sensed voltage will constitute an inner current loop and this takes the current dynamics fast current dynamics.

So, you need to also consider a suitable current sensing method so that you do not lose vital information about the current. So, you need to be careful about the selection of the current sensing technique. Then, what is the right current sense amplifier, the bandwidth and all will come into the picture?

Then, the outer loop is typically a voltage loop and this feedback voltage gain is mainly due to the resistive divider because we need to step down the voltage and this voltage will be taken as the input to the compensator which is an op-amp and we need to make sure that such voltage should not exceed you know or the error. It should not saturate the op amp because op-amp in most commercial products the op-amp will have a single supply rail and it is 0 to 3.3 or even less depending upon the process technology.

So, you have to be careful about the selection of this feedback gain. Then, you have a reference voltage and error voltage and which is multiplied by the voltage controller we have discussed in detail in lecture number 15 as well as lecture number 38 and 39 on how to design a voltage compensator for current mode control. So, you can get detail about this. So, we are not discussing; but we need to first recapitulate the analog current mode control which is a two-loop control.

(Refer Slide Time: 12:35)



What is the advantage? Because of the two loops actually, you have an inner current loop and the outer voltage loop and if you take the transfer function between this point to this point by closing the inner loop, you will get because originally the DC-DC convertor, if you take voltage mode control or direct duty ratio control; that means, we are directly controlling the duty ratio. Then, the dynamics will be driven by this LC. So, you will get naturally you will get a second-order behavior due to the LC pole, you know the filter.

Now, when you close the inner current loop, then you are essentially making the inductor behave like a control current source and virtually, the system will behave like a first-order system. So, by closing this feedback inner loop, you can make the system, the control to output transfer function between this point and this point like an approximate first-order model. And that will simplify the design. This is one of the major advantages of using current mode control. So, you can get a reduced order you know dynamics using time scale separation because you are making the inductor like a control current source.

So, basically that we are assuming that inductor dynamics is pretty fast compared to capacitors, so the pole due to the inductor will go far left-hand side. So, you can get a time scale separation. Then, because you can approximate by a first-order model, so you can simplify the design, and controller design and you can get a very improved robustness because there is no L dependence in the design.

So, you can make the design much more robust. Even there is a variation in the inductor because as long as you control the current properly, there is no problem and you can achieve very high bandwidth without compromising phase margin. But there might be a problem in current mode control because you are only making a first-order system, the response can be sluggish and you may end up with a very over dam response if you try to push the bandwidth to achieve a fast response, then we have discussed in our earlier lecture, the model validation is a concern.

So, you cannot go even beyond one-fifth of the switching frequency. Then, your model will start diverging and the design is invalid. So, within that limit, if you want to design this over-damping system, then you may have some problems and we have discussed how to overcome them.

Either you can add directly load current feedforward or we can incorporate some kind of voltage derivative action by replacing the inductor current. If you consider the voltage derivative action, this inherently retains the inductor dynamics plus it also adds the indirect load information. So, you can achieve a very fast transient using this technique.

But one of the major difficulties is the current sensing. If you are going for a high-frequency application, then there can be some problems in the current sensing. But if you go to an integrated circuit; that means IC, then you can play with various current sensing techniques. You can sense just the high side current using R_DS_on; that is switch, you can use some kind of you know current mirror and you can sense the current.

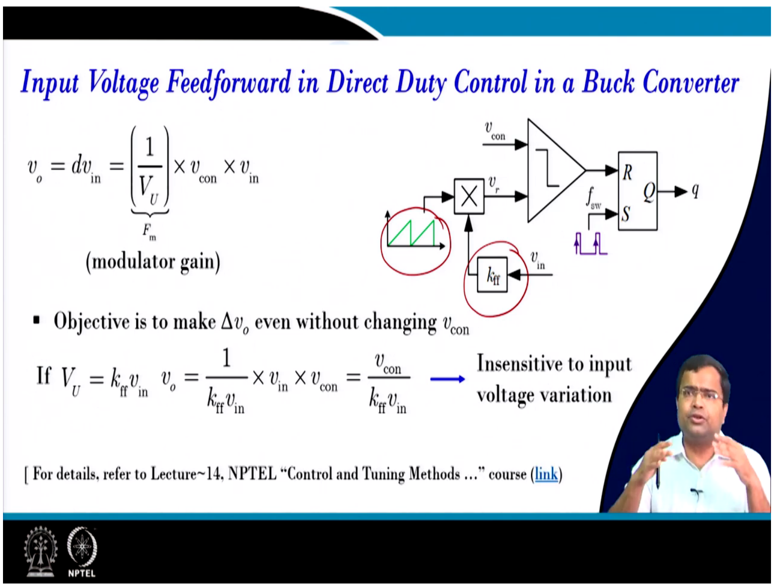
But depending upon what kind of current mode control are you going for because we know about peak current mode control, we know about valley current mode control, we know about average current mode control. So, based on our type of control, then we need to particularly sense the current.

For peak current mode control in a buck converter, we need to sense high-side current. For valley current mode control, we need to sense low side current and it is much easier to sense low side current that is why we have also discussed you know the commercial product, the latest product is going towards constant on-time current mode control. So, we have discussed this in our earlier course.

But in current mode control, fixed frequency let us say peak current mode control or valley current mode control, we saw there is a stability issue in the inner current loop and particularly when you deviate from the fifty percent duty ratio. For peak current mode control, if you go even below 50 percent and above, I mean let us say around 0.4 or so go above, you may end up with the inner loop current loop instability for closed when the whole both the loops are closed and you are operating at a higher gain. So, you may end up with sub-harmonic oscillation.

Similarly, for the valley current mode controller at a low duty ratio, we will let you know the substantial sub-harmonic oscillation problem and we also discussed to overcome we need to add RAM compensation. But excessive RAM can also make the system slow, it will behave like a voltage mode control.

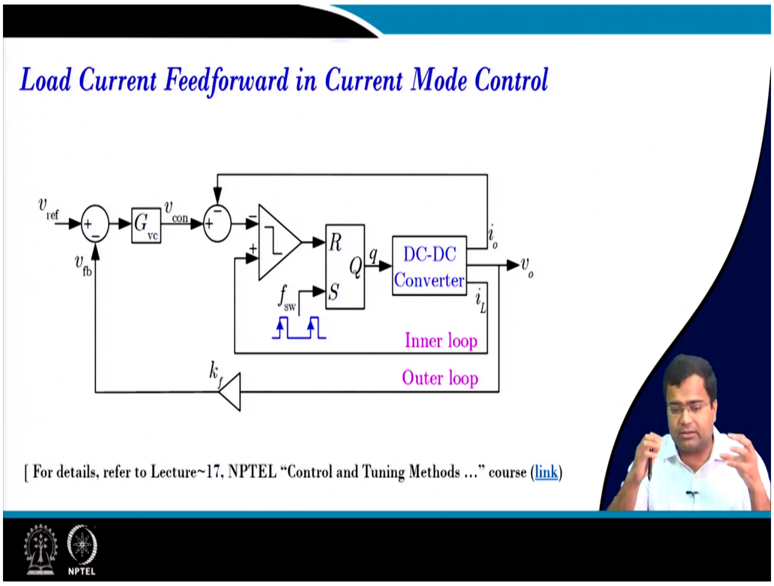
(Refer Slide Time: 17:12)



So, these aspects are discussed in the previous lecture and we have also discussed the input voltage feedforward because voltage feed controllers suffer from you poor line regulation as well as audio susceptibility. So, you can you know make the output voltage more or less insensitive to input variation in a buck converter, if you can change the RAM.

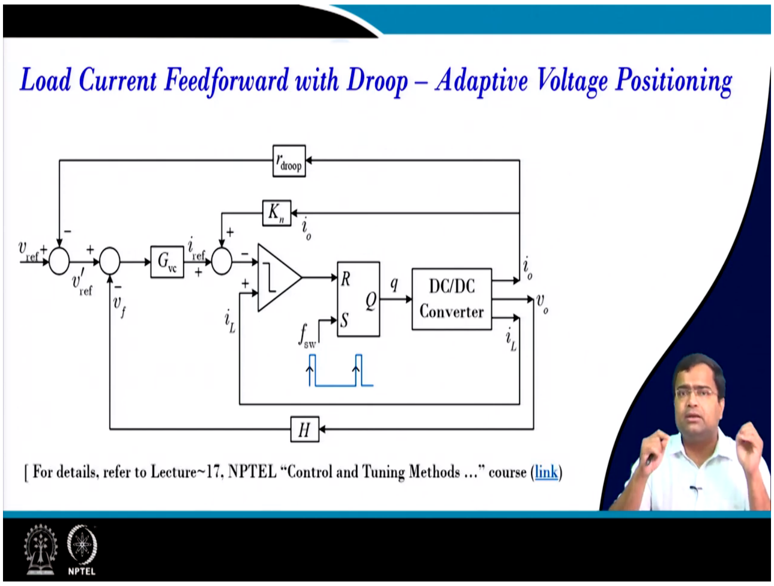
That means, this RAM slope can be adaptively varied based on the input voltage and this can be implemented using a voltage control current source and this current source can charge a capacitor to generate the short waveform. So, this can be and many commercial IC uses that. And we have discussed this aspect in lecture number 14. So, you can refer to it for further detail.

(Refer Slide Time: 17:56)



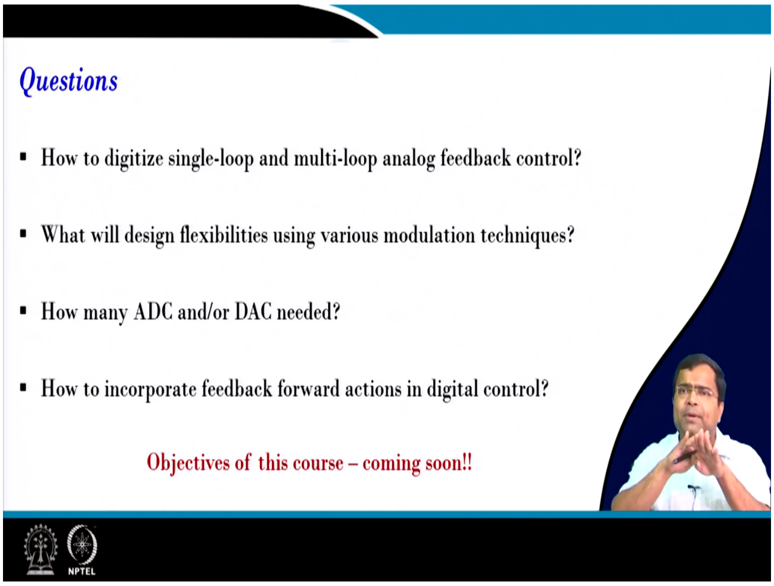
Similarly, we have also discussed load current feedforward in current mode control, which can make the output impedance resistive droop; and you can have an ultra-fast transient and suitable design that can lead to time optimal recovery and this also we have discussed in lecture number 17 that the load current feedforward methodology.

(Refer Slide Time: 18:19)



We have also discussed along with load current feedforward, if we incorporate the droop mechanism, then you can achieve a very fast transient and you can make the output impedance virtually look like a resistance so that it will be almost frequency-independent output impedance and you can respond to the load transient very fast, almost instantaneously. So, this aspect also we have discussed in lecture number 17. So, we have discussed it.

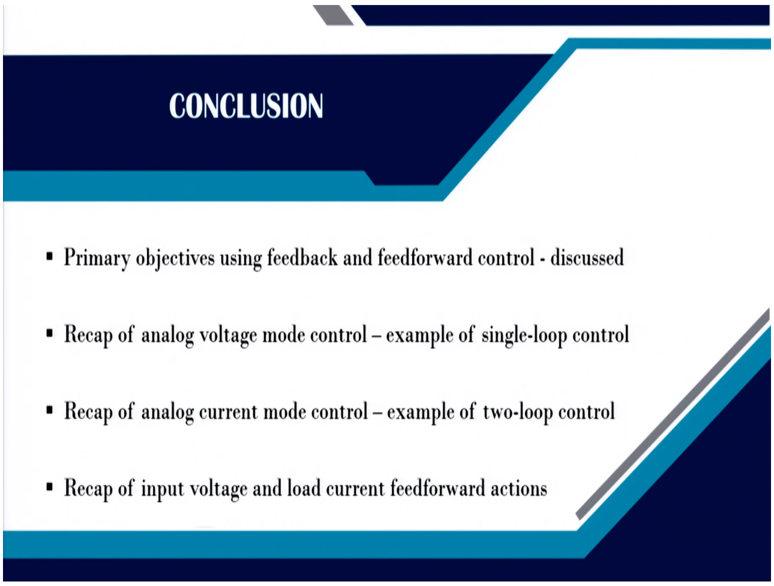
(Refer Slide Time: 18:46)



Now, the question is when you go to digital control, how do digitize this single loop and multi-loop that we have to recapitulate in our analog control right, in this lecture? These are the question that we will be addressing throughout the course. Then, what is the design flexibility, and what will design flexibility be using these various modulation techniques?

Then, how many ADC and DAC will be needed to realize digital control, then how it incorporates feedforward action in digital control? So, for this these are one of the objectives of this course and this will lead to various architectural development using digital control. Even for peak current mode control, you can have three-four types of architecture in digital from the implementation point of view. So, you need to wait for this architectural exploration which will be coming soon.

(Refer Slide Time: 19:38)



So, in summary, we have discussed, we have summarized the primary objective using feedback and feedforward control. Then, we recapitulated analog voltage mode control, an example of single-loop control. We have discussed current mode control which is a two-loop control example, then we have recapitulated input voltage and load current feedforward action in the subsequent lecture, we will slowly digitize this analog loop and we want to see the number of ADC and DAC requirements.

So, with this, I would say that this is the first step to go for digital control and the method of digitization that will be discussed in the subsequent lecture. So, with this, I will finish it here.

Thank you very much.