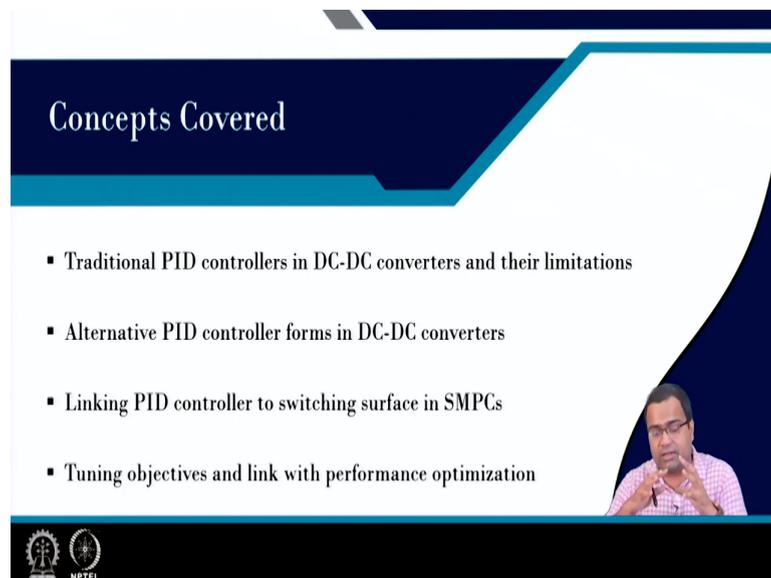


Control and Tuning Methods in Switched Mode Power Converters
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Module - 11
Large Signal Controller Tuning
Lecture - 49
Linking Switching Boundary and PID Controller Structure in SMPCs

Welcome this is lecture number 49. In this lecture we are going to talk about the linking we are going to link Switching Boundary and PID Controller Structure in switch mode power converter.

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Concepts Covered

- Traditional PID controllers in DC-DC converters and their limitations
- Alternative PID controller forms in DC-DC converters
- Linking PID controller to switching surface in SMPCs
- Tuning objectives and link with performance optimization

The slide features a dark blue header with the title 'Concepts Covered' in white. Below the header is a white area containing a bulleted list of four topics. In the bottom right corner of the slide, there is a small video inset showing Prof. Santanu Kapat speaking. At the bottom left of the slide, there are logos for IIT Kharagpur and NPTEL.

So, the concept cover here we are talking about traditional PID controller in DC-DC converter and their limitation, then we want to show alternative PID controller form in DC-DC converter, and then how can you link PID controller to switching surface in switch mode power converter. And what are the tuning objective and link with the performance optimization that we need to identify.

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Introduction to a PID Controller

- Ideal PID controller:

$$G_{PID}(s) = k_p + \frac{k_i}{s} + k_d s$$
$$= \frac{k_d s^2 + k_p s + k_i}{s}$$
$$= k_i \times \frac{\left(1 + \frac{k_p s}{k_i} + \frac{k_d s^2}{k_i}\right)}{s}$$

Handwritten notes:

- Can not be realized because finite BW in an op-amp
- Two zeros one pole
- Physically not realizable!!
- Improper TF



So, first we want to revisit our PID controller, which we have already discussed in the previous lecture during the small signal design. In lecture number 34, we have discussed PID controller tuning in a buck converter using small signal model. So, if you take an ideal PID controller, we generally take a proportional controller gain; it comes with the proportional controller gain.

So, this is our proportional controller, this part is the integral controller, and this is a derivative controller right. But you can write in the compact form in this way, but the problem is that. An ideal PID controller has two zeros and one pole, which is physically not realizable because this is an improper transfer function; improper transfer function.

In fact, an ideal derivative cannot be realized because of finite bandwidth in an op amp. That means we have to think of some practical solutions.

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Introduction to a PID Controller

- Practical PID controller Adding a derivative filter (band-limited derivative)

$$G_{PID}(s) = k_p + \frac{k_i}{s} + \frac{k_d s}{\tau_D s + 1}$$

Handwritten notes:
Ideal derivative: $K_d s$
Band-limited derivative: $\frac{K_d s}{s\tau_D + 1}$
Time constant: $\tau_D \leftarrow \frac{T_{sw}}{10}$



And we have already discussed a practical PID controller. What we do we add a derivative filter which is nothing but this. So that means our ideal one was k_d into s that was our ideal component. We will keep the same thing and we change it to k_d into s by $s \tau_d$ plus 1.

So, this τ_d time constant choice is very critical because if we take the time constant to be very large, then it will not behave like a derivative action. That means we need to choose the τ_d small so that we closely resemble like an actual derivative. But, of course, it will put a limit in the bandwidth because generally this comes from the op amp bandwidth, but you know whenever you are talking about, let us say 1 megahertz converter within some hundreds of megahertz op amp as an error amplifier.

So, as a result, the op amp bandwidth is pretty large. But sometime we may not even want such a high bandwidth for the derivative filter because we need to attenuate certain switching noise. So, in that case, we may want to increase the τ_d slightly. So, generally τ_d is taken like a T_{sw} by 10 or T_{sw} by 20 something like that, nearly like that. So, it is generally taken this less than this ok. But you know it is again the designer's choice whether it is possible to implement it or not ok.

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Introduction to a PID Controller

- Practical PID controller Adding a derivative filter (band-limited derivative)

$$G_{PID}(s) = k_p + \frac{k_i}{s} + \frac{k_d s}{\tau_D s + 1}$$

$\frac{1}{\tau_D} \rightarrow$ High frequency pole

$\frac{k_d s}{s\tau_D + 1} \xrightarrow{\text{ideal}} \frac{k_d s}{s\tau_D + 1} \quad \tau_D \ll T_{sw}$

$s\tau_D + 1 = \left(\frac{s}{\omega_{hf}} + 1\right)$

$\omega_{hf} = \frac{1}{\tau_D}$

- due to BW limit in op-amp
- deliberately added for high frequency noise attenuation



So, we need to be careful about the choice of this tau d it is generally much smaller than T sw should be. So that means a high frequency pole 1 by tau d because we can write s tau D plus 1 in this structure like a s by 1 high frequency pole plus 1 so where this high frequency pole is nothing but 1 by tau D ok. And this high frequency pole due to the bandwidth limit of the op amp as well as sometime in T 2 deliberately add that increase this you know time constant or decrease the high frequency bandwidth so that we can attenuate the noise.

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Introduction to a PID Controller

- Practical PID controller Adding a derivative filter (band-limited derivative)

$$G_{PID}(s) = k_p + \frac{k_i}{s} + \frac{k_d s}{\tau_D s + 1} = \frac{k_p s(\tau_D s + 1) + k_i(\tau_D s + 1) + k_d s^2}{s(\tau_D s + 1)}$$

$$G_{PID} = k_i \times \frac{(1 + k_1 s + k_2 s^2)}{s(\tau_D s + 1)}$$

where $k_1 = \frac{k_p}{k_i} + \tau_D$, $k_2 = \frac{1}{k_i}(k_d + k_p \tau_D)$



So that means we know about this PID controller and we know how to write it down and that we have discussed in detail in lecture number 34.

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Structures of PID Controllers

- Parallel connected PID controller

$$G_{PID}(s) = k_p + \frac{k_i}{s} + \frac{k_d s}{\tau_D s + 1} = \frac{k_p s(\tau_D s + 1) + k_i(\tau_D s + 1) + k_d s^2}{s(\tau_D s + 1)}$$

- Series connected PID controller

$$G_{PID}(s) = \left(k_1 + \frac{k_2}{s} \right) \left(k_1' + \frac{k_2' s}{\tau_D s + 1} \right)$$

Can be framed as $G_{PID}(s) = k_p + \frac{k_i}{s} + \frac{k_d s}{\tau_D s + 1}$



Now, the structure of the PID controller either we can take a PI; parallel PID controller or we can take a series PID controller in this form. And it can be framed into this problem this series controller; that means, this is a PI counterpart, and this is a PD counterpart. So, this can be combined to create a PID control.

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PID Controller – Functionality

PID Gain	Percentage Overshoot	Settling Time	Steady-state Error
Increasing K_p	Increases	Minimal impact	Decreases
Increasing K_I	Increases	Increases	Zero steady-state error
Increasing K_D	Decreases	Decreases	Negligible impact



So, the PID controller is very useful because we know if we increase the proportional gain, the overshoot increases. It has a minimum response; I mean a minimal response in the impact in that settling time, but it reduces the steady state error as the proportional gain increases.

Now, increasing K I has a drastic effect on the settling time and it tries to reduce the steady state error and it also increases the percentage overshoot. But the derivative action try to help because it introduces damping. So, it try to reduce overshoot/undershoot and also reduces settling time because it tries to damp out.

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Limitations of Direct Voltage Derivative in DC-DC Converters

$$\frac{dv_o}{dt} = r_c \frac{di_c}{dt} + L_c \frac{d^2i_c}{dt^2} + \frac{i_c}{C}$$

$v_o = r_c i_c + v_c + L_c \frac{di_c}{dt}$

S. Kapat and P. T. Krein, "Formulation of PID Control for DC-DC Converters Based on Capacitor Current: A Geometric Context," in *IEEE Trans. Pow. Electron.*, vol. 27(3), Mar. 2012

But if you take a PID controller in a DC-DC converter, the derivative part of the PID controller create a trouble. Suppose if you take a buck converter and if you draw the waveform of the buck converter; that means, you know if we draw the lets say. So, we are drawing the voltage and the current waveform.

So, suppose we are drawing the inductor current waveform like this and if we you know extend this. So, because then since there is a ESR first consider the effect duty ESR; if there is an ESR. So, suppose we are talking about r c to be not equal to 0, but L c equal to 0 ESL. We call this as an ESL; Effective Series Inductance.

If we take that to be 0 then how does the ripple look like; so this is my voltage. So, it will look something similar to the current profile. Because this will be dominated if this is m 1 so this slope will be m 1 into r c. That means, if your capacitor is large and if you have some

amount of ESR, then the ripple pure capacitor ripple will be small so, it will be primarily dominated by the ESR ripple.

Now, in presence of ESL, what will happen? Suppose this ESL, so this ESL is very small even it can be you know few nanohenry or even hundreds of picohenry. So, if suppose if you take the derivative of the output voltage; that means, it will be r_c ; because what is the output voltage equation? Output voltage equation here r_c into i_c plus v_c which is nothing, but this voltage is v_c the capacitor voltage plus L_c into $d i_c / d t$, because that is the voltage across this particular part so this brand voltage is here.

Now, if you take the derivative of the output voltage, this is exactly what we are talking about the derivative. What we will notice that this term because i_c . So, it will create like; that means, if you take the derivative, so this is my current; that means you know if you take the capacitor current so if you take; if you remove the average current, it will be the capacitor current.

So, capacitor current will be similar to the triangular wave ok, triangular wave, but it is have a 0 average right, so that means, this axis is my capacitor current axis right so, this axis. Now, if we take the derivative so, here you will get a positive 1 here negative 1 here like this and this is due to this term there is a kind of step. But v_c I mean if you take the derivative of the v_c it is the capacitor current so it will have a triangular part.

That means, i_c into $C D d v_c / d t$ equal to i_c , but the main problem will be this due to this one. Because if you take a double derivative of this; that means, if you take another derivative of this, there will be a spike. So, your output voltage will have a huge spike here. And these spikes will be damp out soon because the inductor is small, but this pikes will come due to this term.

And if you take a direct derivative, these spikes will go inside your controller and you need to attenuate and that is why you talk about practical PID controller where we take k_d into s divided by $\tau_d s + 1$. And if you take τ_d somewhat not very close, but somewhat close. That means you are trying to attenuate this filter and this attenuation also has a penalty because you are actually not taking a derivative action; you are slowing it down.

So, this was reported that you know this was shown in this paper with experimental result. So if you take the actual derivative, there can be a real jump in the output voltage. Though we can reduce this effect by proper layout, but we still it is difficult to reject this effect.

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Limitations of Direct Voltage Derivative in DC-DC Converters

$$\frac{dv_o}{dt} = r_c \frac{di_c}{dt} + L_c \frac{d^2 i_c}{dt^2} + \frac{i_c}{C}$$

Now, the limitation of in a take a boost converter the situation even is dangerous, because if you draw the suppose if you draw the capacitor current diagram rather than inductor current. So, in a boost converter, the capacitor current will have a negative current. Then it will have like this kind of current, so this is my capacitor current. So, during this particular duration; during this duration, this capacitor current is i_L minus i_0 and during this duration your capacitor current is simply minus i_0 .

So, there is a discontinuity due to the inductor current because it is getting connected during the off time and it is getting disconnected during the on time. So, that makes the capacitor current discontinuous for a boost converter. And as a result if you take again the derivative because we have already discussed.

So, what was our output voltage expression? Our output voltage if we take these to be v_c and this to be v_{L_c} then v_0 is equal to v_c plus i_c into r_c plus; if this is my L_c , L_c into $d^2 i_c/dt^2$ sorry dt right. That means, since my capacitor current is already discontinuous, so this actually makes this is already a trouble, because if you differentiate at this point of discontinuity, we will get a huge spike.

If you add a further derivative, then you will get a double derivative so, you will get a double action it will be problematic here. So, it is in a kind of impulse kind of effect you will get and here the derivative of the impulse. So, it can inject a huge kind of spike. That is why you need to select the PID controller for a boost converter very carefully; otherwise, you know it can be a disaster like you know your controller error amplifier will get simply get saturated because of a spike, ok.

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Alternative PID Control Formulation in a Buck Converter

$$\sigma = k_p (v_{ref} - v_o) + k_i \int (v_{ref} - v_o) dt - \frac{k_d}{C} i_c$$

$$k_d \frac{dv_o}{dt} = k_d \times \frac{d(v_{ref} - v_o)}{dt} = -k_d \frac{dv_o}{dt}$$

$$\frac{dv_o}{dt} = \frac{i_c}{C}$$

S. Kapat and P. T. Krein, "Formulation of PID Control for DC-DC Converters Based on Capacitor Current: A Geometric Context," in *IEEE Trans. Pow. Electron.*, vol. 27(3), Mar. 2012.

So that means, generally that is why the PID controller straight away is very difficult to realize. But, we will see in a subsequent lecture that even if we take a practical PID controller with a band limited action, you still can. Because what we are going to do if you link this PID controller with a switching surface, then we can tune this PID controller using the switching surface point of view not from the small signal model. And then we can take back the pure like you know band limited derivative action.

So, alternative way what we did? That we keep the proportional integral same, but we know the derivative which was the k_d into dv_o/dt and what is because the derivative sorry we have taken what was the derivative action, we have taken derivative part because our error voltage is this. So, this is our error voltage right error voltage. So, we took $k_d dv_e/dt$; that means, we have taken k_d into d/dt of $v_{ref} - v_o$ and it is simply $-k_d$ into dv_o/dt .

And if there is no ESR in an ideal case, in ideal case this dv_o/dt is nothing but i_c/c , but in practical case we have ESL effect another effect. So, now, if we take the capacitor

information rather than direct derivative so, it will give something like an ideal derivative action. As if even though the circuit will have ESR, the circuit will have ESL, but by incorporating capacity information, we can actually try to retain the ideal derivative action even for a practical circuit.

So that means, we can resemble the ideal derivative action in a practical circuit by sensing either capacitor current or sensing load minus inductor minus load current or their combination along with the estimation. So, that is possible.

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Alternative PID Control Formulation in a Boost Converter

$$\sigma = k_p (v_{ref} - v_o) + k_i \int (v_{ref} - v_o) dt - \frac{k_d}{C} (i_L - i_n)$$

$$i_n = k_n i_o \quad k_n = \frac{v_{ref}}{v_{in}} \quad k_n = \frac{1}{\frac{v_o}{v_{in}}} \text{ boost} \quad i_n = k_n i_o$$

$$i_c = i_L - i_o$$

$$\langle i_c \rangle = \frac{i_o}{1-D}$$

$$\langle i_c \rangle = \frac{v_o}{v_{in}} i_o$$

So, that means, but if we take a boost converter as I said, the boost converter capacitor current during the positive cycle it is nothing but minus load current and during off phase it is i_L minus i_o . So, we can normalize; that means we want virtually like a capacitor current.

That means, if I draw the boost converter capacitor current, you know we know the capacitor current is simply like this; simply like this. But for a buck converter, what we achieve was something like this. For a buck converter it was like this right, it was like this; that was for a buck converter right. But boost converter this discontinuous jump creates real trouble for direct derivative right.

So, now why cannot we get emulate? Why cannot you emulate something similar for a boost converter and that is exactly what we are doing i_L minus normalize. Because in a buck converter, our capacitor current is nothing but i_L minus i_o because your average inductor

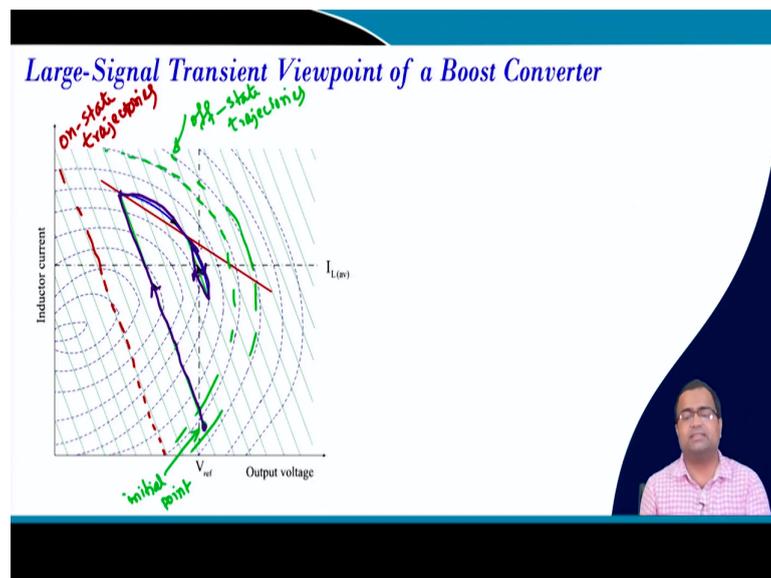
current is same as average load current. But in a boost converter, your i_{0iL} average is nothing but i_0 by $1 - D$. And what is $1 - D$? It is your output voltage by input voltage into load current that is my i_L average ok.

So, suppose if we create a virtual capacitor current by means of inductor current minus the normalized load current. What is a normalized load current? So, this is my normalized load current. So, I am normalizing the load current such that the average value is equal to the average inductor current. So, that their average at steady state will be 0 because under steady state they are average.

So, it is like a sense of capacitor, but not exactly the capacitor current for a boost converter, but it acts like a virtual capacitor current which we are trying to create such profile even for a boost converter, which is something similar to a buck converter. And if you do that, this will look something similar to like a derivative action.

So, for a boost converter, this normalize factor is nothing but i_n is equal to; so, we can take k_n into i_0 where k_n is equal to 1 for buck converter and it is equal to V_0 by V in a steady state for a boost converter. So, we are doing some normalization here and that is the new formulation of PID controller.

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And if we do that we are trying to get how can we relate. So, but one thing we should remember the integral control that we are considering here. It has a very slow dynamics. And

this only effect near steady state provided that the recovery during large signal transient is much faster than the accumulation of the integral action.

But if the integral action accumulation process, the speed of accumulation is comparable with the large signal time the duration, then this will have a very high influence. But we are generally considering the integral slower and we are talking about the time optimal control where the recovery is extremely fast where the, this action comes close to steady state.

So, even though you keep this integral action and if we do not consider this even in the actual formulation and if we incorporate in your actual implementation, they will not make much difference. But rather this will make your error nearly 0 so that your output voltage will be regulated at the desired value.

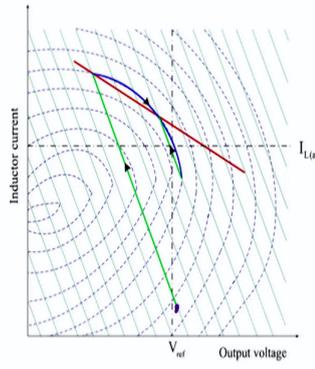
So, now we want to visualize for a boost converter. So, these are the trajectories, on state trajectory. So, on state trajectories say blue line. And if we take the green one; that means, you know if I take this kind of waveform. So, there are a family of this curves; these are my off state trajectories ok.

Now, let us start. This is my starting point, this is my initial point; so, this is my initial condition. This is my starting point, initial point. And what I want suppose it can be a starting point or it can be any arbitrary point I want to reach to steady state, you know; that means, steady state means there will be switching, of course, because if you want to get a boosting operation you need to turn on and off. You cannot operate the converter. Any particular switch configuration continuously right.

So, this is something like our desired behavior; that means we start from this point. You see; we start from this point this point and this is my on state. trajectory it follow this path. Then suppose there is a switching surface, which is a first order surface it hit here and then it turns off and goes like this and here it reaches a steady state; that means, this is a steady state action ok.

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Large-Signal Transient Viewpoint of a Boost Converter



- To reach steady-state from the initial point
- Can we achieve this one switching action?
- Linear switching surface sufficient

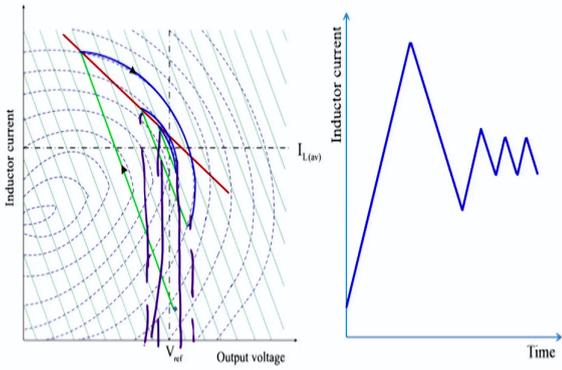
— how to find optimal slope ?



Next to reach steady state from any arbitrary initial point, how can we achieve this in one switching action? Because that is what is my time for optimal recovery or the fastest recovery. Then linear switching surface can you do that because here we are showing a linear switching surface, but we could achieve in one switching action; then how to find the optimal slope or rather I will say if I take a different slope what could be my behavior.

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Large-Signal Transient of a Boost Converter – Higher Slope?

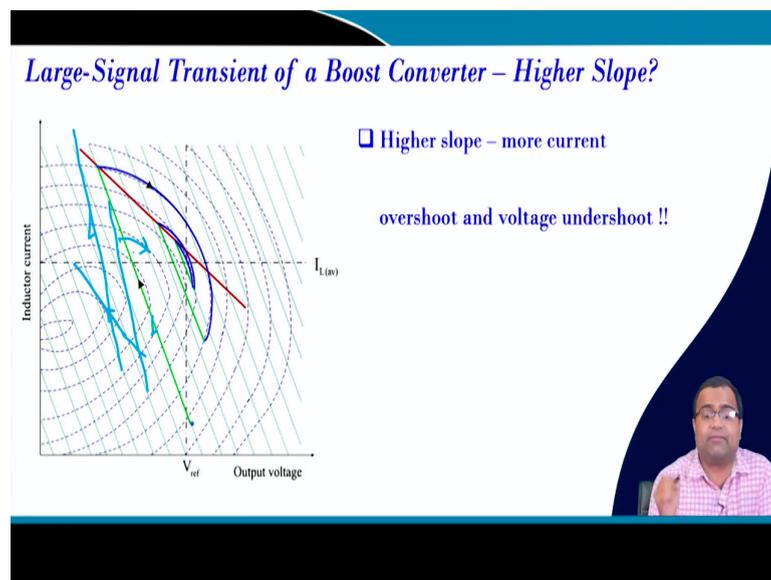


Now, if I increase this slope so earlier, this was the slope I increase the slope then what will by time domain behavior. So, because of the increase in slope your there will be more current

overshoot right and you can see voltage overshoot undershoot also increase. Because this side is my output voltage and this is my desired ripple; this is my ripple voltage, but I am going even either side of the ripple. That means there will be overshoot understood in the output voltage as well.

That means if we increase the slope from here to here, we are getting more overshoot undershoot which is not desirable. Similarly, if you reduce the gain, then you will get kind of over damped response and that I am going to show using experimental result.

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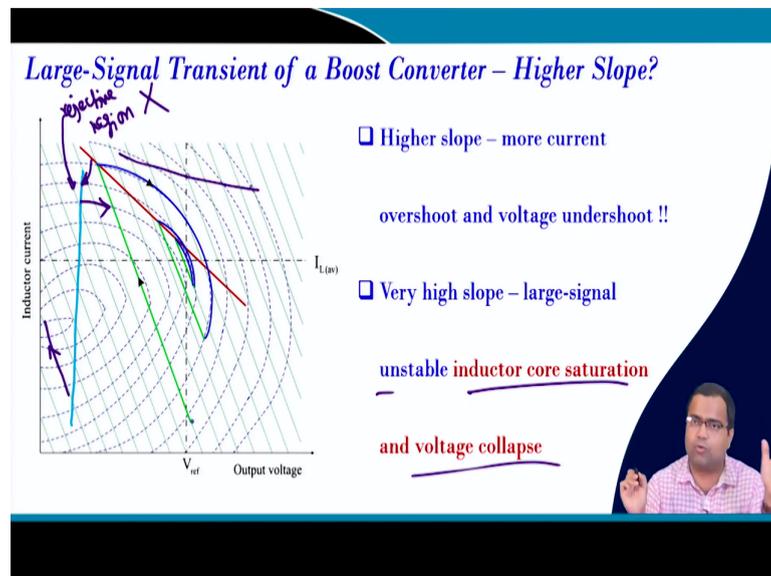
So that means we need to find the optimal slope; that means, higher slope more current overshoot undershoot. In fact, if you choose this slope; suppose if you by mistake, if you take the slope by mistake, you know if you take the slope like this, then it will be unstable. Because the slope is higher than the slope of the on state trajectory magnitude of the slope.

As a result, suppose if this is your switching surface, that means you are actually reversing the switching logic and this; that means, this side trajectory this side it is if I take this trajectory here it is going away from here right. This is the on state trajectory and this side also trajectory is going away.

That means this is the scenario where we get a rejective region; that means, if you further increase the slope and if you make the slope even higher than the magnitude of this. You can

see this is my on state trajectory right. So, my on state trajectory it looks like it is deviating, it is deviating from here.

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I am sorry it should be the other way round, because we are increasing the slope so that means, if I take the slope like this. Because this side my on state trajectory, if on state trajectory is going away from it and this side if you see my off state trajectory is going away. That means, either side of the trajectories are going away. So, this will lead to our rejection region; our rejection region and that is not desirable that will lead to.

So that means, very high large signal unstable and it will simply saturate the inductor because the switch will remain on continuously and it will saturate the inductor core and the voltage will collapse. So, we must select the slope accordingly that means, this slope should be smaller.

You can take smaller slope it will be over damp, but for larger slope you have to be very careful, particularly for a boost converter because you may land up into a rejection region where the system will completely collapse. And your inductor will saturate it will damage the device and voltage will collapse.

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Switching Surface Link to PWM Control – Boost Converter

First-order switching surface

$$\sigma(i_L, v_o) = k_c (I_{L(av)} - i_L) + k_v (V_{ref} - v_o)$$

At switching transition

$$\sigma' = 0 \Rightarrow i_L = k_p (V_{ref} - v_o) + I_{L(av)}$$

CMC with normalized load current feed-forward

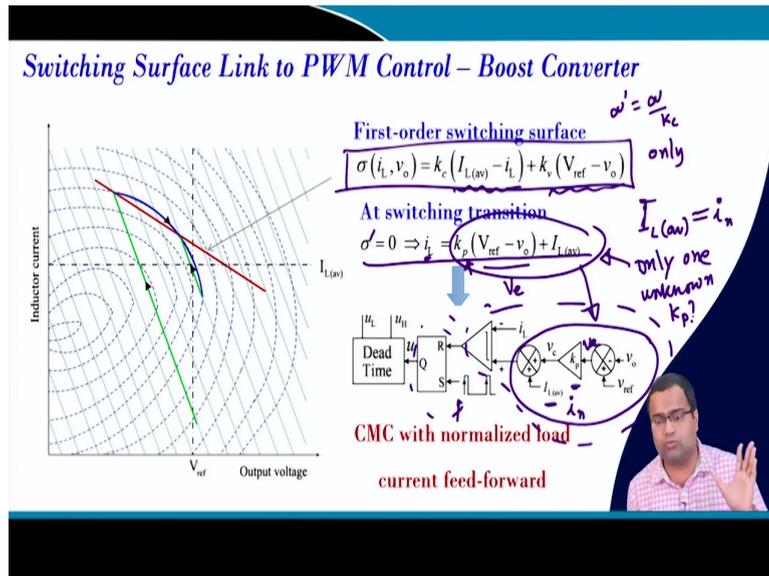
$i_n = k_n i_o$
 $k_p = \frac{k_v}{k_c}$
 $\sigma' = (i_n - i_L) + k_p x$
 $i_L = k_p v_e t$
 $i_n = 0$

So, how can you link with the switching surface with your control logic? So, this is a first order switching surface where k_c is the current loop gain is my average current. And this is exactly what I told it is my normalized current that is nothing but a normalization factor into load current. And this is my inductor current, this is my reference voltage and this is my output voltage.

And if we normalize; that means, if we make what is my k_p it is my k_v sorry k_v by k_c normalize then you will get this switching surface. And this switching surface, if you say i_L is equal to this because you have taken at the point of switching at the switching transition. Even if I write σ now, we got σ dot this σ dash, which is nothing but my I normalize minus i_L plus k_p into V_{ref} minus V_0 .

And at transition it is 0 and this will lead to if I take i_L other side it is k_p into error voltage so this is my error voltage plus our I normalized factor. So, this is my normalized factor; normalized load current, this is my inductor current which I can realize that means this part I can realize using like a current mode control, this is simply my proportional gain multiplied by error voltage. So, if I write down again; that means, if you try to visualize there are there are too many texts.

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So, first this is dash because we have divided sigma dash is nothing but sigma by k c then we will get this equation right. And we know that I L average that capital you can think of it is my normalized load current ok. And if you at the switching transition, it is 0 that means this whole part is nothing but this part. And which looks a proportional gain this proportional gain into error voltage, this is my error voltage.

So, this is my error voltage into proportional gain and that is added with the normalize load current, which is my i n. And the whole thing is subtracted from i L because at the transition, it is a comparator. And that can be linked if I want to use a PWM modulator or we can use many other type modulator and that we are going to discuss in the subsequent lecture.

So, this modulator I have used here a pulse width modulator, but you can also use constant on time hysteresis control technique, but the logic is this up to this part, this part is vital. So, these are normalized load current feed forward where this normalization factor at something similar like a derivative action and this is like a proportional control ok.

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Switching Surface Link to PWM Control – Boost Converter

CMC with normalized load feed-forward

- Switching surface slope –
- Proportional control gain k_p
- Find optimal value of k_p

So, this is a normalized load current feed forward where this proportional gain is nothing but the slope of this surface and that plays a key role in shaping the large signal recovery. That means, if you want to achieve the time optimal recovery. It is the proportional gain; we have to select properly to achieve that to find the optimal value of k_p .

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Large-Signal Transient of a Boost Converter – Increasing Slope

5V output

k_p

Tuning objectives:

- Identify optimal proportional gain k_{op}
- Identify integral gain and activation logic

Now, if we take an experimental case study where this is the output voltage and you can see 1 2 so it is a 5 volt output 5 volt output and input is where the input is 3.3 volt input. Here we take a smaller k_p because I am just playing, but we will formulate for buck

converter with more elaborately and we will give an expression for boost in the subsequent lecture.

But what we did by this formulation if we take a smaller value of k_p you can see it is not the optimal recovery because there are few more switching numbers. But if we set the k_p if we increase in a proper value, it is more or less optimal because you see there is a slight overshoot you know understood in the current, but this is close because we are talking about. And this mismatch is coming because we have a PWM modulator where the PWM modulator itself has a constant.

So, we cannot achieve the perfect time optimally. We will get rather proximate time optimal because of the modulator, will put a constant in the on off time right. If you further increase the gain, then you will see the overshoot will increase significantly and that we have discussed in the phase plane. If we increase the proportional gain, you will get more overshoot undershoot. And if we further increase, it may so happen the whole system will collapse.

So, you have to be very careful, and this will even lead to much higher current undershoot because it is a 2 ampere part division, so much higher current undershoot overshoot peak current. So, this may be close to optimal. This is like close to time optimal response and this is even higher value. It is less and this is like a over damped response.

So, the tuning objective is that we need to identify optimal proportional gain and we also need to identify integral gain because you see there is a small steady state error and this division is 1 volt. So, we are getting a steady state error of around 0.2 volt because we have considered a proportional control. There is no integral control yet.

But, I will show in subsequent lecture this integral control has no role, almost negligible role in the transient shaping, but it will eliminate the steady state error. So, we can use the integral gain tuning using our earlier small signal based approach. We can put some number, but we have to be very careful about this proportional gain.

And the derivative gain which because it is coming from the current loop because we have chosen i_L minus i_n so there is no gain because it is normalized. Because if you go back to our original problem, you know if you use. So, since it is a first order switching surface so we

will have only one unknown parameter only one and there is exactly one only one unknown and that is nothing but k_p .

So, we do not need to take I mean derivative gain is already taken care only one. But only thing, since we are incorporating an integral action like a PID controller which we have discussed even before that. So, this integral gain since its action will be much slower; so we will choose integral gain based on the small signal derivation that is fine and we will only try to eliminate the steady state error ok. So that means our ultimate tuning objective is to find this optimal gain and that we have discussed.

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Summary

- Traditional PID controllers in DC-DC converters and their limitations
- Alternative PID controller forms in DC-DC converters
- Linking PID controller to switching surface in SMPCs
- Tuning objectives and link with performance optimization

$k_p = ?$

So, in summary, traditional PID control in DC-DC converter and their limitation we have discussed. And we saw that direct derivative will cause you know it can introduce significant noise and we have to be very careful, but the alternative PID controller was useful. And that can take the structure of a current mode control with load current feed forward where our ultimate objective is to get the right gain of the proportional controller.

But if we do not want to sense load current, we can even go for voltage mode control as well or even because you know current mode control is a quite common. So, then we can use an estimated load current if we do not want to sense load current.

But the current sensing is required particularly for boost converter where, otherwise you know if you choose a higher gain it may lead to complete collapse because of the rejective

region so you have to be very careful and we should use generally current mode control for boost converter.

So, and we saw that current error inductor minus load current that gives a something like a derivative action which is inherently there. And that is why we can think of a current mode control with a PI controller which will look something similar to a PID controller; the whole overall system.

We have linked a PID controller with switching surface in switch mode power converter and in the subsequent lecture we will show that we can use different type of modulator as well as you know different we have applied even for buck boost as well as buck boost to get similar optimal response. And we have set the tuning objective, and we have linked that performance optimization criteria where the choice of proportional gain seems to be the key factor.

So, in the next lecture we are going to derive analytically what should be the right choice of proportional gain, and that will derive using large signal model where we can achieve time optimal recovery and which was not possible in linear control or small signal model. So, with this I will finish it here.

Thank you very much.