Control and Tuning Methods in Switched Mode Power Converters
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Module - 11
Large Signal Controller Tuning
Lecture - 52
Large-Signal Controller Tuning in Fixed and Variable-Frequency Control

Welcome. This is lecture number 52. In this lecture, we are going to talk about Large-Signal Controller Tuning in Fixed Frequency and Variable-Frequency Control.

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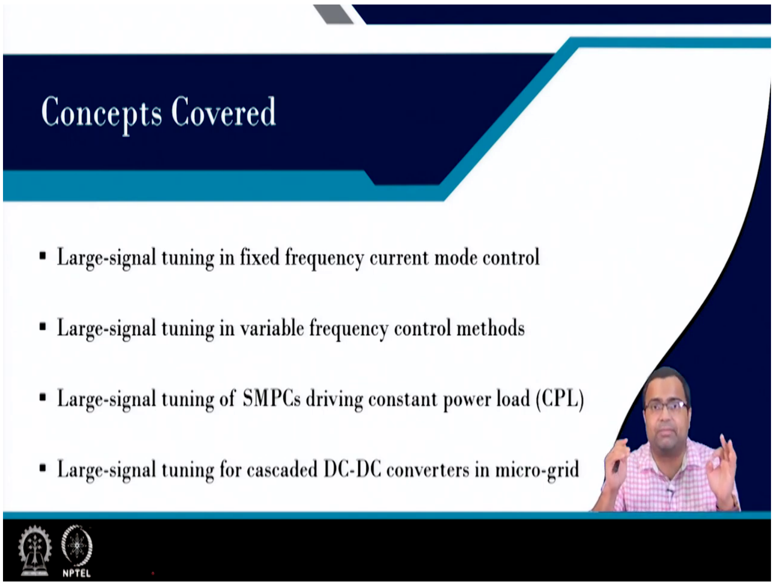

Concepts Covered

- Large-signal tuning in fixed frequency current mode control
- Large-signal tuning in variable frequency control methods
- Large-signal tuning of SMPCs driving constant power load (CPL)
- Large-signal tuning for cascaded DC-DC converters in micro-grid

That means in this lecture, we are going to talk about how the tuning method that we have learned. Large-signal based tuning method that we have learned in the previous two lectures, how it can be implemented across various modulators. That means, we can use a fixed frequency modulator, that we have I have already demonstrated.

Then, we have we can also implement in variable frequency modulator. So, different modulator that we can discuss. So, that means, fixed frequency current mode control, then variable frequency control method, then I will also talk about large-signal tuning for DC-DC converter or switch mode power converter while driving constant power load, because the constant power load is very now you know kind of very important topic.

Because you know we are talking about data center application, we are talking about electric vehicle application, micro-grid application, and such large-signal tuning for cascaded DC-DC converter in micro-grid application. So, these are the thing that we are going to discuss today.

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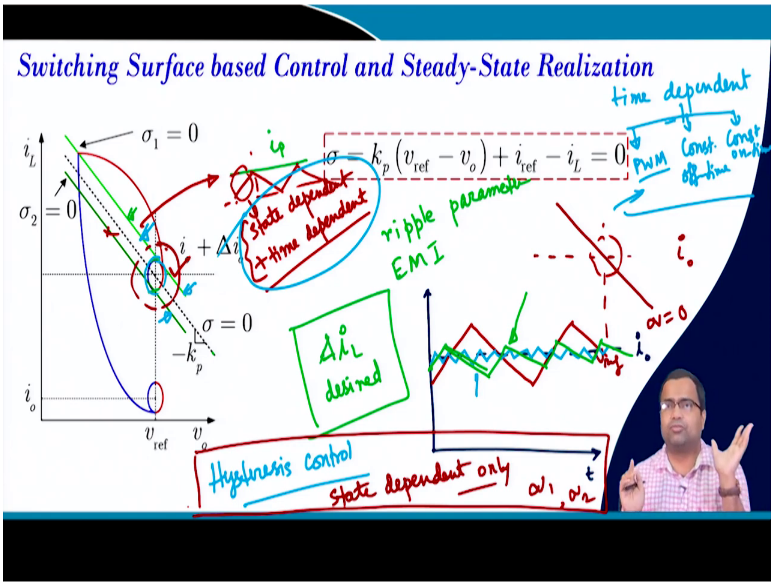

Switching Surface based Control and Steady-State Realization

$$\sigma = k_p\left(v_{\text{ref}} - v_o\right) + i_{\text{ref}} - i_L = 0$$

So, first, you know this part we have discussed. That means, if we want to realize our controller tuning this sigma x, which is nothing but the switching surface and which takes the air voltage into proportional gain plus the current air, ok. Now, we have seen that this sigma is nothing but the dotted line, right? But in reality, when we want to implement we never use this ideal sigma here. Why?

Because we cannot expect the switch will turn off, and this sigma it is not like that. So, if you want to just try to keep the trajectory very close to that sigma, then, or in this case, you know it cannot be because it will actually move away. So, we cannot turn use this sigma because this is particularly important when you come to a steady state. That means I am trying to highlight this particular part.

So, if you take the sigma here, ok, this is the line, this is let us say sigma equal to 0, and suppose this is my trajectory, that means, I want to operate like this or I want to because this is under steady state, so I can I can remove this. So, I will choose one operating point here, that mean let us say this is my operating point, and this is my operating point, this is my load current, this is my reference voltage.

Now, I want to operate. So, there is one possibility, that means, the trajectory can operate very fast, that means, very, very fast. That means, it turns on and off, like inductor current can be negligibly small, very, very small. This can lead to some 100s of megahertz switching frequency and your device can get barred because it can get it can damage because this is kind of chattering behaviour and you may not get any fix switching frequency, ok, arbitrary switch.

So, we cannot realize an ideal switching surface, ok under steady state. So, we need to introduce some kind of ripple; we need to allow some kind of ripple, right? So, our basic objective is that we want to allow, that means, we have identified that if I draw the inductor current waveform the timing diagram; I am talking about the scenario during this part, this part. So, there is one possibility we can have inductor current like this, like this.

There are other possibility, that means, if I keep this average value constant, this is my i 0. We can also operate like you extremely fast switching. But this may not be desirable because very high switching frequency may you know lead to lot of switching loss and if your device does not support such high switching frequencies, it can damage the device. So, we need to select properly the switching frequency.

Similarly, the red one may not be desirable because the ripple may be too large. So, you may need even some other like sorry, so you may need something like, so ripple. So, I should be flexible. So, who decide this ripple? Whether large small whatever, so this comes from the design point of view. That means, what is my acceptable ripple? Then what is like because it will help.

So, what are the parameter in a steady state? Ripple parameter is one. Then, EMI filter, because if we do not specify what is my operating frequency, the switching frequency, then it will be very hard to design a EMI filter because EMI filter should not be designed for a wide switching frequency range because it is like a low-pass filter. So, then you need to put the bandwidth to be very low and that can affect the transient response of the converter.

So, we need to provide some kind of band of switching frequency, some narrow band. I do not want to vary beyond that. Even if you go to automotive product, generally most of the switching converter operate close to 2 megahertz switching frequency, that is the standard norm from EMI point of view.

So, the objective is that we have some ripple constraint, that means we cannot reduce too low, then the switching frequency will be very high. And that switching frequency can lead to lot of switching loss and the efficiency can drop. We cannot have a very large current ripple.

So, who will decide? That means, some delta i L which will be desired that, I need to say the desired current ripple, ok. But how can we incorporate such desired current ripple here? That means, I want to implement the switching surface, so we cannot implement a perfect switching surface for this operation.

So, one way we can use the top surface, that means, if we add some delta the green one, as my let us say it is my peak current, something like that, and then this is my peak current, and this the bottom side of a ripple current will be decided by my pulse width modulator, time period. That means, this I mean we are using one state dependent switching plus time dependent switching.

So, it is a combination of state dependent and time dependent and the pulse width modulator put a time constraint, that means your sum of on and off time should be constant. But the state dependent switching, if we use the trailing edge modulation, then the on time come from this logic, ok. And the time dependent comes from the timing, like you know what is your time period.

So, the bottom line is this green colour can be used as this peak current and then in pulse width modulator, we are actually not using this surface. That means, because it is a trailing edge modulation, it just operates based on this one. So, how then, how can I ensure that it will track in an average sense? So, then you have to either decide that I will provide some ripple that will follow target trajectory.

So, it is a trajectory shaping problem. So, one of the objective, that means, we can, and that is exactly we did in the previous lecture. When we derive the optimal parameter, we have ignored the effect due to the ripple. And that is why we are getting slight mismatch, but that is ok. But there we are, using a fixed frequency modulator. So, there is a constraint, that means, you may not get perfect time optimal because of this.

But if we use a combination of state dependent and time dependent, this combination, then the time dependent, time dependent you have three options, one is PWM, where the time period is constant, the total time period is constant. One we know constant off time, where the off time is constant, and the other is constant on time. So, there are three choices, if I do time dependent, one I take total time is constant that is my PWM, then you can use either trailing edge or leading edge. Constant off time, when the off time is constant or the constant on time.

So, these three can be set to decide what will be my ripple, but in either of these, each of these techniques, it only uses one surface and the other surface is open, that means, that is driven by the timing parameter. But if you take a hysteresis control, hysteresis control and that we have discussed, that this band is represented by hysteresis.

So, hysteresis control it gives a direct because it is nothing, but the state dependent in both sides. So, it is state dependent only. There is no time dependent. That means, this requires both sigma 1 and sigma 2, that means, top and bottom surface, where the average will be your actual sigma, ok.

So, in this lecture, we are going to talk about the tuning parameter that we have derived that equation will remain same, but you can change the modulator, that is it, ok. That means, the whatever we have derived that will remain same. So, we can apply that large-signal tuning both for fixed frequency modulation, then constant off time, constant on time as well as the hysteresis control.

So, all types of across the modulation technique as well as the variable frequency control technique that we have learned in the previous lecture are equally applicable, I mean the large-signal tuning. You know all these different fixed frequency and variable frequency implementation we have learned in the very beginning. Like you know, first or second week, that we can bring back and we can apply this large-signal tuning for any of this control strategy.

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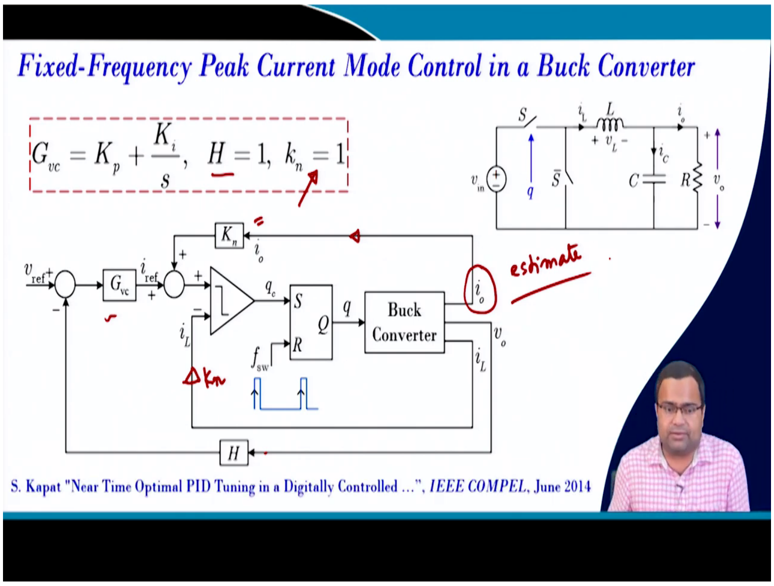

Fixed-Frequency Peak Current Mode Control in a Buck Converter

$$G_{vc} = K_p + \frac{K_i}{s}, \quad H = 1, \quad k_n = 1$$

S. Kapat "Near Time Optimal PID Tuning in a Digitally Controlled ...", IEEE COMPEL, June 2014

So, the first we will talk about peak current mode control. We are using a load current feed forward and this normalization factor will be one for buck converter and the feedback gain, so you can incorporate. Once you want to use the feedback gain, then accordingly you have to scale this parameter, because we are using a feedback gain.

So, in current mode control, we are for buck converter. The normalization factor is 1, that means, we are directly taking load current. But if we use any feedback gain for the current loop, the same gain, that means, this is also K n. If you let us say K n equal to 0.5, then this K n should be 0.5. That means, the load current and the inductor current they should be in the same scale.

Now, this question may come, this relation requires again sensing a load current. But suppose you are talking about, you are driving an LED using a buck converter, right or you are driving a let us say you know constant power load, or you are driving for example, in micro-grid application, we talk about droop control, right, where we sense the load current because we want to adjust the droop. So, there is also available.

Similarly, if we talk about LED driving, LED available, right or you know battery charging does not require fast transient. So, that is, that does not come into the picture. Even for processor application you know this load current can be estimated because if you can understand that the task requirement, if you can interact with you know the power converter, power management unit with the actual processor load task scheduler, right? And in digital control, that may be possible.

So, you can know a priori that the load transient is going to come, and the step size of the load can come based on the task intensity like how much energy is required, right? But otherwise, you can estimate this load. So, you can estimate this load current. And we have already shown that even you can apply this tuning to voltage mode, where you do not need to sense inductor current or load current, right? So, that is also possible. So, that means, you can apply.

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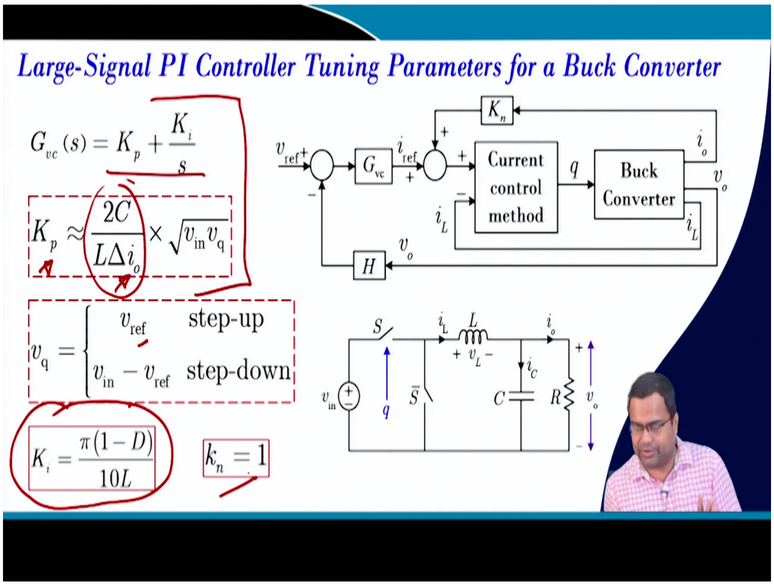

Large-Signal PI Controller Tuning Parameters for a Buck Converter

$$G_{vc}(s) = K_p + \frac{K_i}{s}$$

$$K_p \approx \frac{2C}{L\Delta i_o} \times \sqrt{v_{in} v_q}$$

$$v_q = \begin{cases} v_{ref} & \text{step-up} \\ v_{in} - v_{ref} & \text{step-down} \end{cases}$$

$$K_i = \frac{\pi(1-D)}{10L}$$

$$k_n = 1$$

And this is already reported. Then you can apply this technique for current mode control that we have just now apply. So, current mode control where the tuning parameters, we have already discussed, right earlier. That means, if you take a PI controller for the current loop the proportional gain is nothing, but it is the function of your L, C. That means, the inductor capacitor, the step size of the load, square root of input voltage v q, where it is equal to v ref for refer step up and v in minus v ref for step down, ok.

And we have already discussed that K i equal to it is we have derived this integral gain from small signal model, and k n is the normalized frequency.

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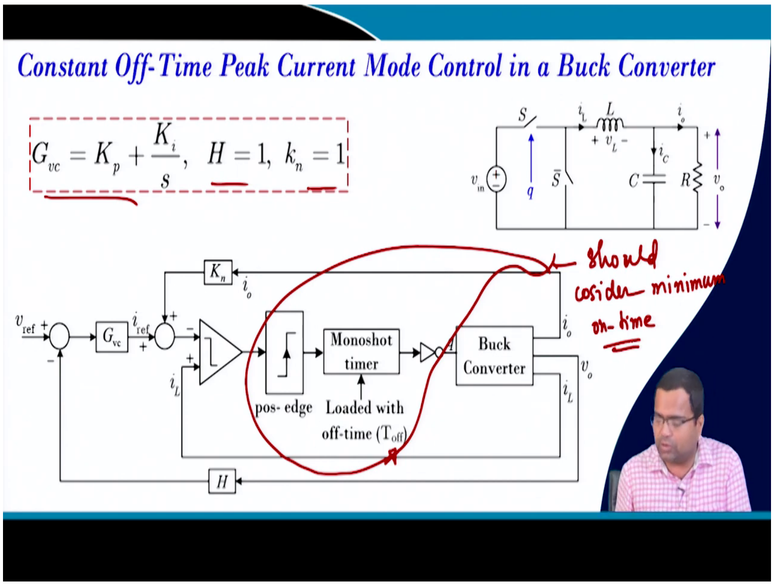

Constant Off-Time Peak Current Mode Control in a Buck Converter

$G_{vc} = K_p + \frac{K_i}{s}, \quad H = 1, \quad k_n = 1$

should cosider minimum on-time

So, now we can also apply constant off time because this is analogous to peak current mode control and constant off time. In fact, we will discuss in the last week or the next week, when we take the case study and show MATLAB simulation. So, if we apply peak current mode control, if we apply constant off time control, and then if we apply constant on time control, using the same control again how is it going to respond, what are the change difference in the response, right.

So, in this case, we are again considering PI control, H equal to 1, K n equal to 1, but we need to set the right off time, so that our time period is maintained at the desired value or at least close to the desired value.

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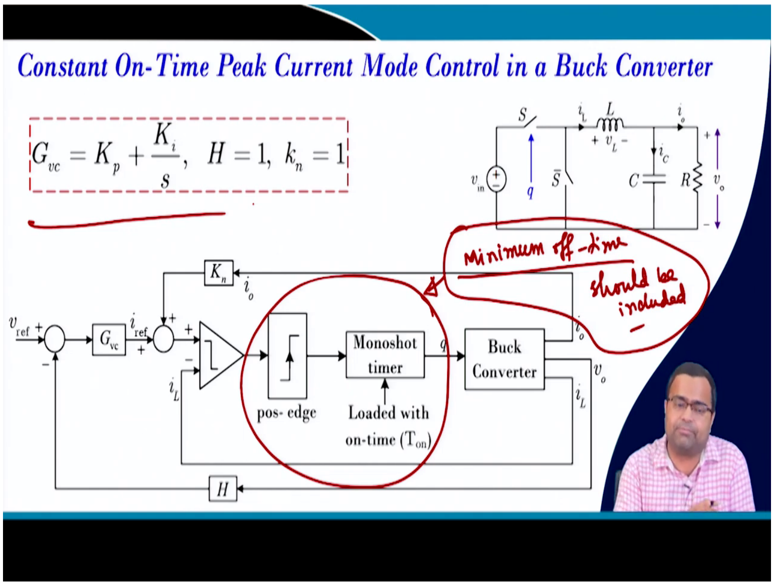

Constant On-Time Peak Current Mode Control in a Buck Converter

$$G_{vc} = K_p + \frac{K_i}{s}, \quad H = 1, \quad k_n = 1$$

Minimum off-time should be included

We can all also apply to constant on time. So, it is only we are changing the modulator. In fact, I have discussed this is not so simple the constant on time because here it is just for sake of simplicity, we have just taken the constant on time modulator, but it should also include the minimum off time that also need to be, should be included.

Here just to show the logic I have shown, but this should be included and that we have discussed in detail in I think week 2, ok. Otherwise, it will collapse. And we have also discussed in a I think week 4, youth implementation that we should include that minimum on time for constant off time control and minimum off time for constant off time on time control, otherwise it will collapse during the transient.

So, similarly, if we take this one, we should incorporate here, we should incorporate, should consider minimum on time, ok, should consider minimum on time. Here also, the same tuning parameter that I have derived can be used. And again, I am telling we will go in the next week and so on by solve the case study in MATLAB.

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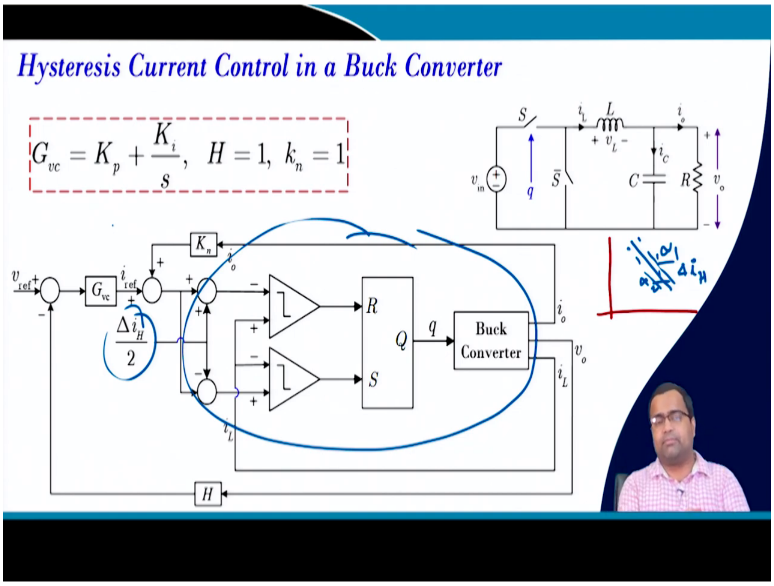

Hysteresis Current Control in a Buck Converter

$G_{vc} = K_p + \frac{K_i}{s}, \quad H = 1, \; k_n = 1$

Now, if we implement hysteresis control, that also we can do. In fact, this will be the perfect solution because we have talked about if we take the phase plane or actual switching surface was this and then we have created this band, sigma 1, sigma 2, and we have introduced something like a delta i H hysteresis band. And then that band we can divide and we can implement.

So, it is a hysteresis control that we have already discussed, and the same controller parameter, that means, this optimal tuning will work for fixed frequency control, hysteresis control, constant on time, constant off time and we are going to show result in the next step.

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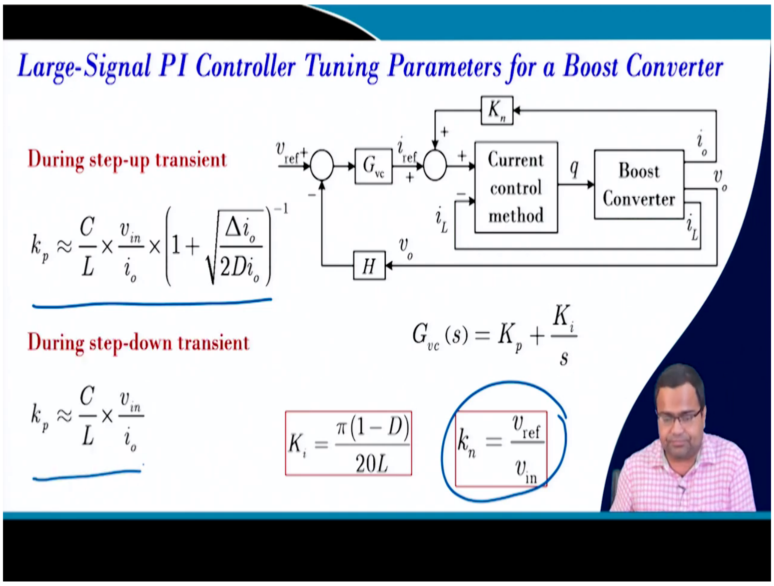

Large-Signal PI Controller Tuning Parameters for a Boost Converter

During step-up transient

$$k_p \approx \frac{C}{L}\times\frac{v_{in}}{i_o}\times\left(1+\sqrt{\frac{\Delta i_o}{2Di_o}}\right)^{-1}$$

During step-down transient

$$k_p \approx \frac{C}{L}\times\frac{v_{in}}{i_o}$$

$$G_{vc}(s)=K_p+\frac{K_i}{s}$$

$$K_i=\frac{\pi(1-D)}{20L}$$

$$k_n=\frac{v_{ref}}{v_{in}}$$

Now, if you take a boost converter, again, we can do current mode control with normalized load current feed forward. And here the normalization factor will be v ref by v in. And we have derived for step up transient, the proportional gain can be approximated by this. For step down it can be approximated like this.

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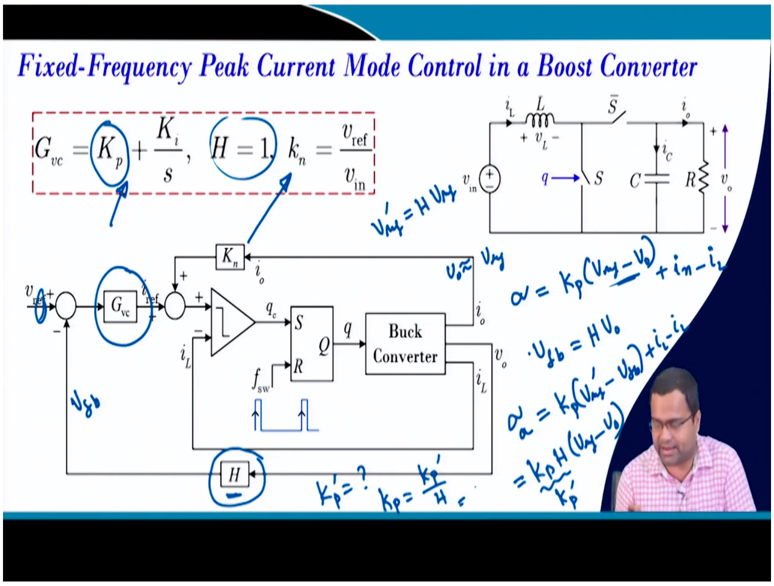

Fixed-Frequency Peak Current Mode Control in a Boost Converter

$$G_{vc}=K_p+\frac{K_i}{s},\quad H=1,\quad k_n=\frac{v_{ref}}{v_{in}}$$

Now, we can implement in fixed frequency control. We have to set the right parameter, ok. It is the PI controller. k n equal to this, that means, sorry, this is the k n. So, our k n equal to this. Then feedback gain if I take directly the output voltage. Or if we incorporate the feedback gain, then how are we going to change the gain that have to scale. Because since your output voltage is scale, that means you can think of; if we go back towards sigma, what are our sigma? Our k p v ref minus v 0 plus our normalized current minus the load current.

Now, if we use the step-down ratio here v 0, that means, let us say we are talking about v feedback. This is my v feedback, which is nothing, but H times of v 0, right? So, we cannot use suppose if we are sensing the feedback voltage, so then our actual, so this is like an actual realization will be k p v ref dash minus v feedback plus i n minus i L. And this can be written as k p. What is v ref dash? v ref dash is nothing, but H into v ref that means whatever factor you will multiply with the output voltage.

That means, whatever step-down ratio you consider here the same step-down ratio you should consider here, because you need to scale v ref. So that our ultimate objective to reach v you know v 0 to be nearly equal to v ref. That is my final objective, right? So, if you do that, that means I can take the feedback gain out v ref minus v 0. Now, it is v 0.

So, this you can think of our k p dash. That means our k p dash. That means this is our proportional control, but this is not the optimal gain. So, that means, whatever we have formulated it was k p dash that we have formulated. That is the optimal gain. So, our actual k p will be, actual k p will be k p dash divided by H, right because k p into H is your k p dash. So, it is just a scaling factor.

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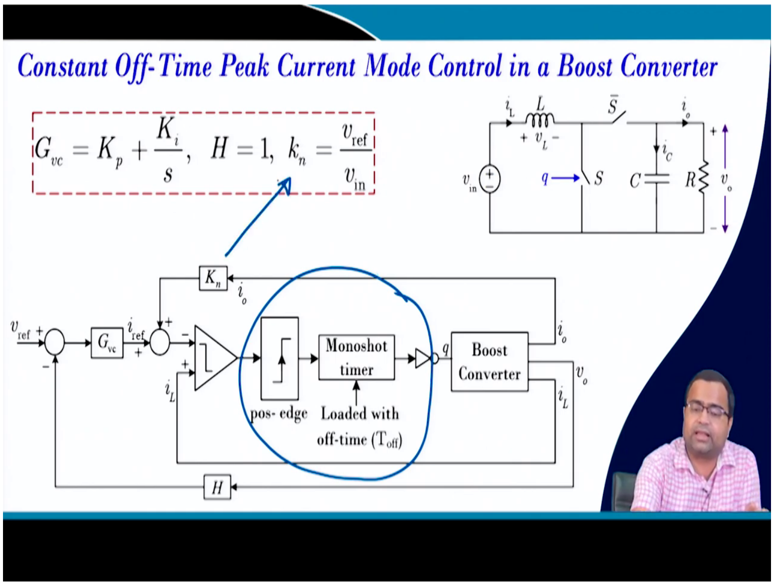

Constant Off-Time Peak Current Mode Control in a Boost Converter

$G_{vc} = K_p + \frac{K_i}{s}$, $H = 1$, $k_n = \frac{v_{ref}}{v_{in}}$

Now, for constant off time, again we can we have we should along with this we should use minimum on time, and then same PI controller, same normalization factor that we have discussed, like that we can use.

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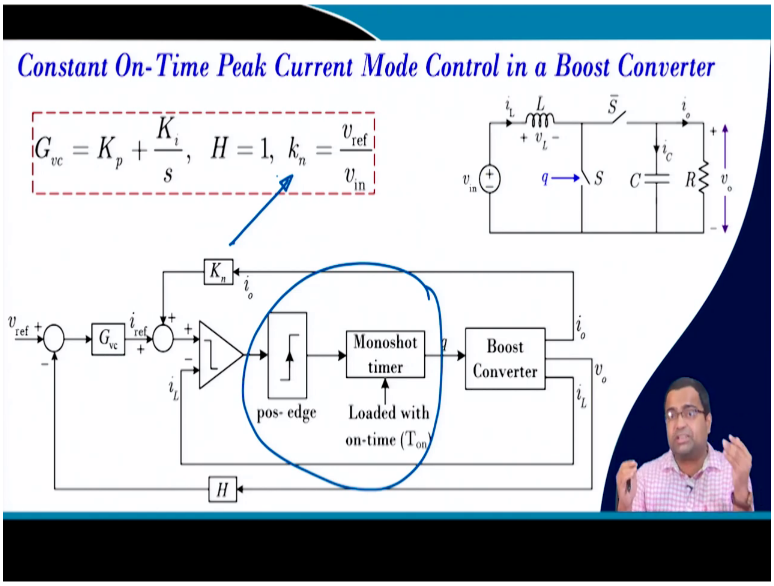

Constant On-Time Peak Current Mode Control in a Boost Converter

$$G_{vc} = K_p + \frac{K_i}{s}, \quad H = 1, \quad k_n = \frac{v_{\text{ref}}}{v_{\text{in}}}$$

We can we also implement constant on time, again we need to incorporate minimum off time and here also the normalization factor is this and same PI control. So, we will show you that if you use this optimal gain for different modulator, we want to check what is the difference in the performance and that we will consider.

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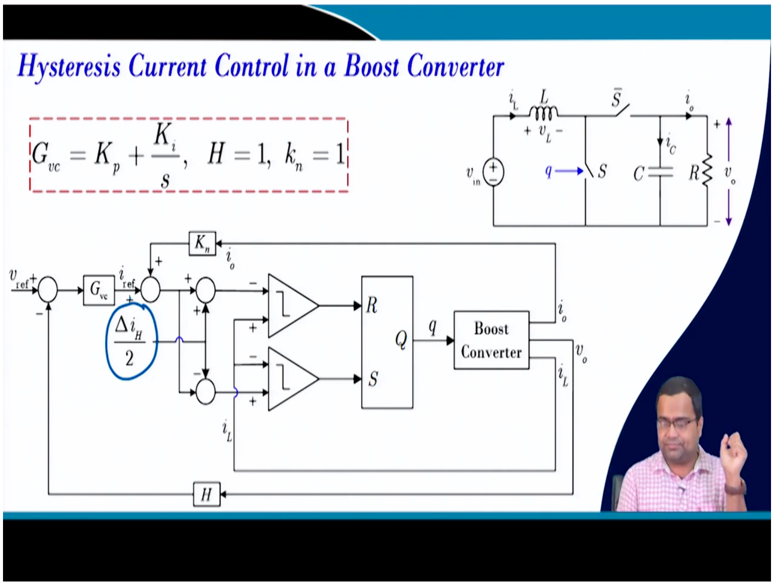

Hysteresis Current Control in a Boost Converter

$$G_{vc} = K_p + \frac{K_i}{s}, \quad H = 1, \quad k_n = 1$$

And we can also do hysteresis. In fact, we discuss that hysteresis is a more perfect solution. But remember, in voltage mode, in we should not use voltage hysteresis control for boost converter, because of the non-minimum phase behaviour. Because you know because of the non-minimum phase behaviour, under step up load transient response if the system can collapse, unless you put a limit on the time on time, ok.

So, this voltage hysteresis is controlled by adjusting is the hysteresis band, we can control the switching frequency. For the previous one, we can control the switching frequency by adjusting this on time. We can control the switching frequency by the adjusting this off time. And for fixed frequency control, it is already fixed frequency, time period is fixed. So, that means, we can implement all these logics.

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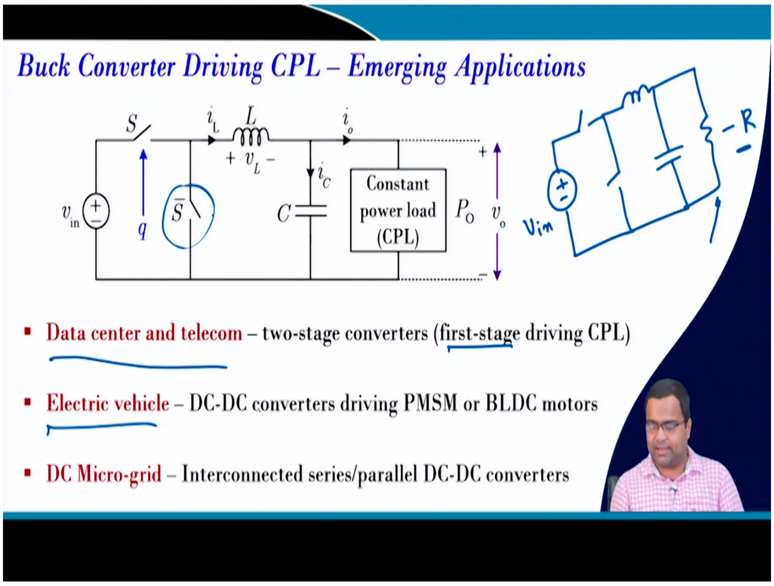

Buck Converter Driving CPL – Emerging Applications

- Data center and telecom – two-stage converters (first-stage driving CPL)
- Electric vehicle – DC-DC converters driving PMSM or BLDC motors
- DC Micro-grid – Interconnected series/parallel DC-DC converters

Next, we are coming about the constant power load. Because of the constant power load we can we can see many applications of constant power load. So, I am taking a buck converter, but this can be also extended for boost converter driving constant power load. Now, if you take data centre and telecom application, so two-stage converters are quite common, where the first stage, as if the second stage, is very tightly regulated, it is considered being constant power load.

So, the first is like driving a constant power load. The first stage is not tightly regulated, or it is not very high frequency, the second stage is much faster, so it is to there is a constant power load. Similarly, if you go to electric vehicle, so the DC-DC converter which is used for drive trail suppose your DC-DC converter which is connected between battery, and it is output is connected to let us say your BLDC motor drive or the permanent magnet synchronous motor drive, where the driver is driving an actual inverter load, right.

Now, when the car runs under constant speed, right, then it is the constant power load. That means it is delivering the constant power where the vehicle is running almost like a constant velocity, right? So, under this condition, then the DC-DC converter which is actually driving the driver of the motor, or basically the inverter, that inverter as well as the motor the whole thing will look like a constant power load to the DC-DC converter. And this is also another application where.

And it is well known this constant power load actually introduces the incremental negative resistance effect. That means, if it can be approximated like an actual buck converter. So, you know, and we have discussed in week 3, there was one dedicated session where we talk about cascaded converter, where I have shown you using simulation that you can, actually; suppose this is your buck converter inductor, and this is your capacitor, and this can be approximated as minus R, the incremental resistance load.

And we have shown that if we use an actual two-stage converter. And if you simplify the second stage is the constant power load, there will be slight deviation. But the average response is close, so the constant power load will introduce a negative incremental resistance effect and it will lead to open loop unstable system.

So, if you run this DC-DC converter under open loop, in general the open loop converter will be unstable focus. So, it will oscillation will keep on growing up, and if we apply a diode like a conventional buck converter, then it will get stuck because of the DC, the 0 current, and then it will it may you know lead to limit cycle oscillation. So, there is extensive research on that, but I am not going to that.

So, now in this constant power load also, our tuning method can be applied for both stabilizing the converter and to get the fastest response. And the micro-grid also we can have interconnected since parallel converter, where one of the converter can be treated as a constant power load and the other as if it is driving a CPL.

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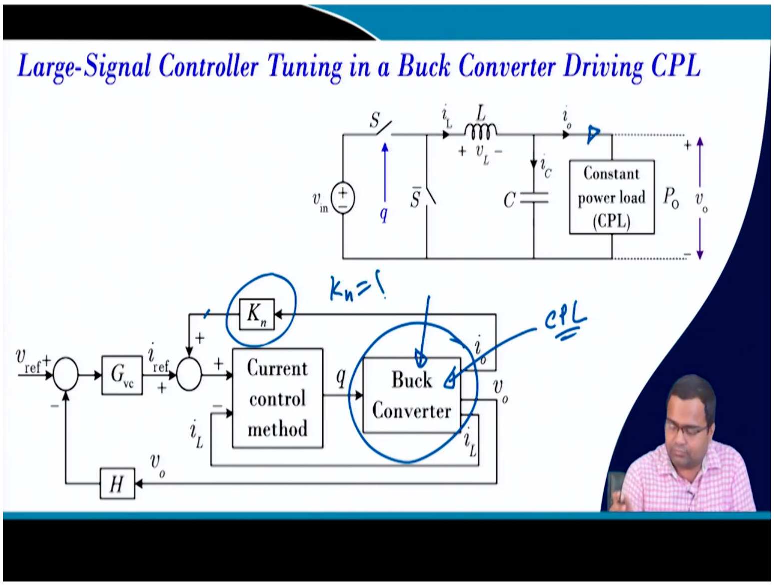

Large-Signal Controller Tuning in a Buck Converter Driving CPL

So, in large-signal CPL again this buck converter where the load is incorporated here, and we are sensing the load current. That means we are sensing this load current. So, here the CPL is also there. It is CPL load, is there. So, here the same method. We can take the normalized load current feed forward.

So, in buck converter, since the average inductor current same as the average load current, so this K n will be 1, ok. So, we can apply and we can set the tuning rule here. And we want to see what will be my tuning parameter when you are driving a constant power loop.

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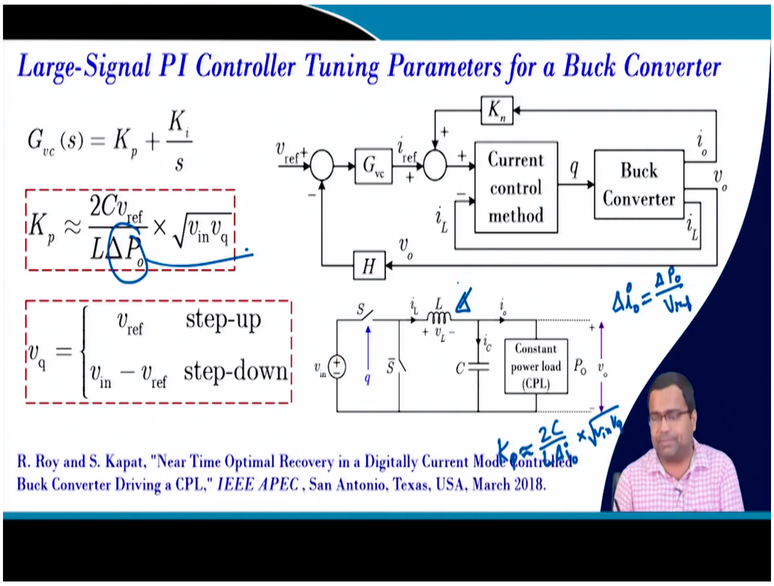

Large-Signal PI Controller Tuning Parameters for a Buck Converter

$$G_{vc}(s) = K_p + \frac{K_i}{s}$$

$$K_p \approx \frac{2Cv_{ref}}{L\Delta P_o} \times \sqrt{v_{in} v_q}$$

$$v_q = \begin{cases} v_{ref} & \text{step-up} \\ v_{in} - v_{ref} & \text{step-down} \end{cases}$$

$$\Delta i_o = \frac{\Delta P_o}{V_{ref}}$$

$$K_p \approx \frac{2C}{L\Delta i_o} \times \sqrt{v_{in} v_q}$$

R. Roy and S. Kapat, "Near Time Optimal Recovery in a Digitally Current Mode Controlled Buck Converter Driving a CPL," *IEEE APEC*, San Antonio, Texas, USA, March 2018.

So, if we set it K p equal to 2C because only thing here we are changing earlier this quantity, you know earlier it was for constant current load we got K p was equal to approximately equal to 2C by L delta i 0 into that your v in v q and v q also we have we know.

Now, here we have replaced delta i 0 equal to our power, sorry constant power yeah, if there is a step change in the power divided by our actual voltage, that is the reference voltage. So, voltage into current is the power. So, the voltage is considered to be nearly constant. So, any step change in power as if will be can be translated as a load and that can be replaced and we will get the same result, and this is way all this we have published. And this will lead to the optimal response for the buck converter driving CPL, ok.

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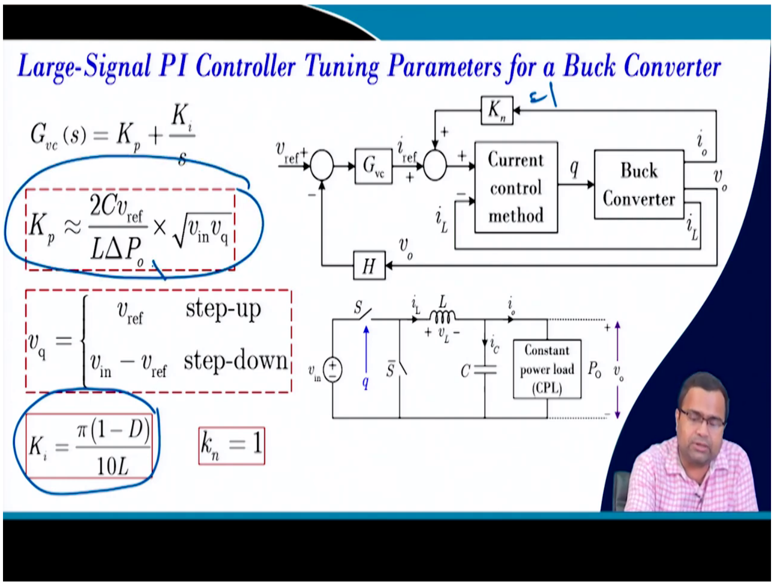

Large-Signal PI Controller Tuning Parameters for a Buck Converter

$$G_{vc}(s) = K_p + \frac{K_i}{s}$$

$$K_p \approx \frac{2Cv_{\text{ref}}}{L\Delta P_o} \times \sqrt{v_{\text{in}} v_{\text{q}}}$$

$$v_{\text{q}} = \begin{cases} v_{\text{ref}} & \text{step-up} \\ v_{\text{in}} - v_{\text{ref}} & \text{step-down} \end{cases}$$

$$K_i = \frac{\pi(1-D)}{10L}$$

$$k_n = 1$$

So, now, that means, the overall tuning parameter, if you want to drive constant power load, and again, we will consider this case study in the next week using MATLAB simulation, that means if you drive a constant power load using by setting this optimal parameter you can get the optimal recovery. It will not only stabilize, but it will achieve fastest transient response.

So, where the normalization factor is 1, and your integral gain it is coming from the, it is the same as the buck converter driving a constant current load is like a, it is coming from small signal model, and this can be derived, here this is the load power step.

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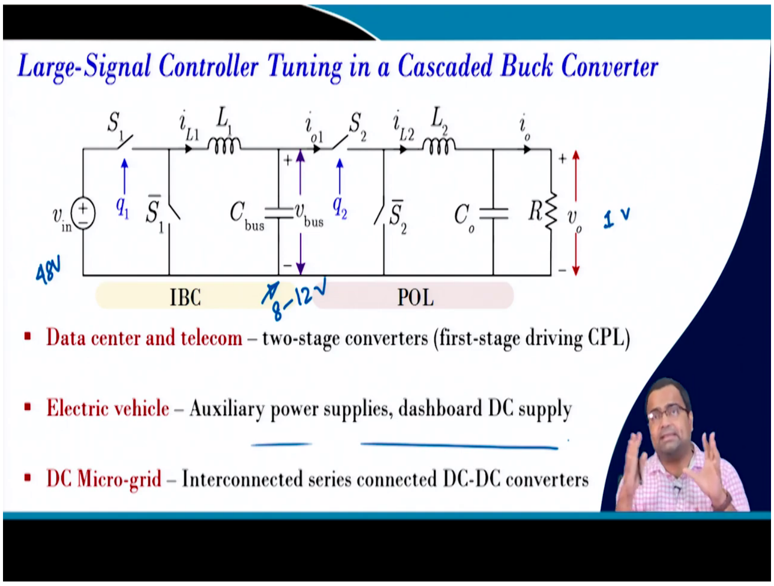

Large-Signal Controller Tuning in a Cascaded Buck Converter

- Data center and telecom – two-stage converters (first-stage driving CPL)
- Electric vehicle – Auxiliary power supplies, dashboard DC supply
- DC Micro-grid – Interconnected series connected DC-DC converters

Now, the constant power load was an in one case can be approximated like another converter, but it need not to be always two converters. This is one of the example. For example, I told you suppose a buck converter driving or a boost converter is driving a an inverter load which is diving a motor, right? So, the boost converter as if is driving the CPL, where the CPL can be treated as a constant power load.

But this is another application where the two converters are used and this is commonly used in data centre and telecom application, where suppose if we are using a very high voltage like you know earlier, like a 48 volt. So, here roughly it is nominal 48 volt. And this bus voltage is generally set to 8 to 12 volt, and the output is generally close to 1 volt. So, that means it is a two-stage converter, 48 to 12 or 8, then 8 to 1.

But now though there is like extensive research going on regarding direct conversion from 48 to 1 volt, but it is found that even if you use merging two converter, either you can use hybrid switch capacitor converter or isolated converter or merging these two converter, it turns out to be the effective solution if you use the two-stage architecture.

That means, in the first stage, generally people use the hybrid switch type architecture to step it down and in some time LLC converters are used which are very very efficient where you need to maintain very tight voltage regulation, like 48 to 12 volt. If you specify 48 to 12, then it can give very high efficiency and then the second stage you can use the multi-phase converter.

So, whatever it is the two-stage converter. Since the second stage is very tightly regulated, and it is a very high bandwidth, so this will look like a constant power load for the IBC. And ever if you consider two converters separately, so then we can also apply our tuning rule.

And this is also used for electric vehicle for auxiliary power supply, because if we are going for 12 volt battery, again you are generating very low voltage, either you can go two-stage or if you are using high voltage because in electric vehicle we have a high voltage battery, we have a low voltage battery. So, sometime we need to convert from high voltage to low voltage and then from low voltage battery is driving an auxiliary load. So, all this scenario you can come across two-stage converter as well.

And DC micro-grid, you can find multiple converter connector in since parallel value. So, it can constitute something like a two-stage architecture.

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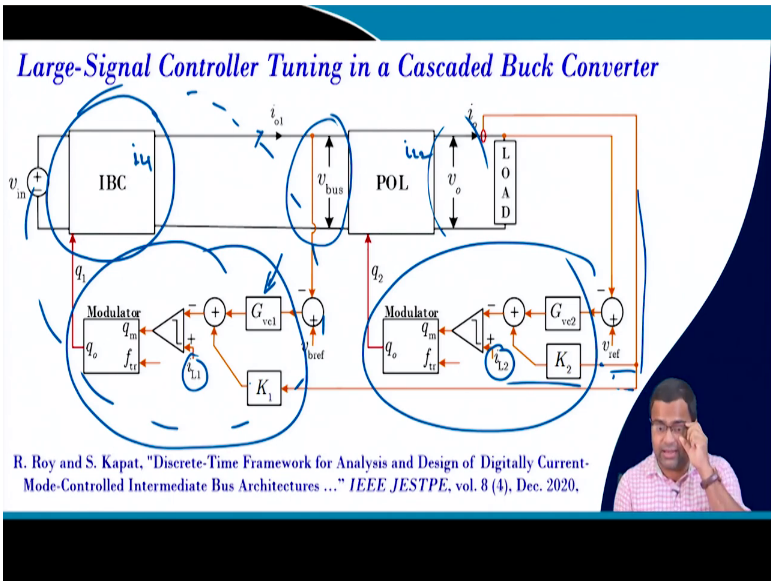

Large-Signal Controller Tuning in a Cascaded Buck Converter

R. Roy and S. Kapat, "Discrete-Time Framework for Analysis and Design of Digitally Current-Mode-Controlled Intermediate Bus Architectures ..." *IEEE JESTPE*, vol. 8 (4), Dec. 2020.

So, in such an application, we can apply our tuning rule, where the two converters are driven separately by two current mode control methods. This is its own current mode control, and this is it is another current mode control.

Again, each of them is like a buck converter where we can take any modulator that we have discussed, either you can apply fixed frequency control, either you can apply hysteresis control, either you can apply constant on time, constant off time, whatever control that can be applied. So, that is why it is a modulator.

And here each converter that we are going to see what type of controller structure we are taking. So, it is a current mode control. So, it is sensing the inductor current from here and we are also sensing the inductor current from here. So, both are current mode control.

And in this case, we are using a load current feet forward directly, that we have discussed. But for the first stage, we do not need to sense the load current here because we can extract the load indirectly from this expression by because we already know we are sensing the bus voltage and we are already regulating the output voltage. From till these two voltage information and the output current information, we can directly obtain what is the load current.

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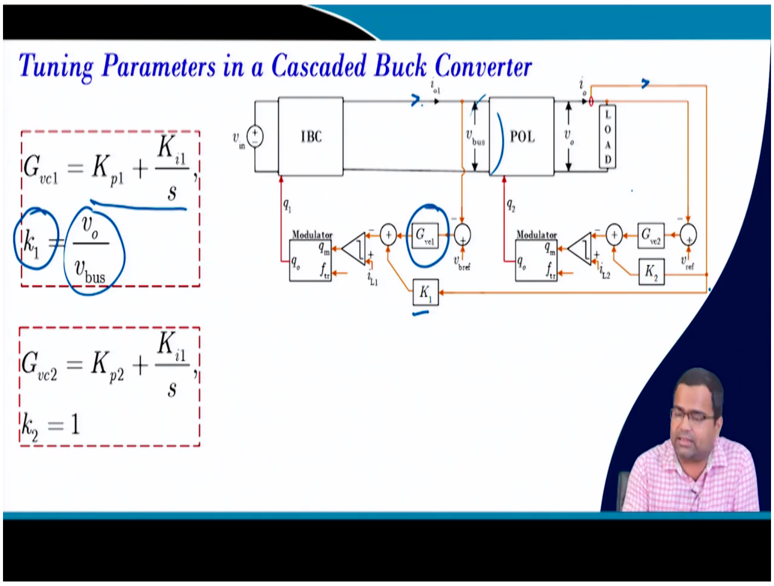

Tuning Parameters in a Cascaded Buck Converter

$$G_{vc1} = K_{p1} + \frac{K_{i1}}{s},$$

$$k_1 = \frac{v_o}{v_{bus}}$$

$$G_{vc2} = K_{p2} + \frac{K_{i1}}{s},$$

$$k_2 = 1$$

So, this we have already implemented, and we have shown the individual converter, we can. So, for the first stage IBC, it is again a PI controller. This is again a PI controller, and this gain k 1, I told you that it is scaling from output to this load current, right? Because this load current, since this voltage is high will be smaller than this load current. So, that is why it is a scaling by v 0 by v bus, because v 0 is lower than v bus voltage. So, it is the feed forward, but it is coming from the second stage.

Again, for the second stage, it is again a PI controller where the normalization factor is 1 here, ok.

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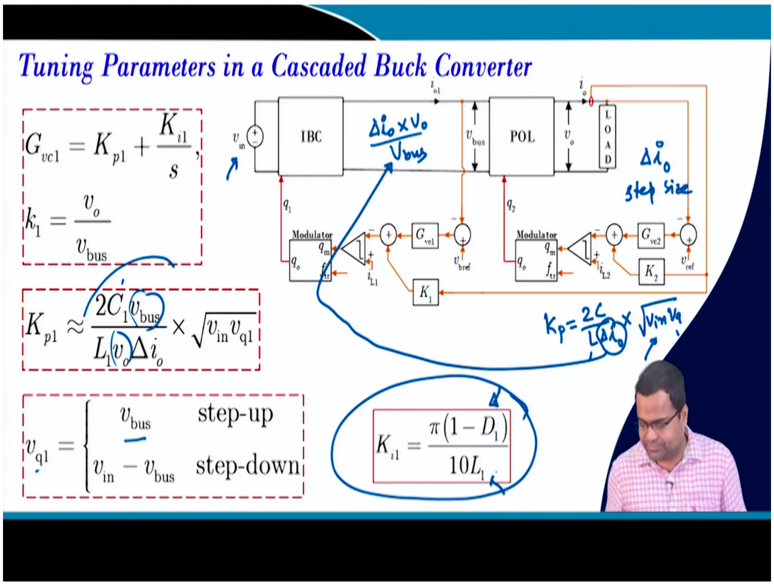

Tuning Parameters in a Cascaded Buck Converter

$$G_{vc1} = K_{p1} + \frac{K_{i1}}{s},$$

$$k_1 = \frac{v_o}{v_{bus}}$$

$$K_{p1} \approx \frac{2C_1 v_{bus}}{L_1 v_o \Delta i_o} \times \sqrt{v_{in} v_{q1}}$$

$$v_{q1} = \begin{cases} v_{bus} & \text{step-up} \\ v_{in} - v_{bus} & \text{step-down} \end{cases}$$

$$K_{i1} = \frac{\pi(1-D_1)}{10L_1}$$

$$\frac{\Delta i_o \times V_o}{V_{bus}}$$

Δi_o step size

$$K_p = \frac{2C}{L \Delta i_o} \times \sqrt{V_{in} V_q}$$

Now, we can apply this tuning parameter. So, the first stage the tuning parameter, since it is coming from this load step size. That means, if it undergoes a delta load step, step size, then we can easily apply. But remember, we are talking about the first stage, right? So, if there is a delta i 0 load step, here it will be reflected as delta i 0 into v 0 by v bus. That is why this factor is coming, v 0 by v bus is coming. Because what was our for a normal buck converter, we know k p is 2C by L delta i 0 into your v in into v q.

So, for the first stage, the input voltage is directly your input voltage, this one; v q that we have to find out. For the first stage, the output of this intermediate bus capacitor is C 1, an intermediate bus inductor for the first stage inductor is L 1. So, it is given. And this delta i 0 for the first stage is nothing, but that we have discussed is this one, right?

So, this is replaced. And what is this? So, v q 1, it leads to the output voltage; it is the bus voltage or v in minus v bus. And this is the same method that we are using where the D 1 is the steady state duty ratio for the first stage and L 1 is the inductor. Again, we are using this concept, ok.

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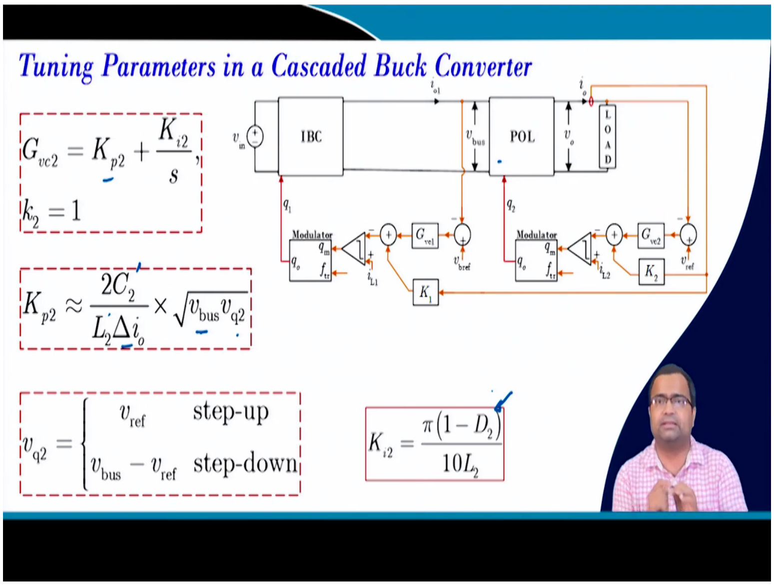

Tuning Parameters in a Cascaded Buck Converter

$$G_{vc2} = K_{p2} + \frac{K_{i2}}{s},$$
$$k_2 = 1$$

$$K_{p2} \approx \frac{2C_2}{L_2 \Delta i_o} \times \sqrt{v_{bus} v_{q2}}$$

$$v_{q2} = \begin{cases} v_{ref} & \text{step-up} \\ v_{bus} - v_{ref} & \text{step-down} \end{cases}$$

$$K_{i2} = \frac{\pi(1 - D_2)}{10 L_2}$$

For the second stage we can use K p 2, K i 2. That means, proportional gain two integral gain two K p 2 is step forward it is C 2 L 2 delta i 0, and here it is the bus voltage is the input for the second stage, right.

And what is v q 2? It is v ref or v r v bus minus v ref. And K i 2, again, it is D 2 L 2, only it will be updated this value and the normalization factor is this. And this thing we are going to discuss using simulation because we have discussed in like week 3, about how to control the two-stage converter and also CPL. So, in the subsequent lecture, we are going to see you know the tuning of this cascaded converter, large-signal based tuning. We will take case study with MATLAB simulation.

So, today, we just finish the all the tuning parameters for this cascaded converter.

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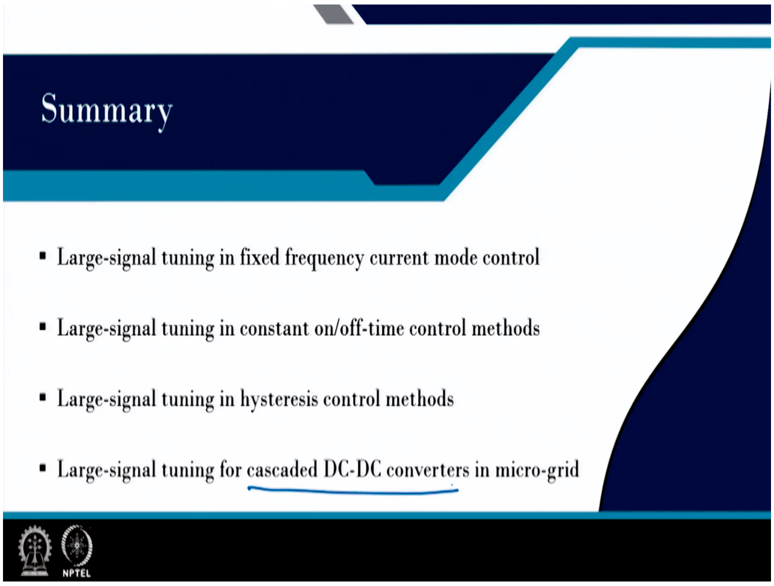

Summary

- Large-signal tuning in fixed frequency current mode control
- Large-signal tuning in constant on/off-time control methods
- Large-signal tuning in hysteresis control methods
- Large-signal tuning for cascaded DC-DC converters in micro-grid

So, with this I will summarize we have discussed large-signal tuning in fixed frequency current mode control. We have discussed large-signal tuning in constant on off time control method. We have discussed large-signal tuning in hysteresis control method. And we have also discussed large-signal tuning for cascaded DC-DC converter as well as the constant power load.

So, all this discuss, that means, large-signal can be applied. And in fact, we can also consider boost converter using cascaded stage. So, I am not going into that. But I think the large-signal can be applied for a wide variety of converter topology as well as architecture. So, with this I want to finish it here.

Thank you very much.