Control and Tuning Methods in Switched Mode Power Converters
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Module - 11
Large Signal Controller Tuning
Lecture - 51
Large-Signal Controller Tuning in Boost and Buck-Boost Converters

Welcome, this is lecture number 51. In this lecture we are going to talk about Large Signal Controller Tuning in Boost as well as Buck-Boost Converter.

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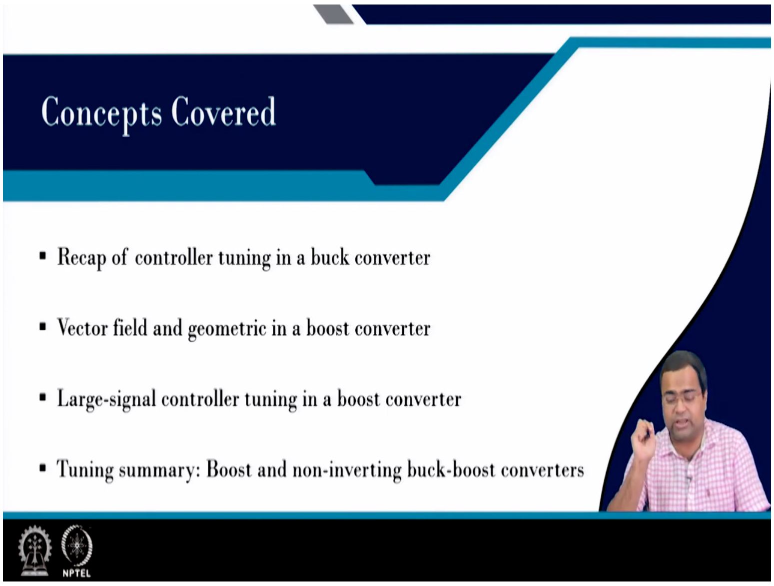

So, here we will first recapitulate what we did for a buck converter then we need to see the vector field and the geometric aspect in a boost converter then large signal controller tuning in a boost converter and the tuning parameter summary boost as well as non inverting buck boost converter.

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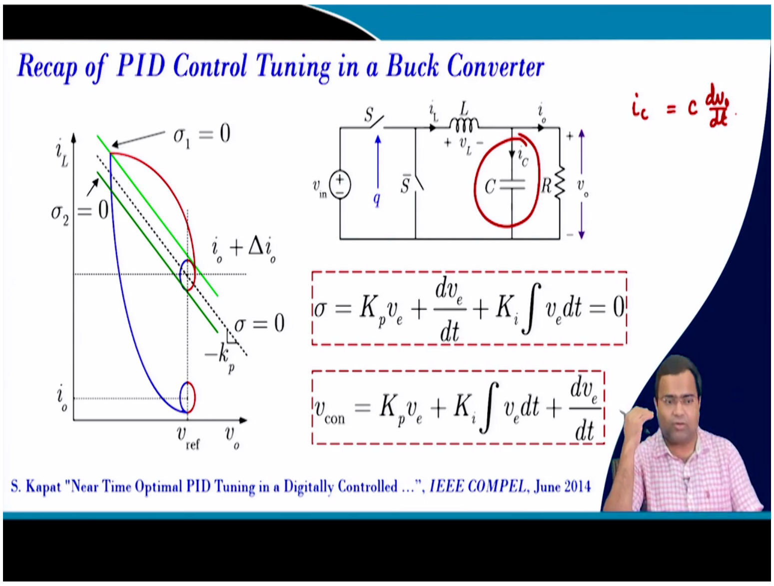

So, first if we recapitulate in our PID controller tuning, in a buck converter we have framed this into a PID controller problem where we talked about the switching surface takes the form of a PD controller. And we can incorporate an integral action in order to reach a steady state of almost zero steady state error.

But we have discussed that it is the PD controller primary the proportional controller gain, which drives the transient performance. That means, if we set it optimally, we will get close to time optimal solution ok. That part analytical part we have discussed in the previous lecture.

In this lecture, we cannot fit in a PD controller in a boost converter because the voltage derivative in a boost converter is discontinuous right because you know if you take a boost converter. For example, so we have discussed that PID controller for a buck it was straightforward. Because in buck converter you are your, if you see the capacitor current capacitor current. If you see i c in continuous conduction mode, it is c d v 0 d t in case of an ideal case. So, there is no problem we can frame it into PID controller.

But in a boost converter, the capacitor current is discontinuous when on time it is simply minus of load current and during off time it is i l minus i 0. So, it is not like in the form of voltage. So, we will call it as a PI controller with current mode control rather than PID controller.

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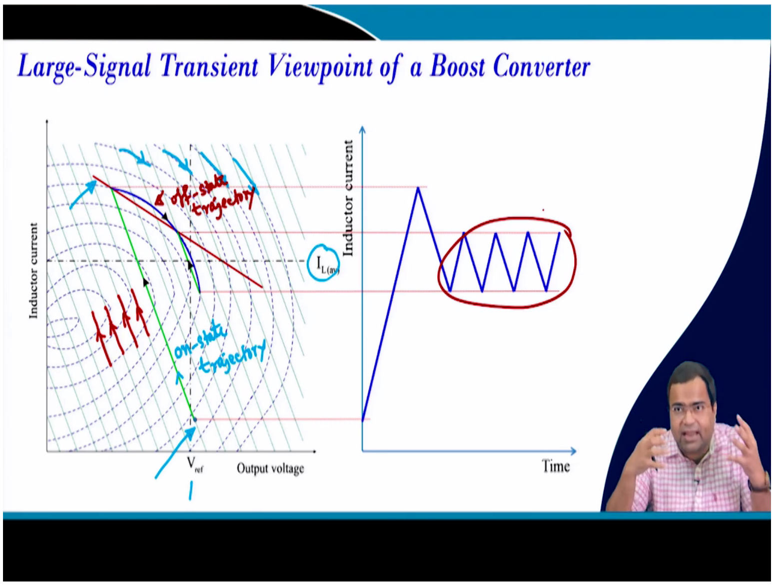

But we want to see the large signal. We want to see the viewpoint we have discussed multiple times about the vector field in lecture number 42. We have drawn how to draw using MATLAB 43. There we have also discussed the vector field in 45. So, here again we recollect that if we take the vector field, let us say these are the on state trajectory like a vector field of a boost converter, you see.

And, so depending upon the number of you know initial condition you can draw and this represents our off state trajectory vector field and we have already discussed how to draw such vector fields right. Now, we want to this is my initial condition. We want to reach this initial condition to our steady state point where the average inductor current is IL average and the average output voltage will be V ref that is our steady state point.

And you know under steady state it will have an on off operation because we need to have a free switching frequency because it is a switching converter right. So, if we take a surface and we have already discussed the switching surface the red one indicate a switching surface which is a first order surface and if we set the surface slope in such a way when the initial condition is start the on state trajectory. This is the on state trajectory and this is the off state trajectory. This is our off state trajectory it hit in such a way it reaches steady state point right.

And it is in one switching action it goes back to steady state and these are the steady state switching operation right, but how to get that. So, we want to relate first ok.

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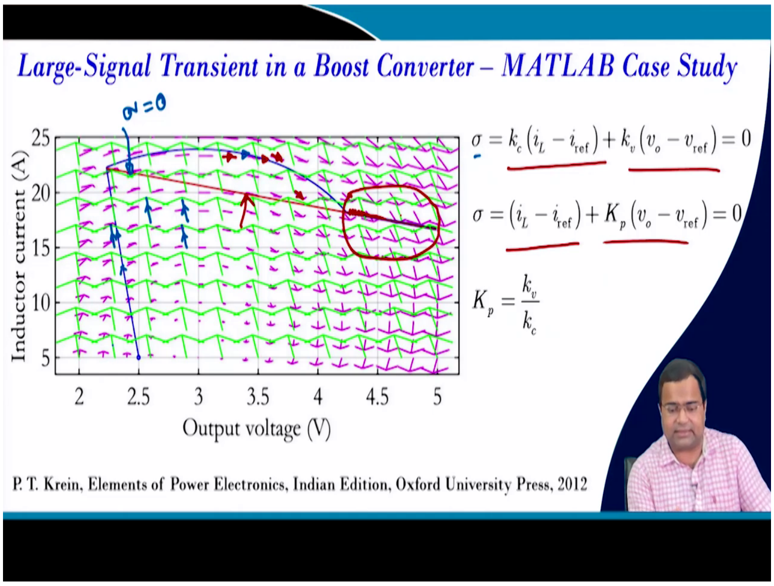

The first point again we are taking the switching surface and this switching surface will show you it takes the form of a k c into the current error k v into the voltage error and since it is equal to 0 we can normalize it in terms of current error plus gain into voltage error equal to 0. And this you can get from this you know elements of power electronics book that geometrical aspect.

And here you will notice that in this method these are the on state trajectory vector field the green line that mean this is the on state trajectory and you see this trajectory and this trajectory they are parallel right, but it is not necessary this trajectory will parallel to this line. So, you have to take the closed point and have to draw the vector field that we have discussed.

Once it hits this red, this is my red surface. The red trace indicates the surface, which is sigma x equal to 0 and this is my sigma x. Then it takes the off state trajectory and the off state trajectory. You will find that this off state trajectory this is the off state trajectory it is parallel to this path and which is the off state vector field the vector field of the off state trajectory.

That means this is very consistent and once it comes here in this region, they have a normal on off operation and with a very high switching frequency; that means the ripple is almost not visible, but it is actually going. And this concept is something similar to our sliding mode control that we have learned in lecture number 45.

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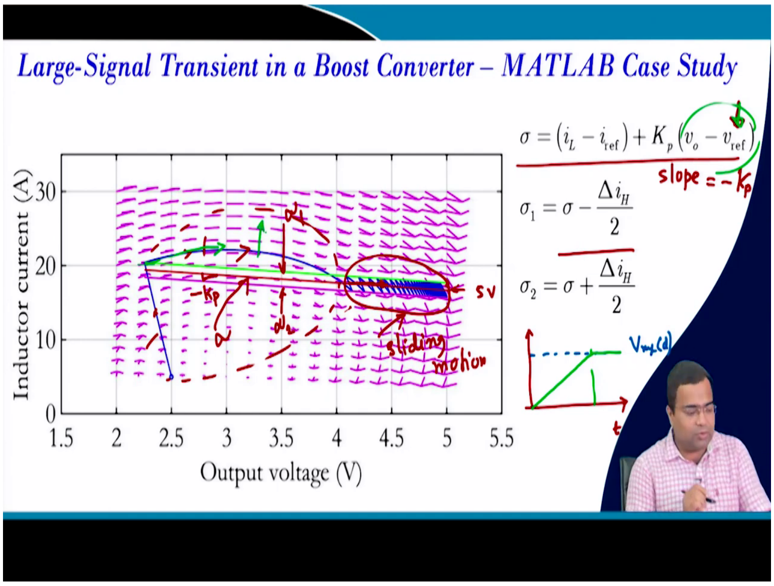

Now, since we discussed this, the surface we discussed, but the band, there has to be some band, otherwise your switching frequency will be extremely high and that is practically not feasible. Your device will not operate or it can even damage get damage. We need to incorporate you know this band; that means, this is my sigma 1, this is sigma 2, and this one is my sigma.

So, around the sigma we will have a sigma 1 sigma 2 that is just a band hysteresis band ok and sigma 1 is sigma minus delta H by 2 sigma plus delta H by 2. So, some band is inserted so that you know once it reaches here then it stays within this band and this is something similar to your sliding motion. And you have to ensure that on an average this trajectory goes towards the desired point where my output desired value is 5 volt and input current I mean average inductor current is roughly around you know I think 18 or so ok.

Now, what we discuss we have taken this slope and we discuss this slope is minus K P; that means, if you take the slope here, the slope here is nothing but minus K P. Now, this slope plays a significant role. You see, once it comes within the band, it takes a lot of time. So, it is like an over damped response and it takes multiple cycle to reach.

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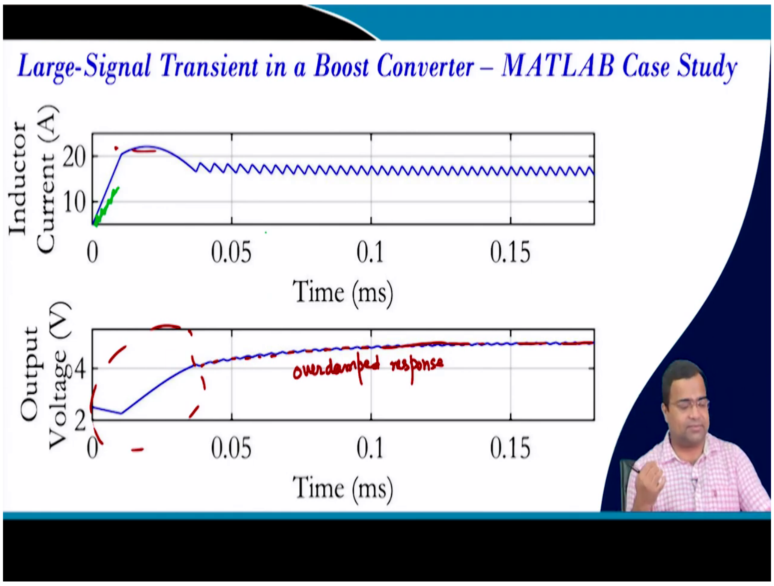

And if you see the transient behavior it comes here, then voltage here it takes a large number of cycles to come to 5 volt so this is something like a over damped response over damped or is like a first order response. Because if you take the average trajectory, it is like an over damped system like a first order response, but during this time if you go back this action we should not apply averaging.

Because of this as well as this, there is a large time when you cannot do this on off operation because it is driven by the offset trajectory so you do not have any choice. Similarly on state trajectory, so you need to quickly come to this point, otherwise this can lead to very large overshoot undershoot ok.

So, this is that is why the current overshoot is pretty high and we can’t do anything because this is the offset trajectory. So, that is one of the problems in a boost converter. When you want to start up circuit you have to be very careful about your startup process. Because typically what people do, you need to slowly ramp up this V ref; that means, some kind of soft start.

Otherwise, if you suddenly apply, then your trajectory will be forced to go like this and you will end up with a huge current overshoot. Because once you start this closed loop operation, if you slowly increase; that means, you know generally if you take a time domain. In fact, we discuss in you know I forgot the lecture number the startup software.

So, this is our typical V ref our V ref desired, but actually in order to get startup for boost converter we should raise the voltage like this and then keep it here. So, you need to put some kind of sleeve limit. So, that this slowly increases and this error because your initial voltage is 0 it start so it slowly starts up so that we have to take into account.

Otherwise, you will be bound to have such a large current transient and which is unavoidable and it can damage your switch because it requires a huge rating of your devices to support such a high current overshoot, due to the closed loop operation. But if you start rising the voltage like you know slowly kind of thing because you may not get off operation because your voltage is starting from 0. So, it will, like you know, rise. So, you need to be very careful about the operation of the boost converter right.

So, because your reference voltage initially inductor voltage is high, but output voltage is very low, so you need to slowly rise. So, you need to consider a special startup circuit, so that is very important for a boost converter. But in case of surface based design we can always put a limit, but we may not avoid this path which can have a high current because you know this direction is the current direction ok. So; that means, we need to take care about the current limit in a boost converter in a way so that it will not exceed the device or the inductor limit otherwise it will saturate the inductor.

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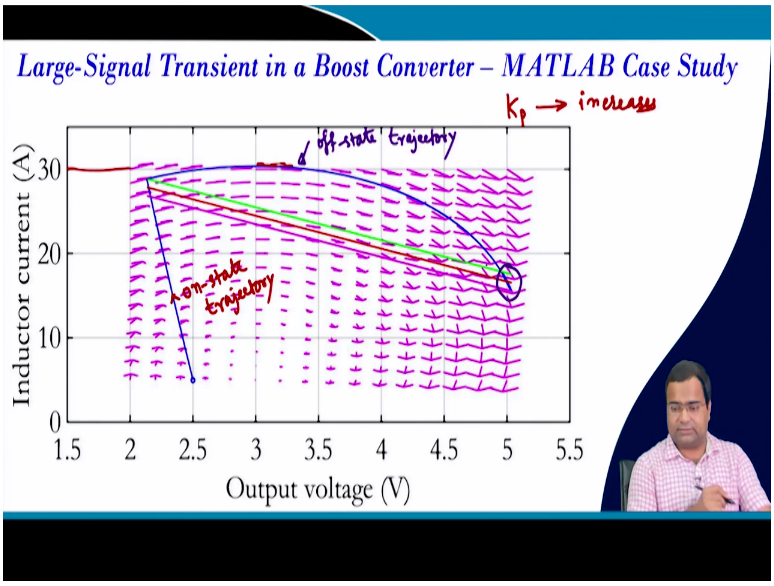

Now, imagine if we can increase this slope. So, what we did now we have increased the slope we have K p is now we have increased we have increased the slope. If we increase the slope, then you see it hit current overshoot has increased, because if you go back to the previous slide the current overshoot was around 22 ampere not very high. But here it is around thirty ampere. It goes up to 30 ampere this is my current right. But interestingly you see it, this is my on state trajectory; this is my on state trajectory, and this is my off state trajectory and it goes and here it gets settled.

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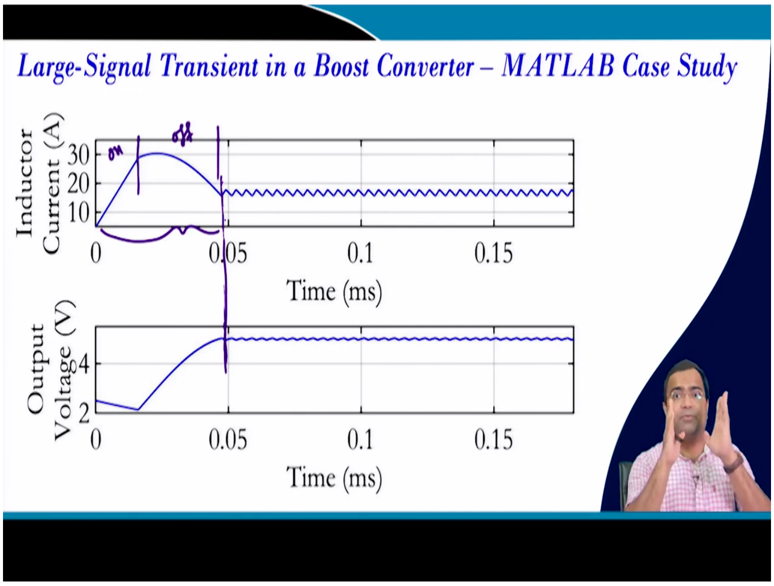

That means if you take the time domain as if it start doing its it comes to the steady state immediately here like here. So, here we have turned on this is my on state and this is like our off state. So; that means, during this whole process, a switch changes its stating only once and that is called the time optimal control the fastest recovery is possible.

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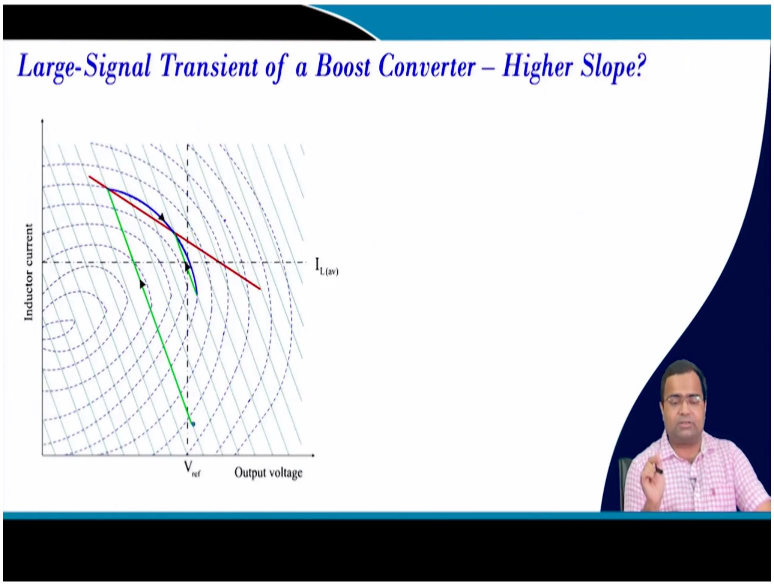

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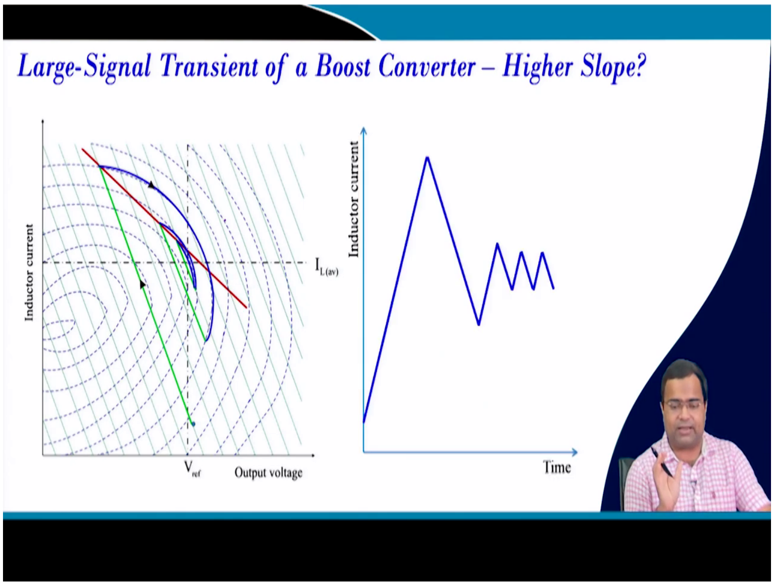

But suppose if we increase the slope so; that means we get to get the right slope to get this time optimal recovery.

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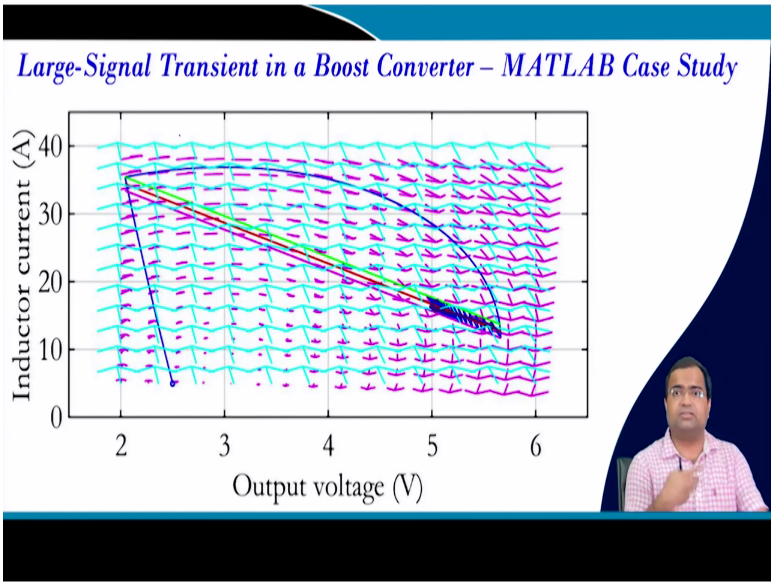

If you increase the slope, then what will happen. Your current will hit this side and then come back towards your desired point.

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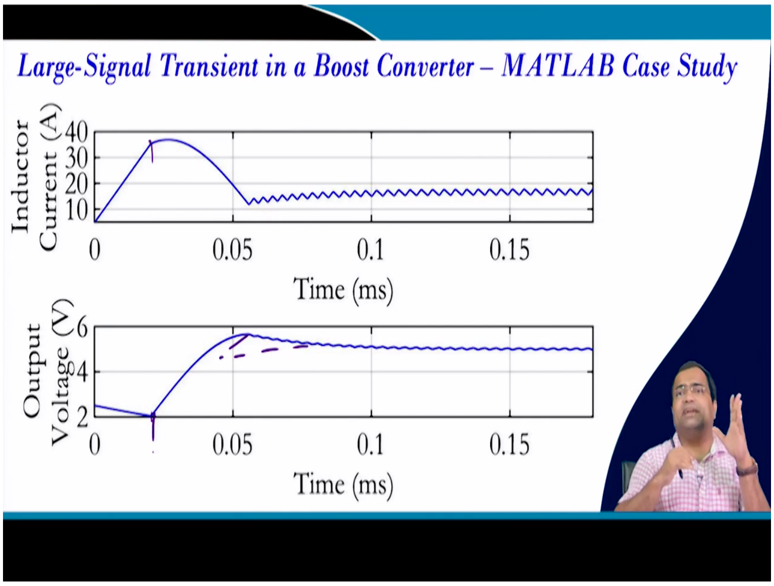

And this is how your output voltage initially goes higher than the expected value and current overshoot also increases drastically. Earlier it was 30 ampere that is around 36 37 ampere which is not acceptable. So, it is very important to select this line very carefully otherwise it may saturate the inductor or it may damage your devices and it can large voltage overshoot can also happen.

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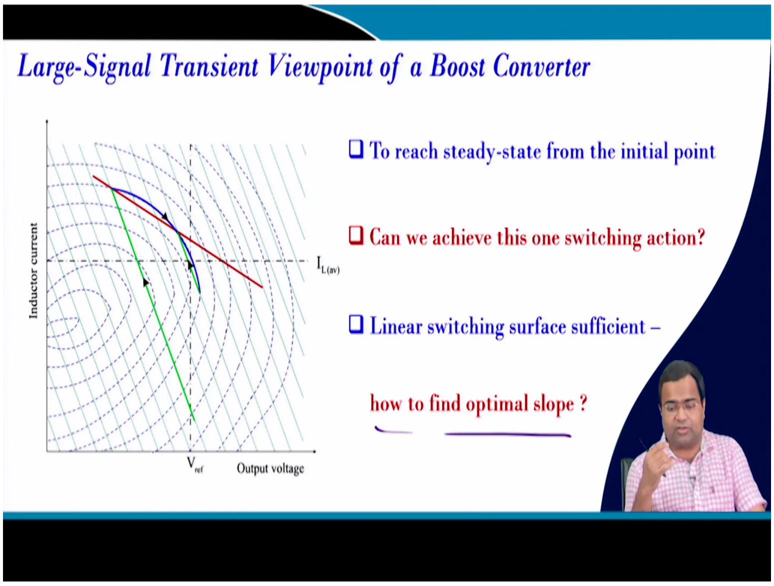

So, thus; that means, to reach a steady state from any initial condition, we can achieve this in one switching action yes, linear switching surface is enough, but we need to find the optimal gain that we have seen.

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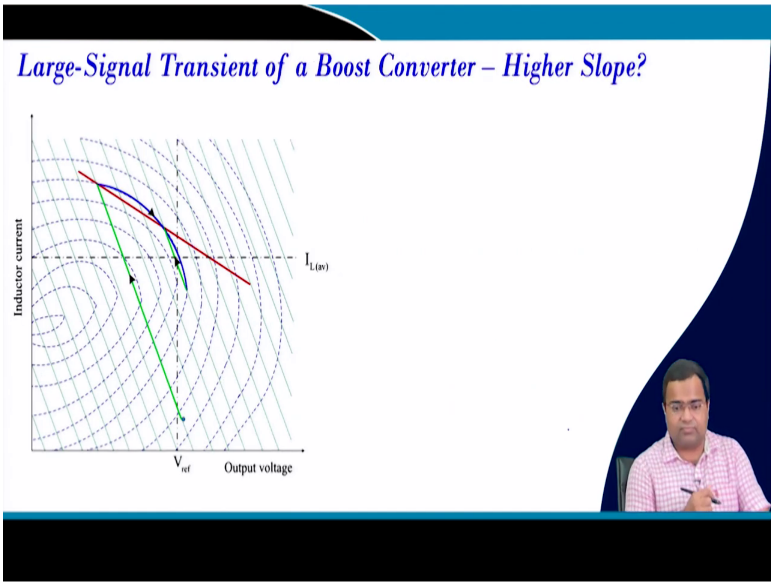

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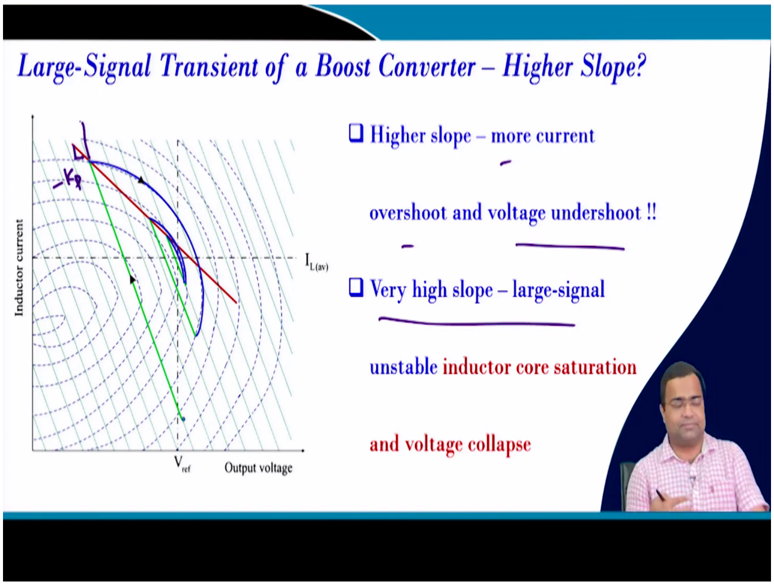

Now, if we increase the slope that we have seen, the more current overshoot and voltage undershoot also increases because even if you see the voltage undershoot here it will also increase because you are on time is large. So, in boost converter there is a problem in boost converter if you are on time increases the voltage also undershoot increases, because the voltage discharges this time and that is not the case of buck converter ok.

So; that means, your voltage undershoot increases and very high slope your last signal because if you take the slope this slope minus K P in such a way this slope is become long larger than this magnitude larger than the onset trajectory then system will collapse it will go to the rejected region ok. So, but how to link this switching surface with the controller. So, we told that this is k c into k v and if you separate out it will be proportional control with load current feed power.

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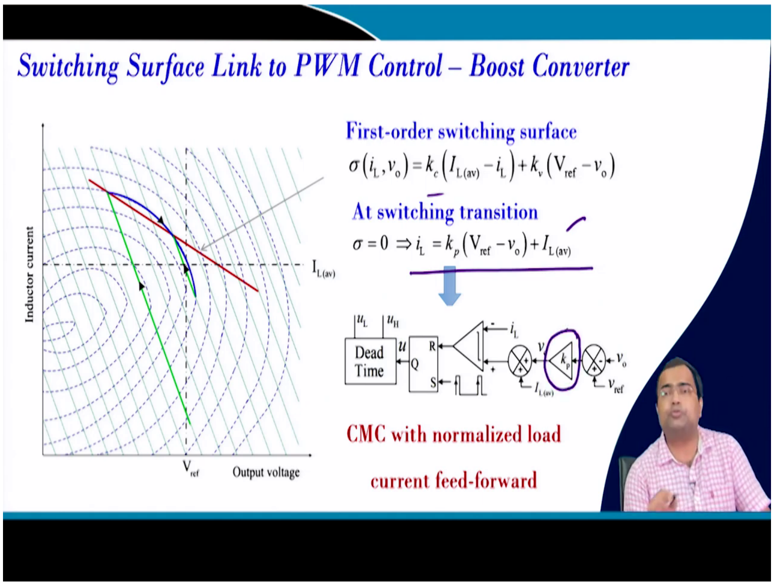

So, it turns out to be a current mode control with load current feed forward where you need to set the proportional gain correctly.

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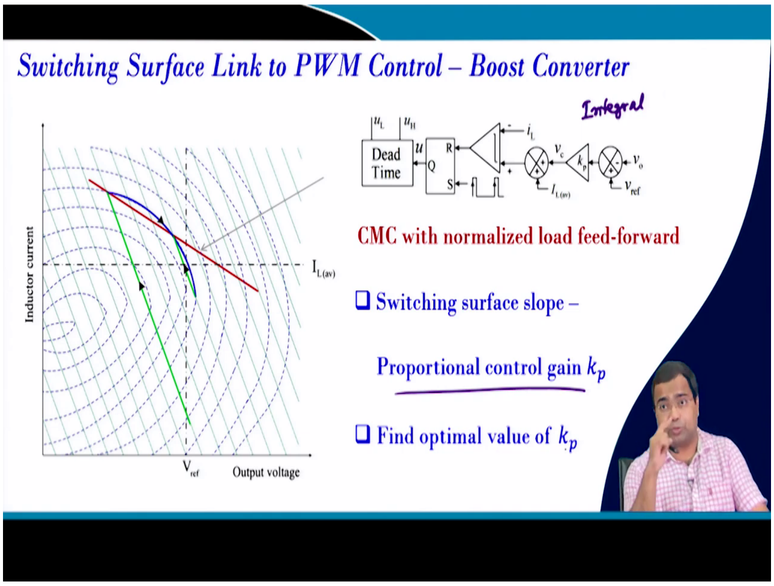

So, the objective here to find the optimal gain of the proportional controller to achieve time optimal recovery. Again if you go to the previous lecture where in buck converter we have discussed we need to also incorporate an integral action because that will ensure almost zero steady state error and that integral action will happen slowly it will have negligible impact in the last signal recovery.

So, we can design the integral controller just by using small signal model, but we need to find the proportional gain using large signal model.

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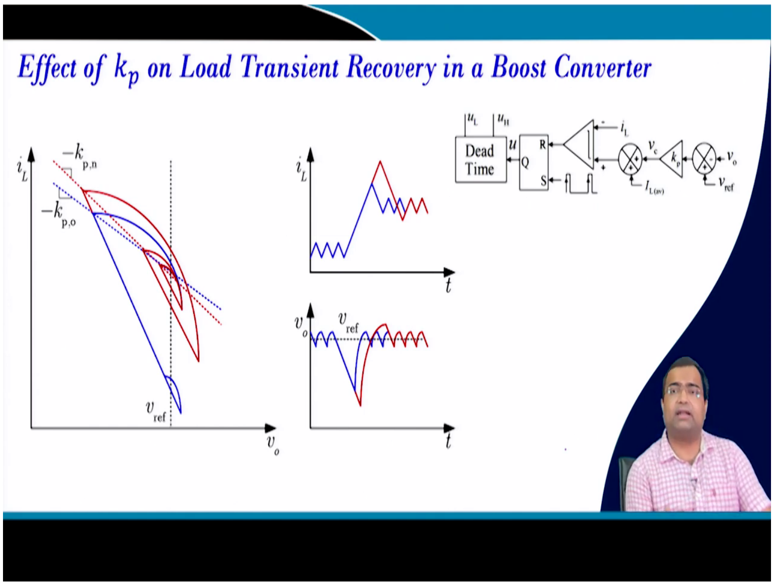

So, if you choose a larger gain you will get more overshoot and that we have discussed.

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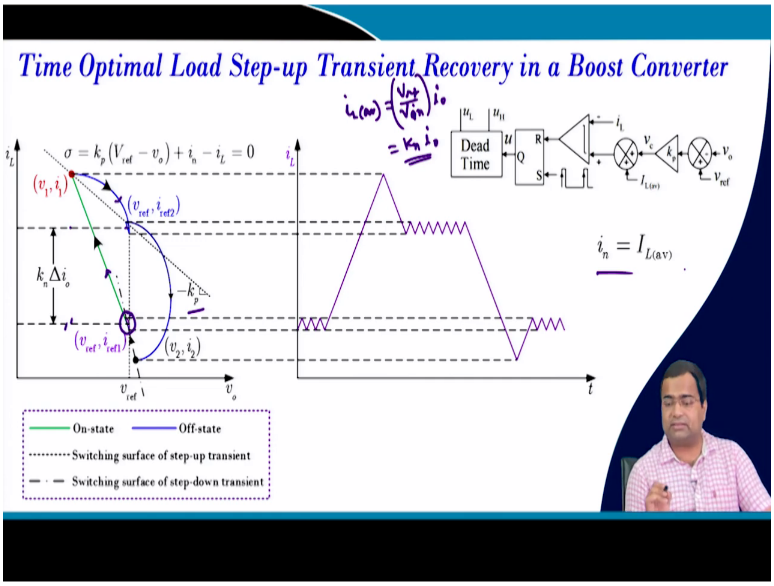

So, you have to be careful about the optimal recovery. If you derive this optimal recovery, that means this was our initial steady state behavior before the load transient step takes place and this is after load transient. Interestingly, the average inductor current in a boost converter that means your average inductor current is nothing but V ref into V in into load current.

So, here this we call it as a normalization factor into i 0. So; that means, any step change in the load current will appear like a normalization factor in the step change; that means the step change in the inductor current that needs to go; that means, we need to change this inductor average value, which will be k normalization time into the load step size. And now we need to get the optimal slope and which is minus k p, that is my problem, my objective.

So, this is my on state trajectory. This is my offset trajectory and you can derive the same thing for the step down as well. We have discussed the i n average is a normalized current load current is nothing but your average inductor current.

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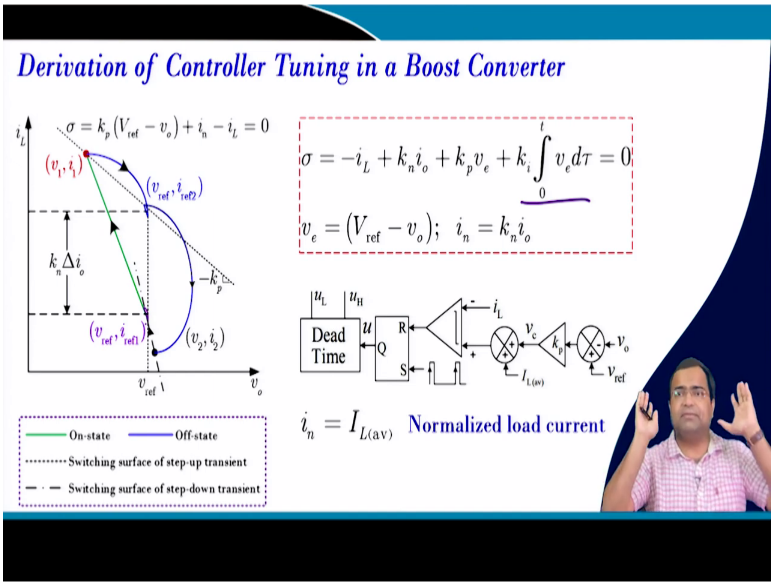

So, now if we write the switching surface equation and if we incorporate integral gain and I told you the integral gain, we do not consider during a large signal recovery. Because this effect will only come during steady state and it has no influence, only it will shift the offset point to its desired; that means, it will shift the output voltage to the desired V ref that is the function.

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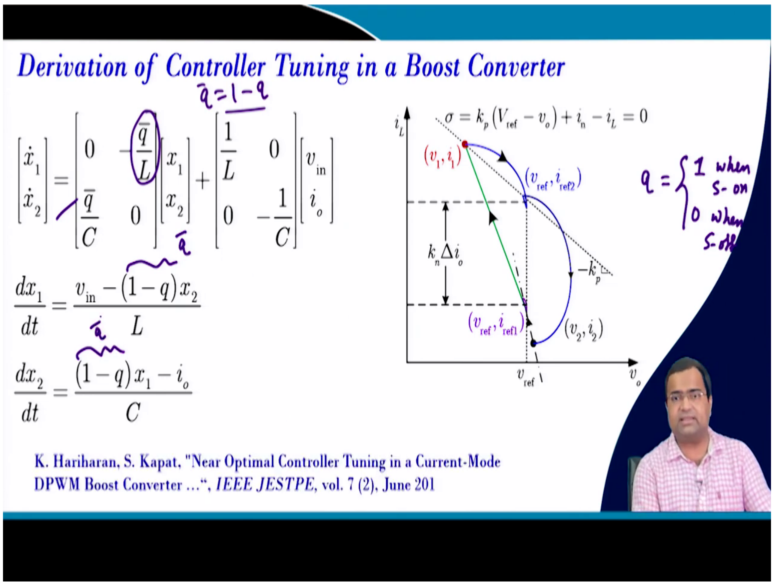

So, during the large signal recovery, we will not consider the integral x. Now, again, if you like a buck converter here, you see the q 1 q is equal to 1 when s is on and it is 0 when s is off; that means, switch off. So, here q bar is nothing but 1 minus q ok and here also we have a q bar. So, you can write this state space equation dx 1dt you can obtain dx 2 dt and we have written here this whole thing we represented by q bar this will represented by q bar ok. So, this is in this paper we have derived in detail it is available.

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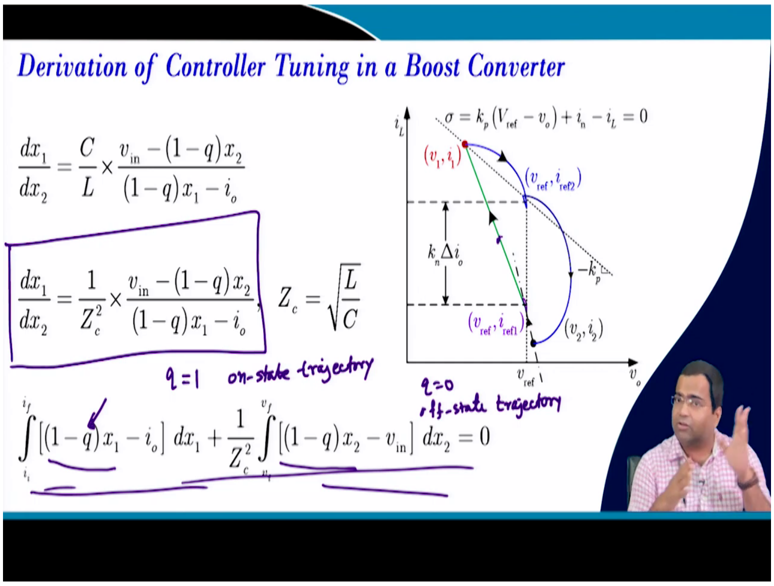

So, again, if you write dx 1 if you write dx 1 by dx 2 you will get this expression. Now you need to solve this by means of integration because you just have to solve this equation. But we are not going to show each and every derivation step in the boost converter because the derivation is quite cumbersome. it is complex, rather we want to just show the step.

So, this is the solution that we can obtain where q we have to decide whether we are talking about on state trajectory of the offset trajectory. For on state we have to take q equal to 1 for the on state trajectory; on state trajectory and it is equal to 0 for off state trajectory for off state trajectory. So, on state and offset trajectory are simply nothing but by changing the q value from 1 to 0. Otherwise this equation is applicable for both the trajectory only you have to check you have to substitute the suitable q value.

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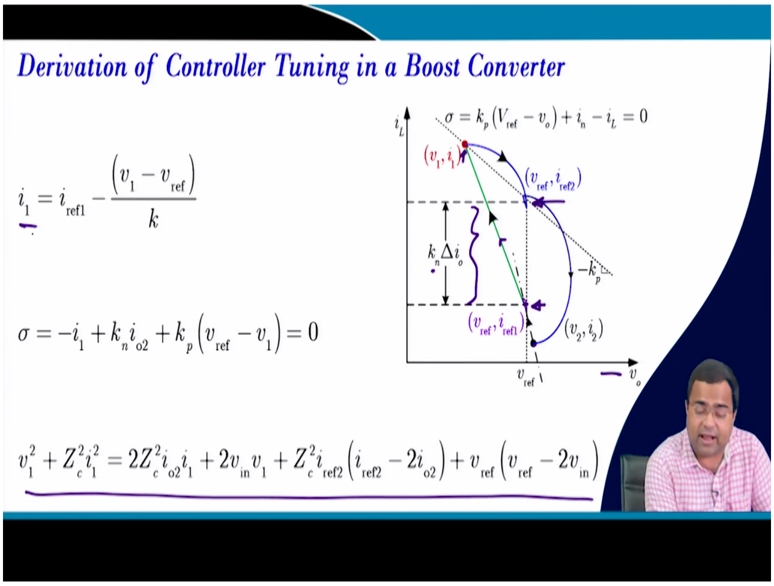

Now, here it is v 1 i 1 because this is a point and where v 0 is my x axis and i l on the y axis. So, our initial operating point is, you know, here. So, where we need to substitute here; that means, if we take this to be our initial average inductor current and this to be our final average inductor current.

And this is the average current change, which is a function of load step size into the normalized factor right. Then we can find out i 1 and this equation is simple because it is a straight line equation because if you go back. If you substitute q equal to 1 this term will vanish. This term will vanish.

So, it will just solution of one first order equation it will look like a first order because it is like a line it will not pass through origin, but it is the negative slope, but the off state trajectory equation will be somewhat complex that is why we are not going to derive it completely. We can write v 1 i 1 is the final condition for on state and v 1 i 1 is the initial condition for the off state. And the final state is v ref i ref 2 and this is v ref i ref 1, i ref 1 is the reference current before transient i ref 2 is the reference line after transient.

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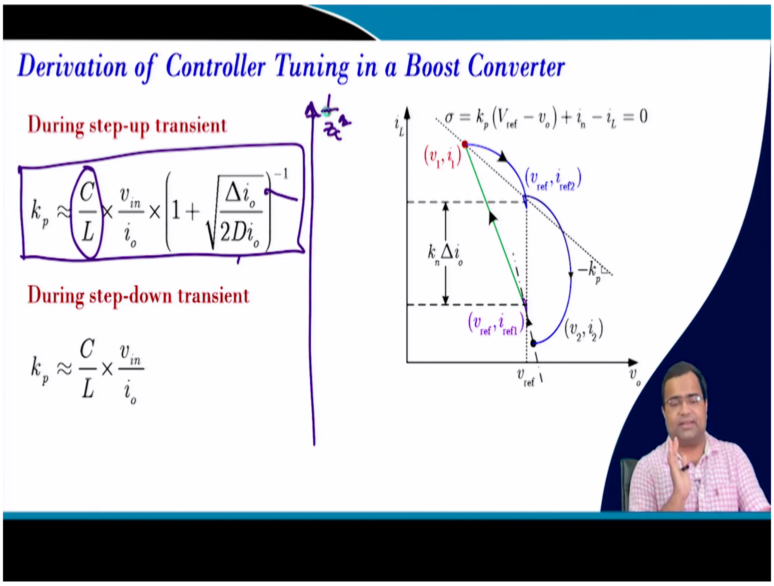

If you substitute and solve it you will get an approximate original equation is quite complex, but the approximate because there are some terms which has almost negligible impact. But if you separate out the actual term which is dominating, you will get the approximate relationship this and this is nothing but our 1 by z c square, the characteristic impedance square and input by output.

So, you will see you need to know the load current duty ratio anyway you can get it if you do digital, control you can get the on state off state. But else you are assuming it is known reasonably, it does not vary too much, but here you need to get the information of input voltage and load current.

So, the input voltage you can access because it is the voltage if you go to any commercial i c we can have a provision for input voltage sensing, but the load current sensing is the difficult task. We generally do not go for actual sensing of load current though for boost converter the load current is somewhat lower because if you are going for high voltage low current application, but still it is not very much recommended, but we can use an estimated load current algorithm.

Suppose we did it for you to know if we go for LED driver then again the load current can be obtained by you know because in LED driving we have to go for PWM dimming where the actual nominal current we know it. And when we are going to turn on and off that signal is also generated from our controller.

So, by staying by taking the state of the signal, we will know the load step size because we know the nominal current it is possible. And of step down transient it is simply C by L mean by i 0. So, we can summarize this step, but we are not going to get go into the actual derivation because as I said the expressions is somewhat complex so that is why we avoid here.

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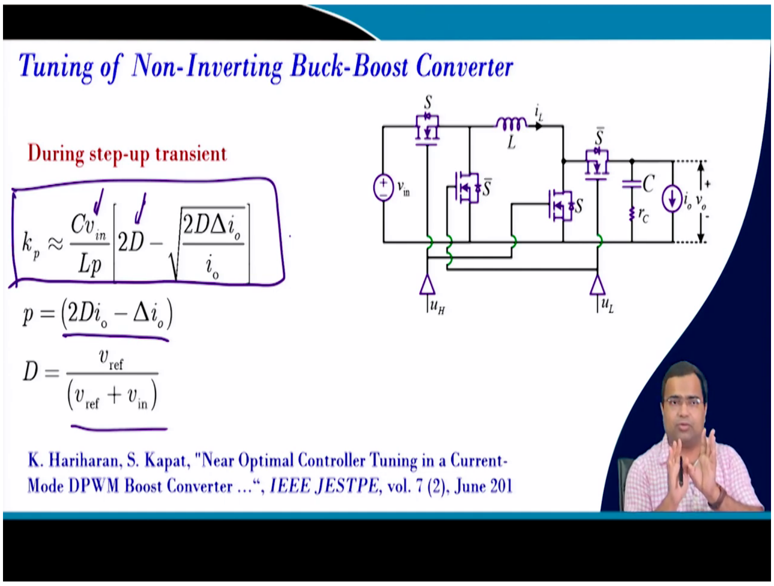

Similarly, for a non-inverting buck boost also, we have derived, but this derivation is quite complex but we got the simplified expression of the proportional gain where, duty ratio we know we can find our input voltage if we sense, but we need to know the load kind of information where all this information can be obtained otherwise.

Because input voltage we can have an arrangement for sensing, but load current either we have to estimate then we can plug in this into lookup table, but how to change it. So, in we can compute or you can create a lookup table because we have discussed the gain scheduling.

So, such gain scheduling can be incorporated in large signal tuning where we can get the parameter value for a certain load condition or input voltage condition otherwise you can do computation because that is not a very complex term we can do it in our digital controller platform.

So, this is also discussed in this paper. So, we can go for this our tuning large signal tuning method for buck boost as well as this was extended for you know cascaded DC DC converter and that will see in show you in experimental result maybe in the last week we show you. That was also applied, and it is not very difficult, it is also simple.

So, this tuning method can be applied for buck boost buck boost two stage cascaded converter even if the cascaded has a buck and boost or to buck to boost. So, we can extend this technique only thing we need to get. We need to have load current information either if you do not sense by some means of estimation.

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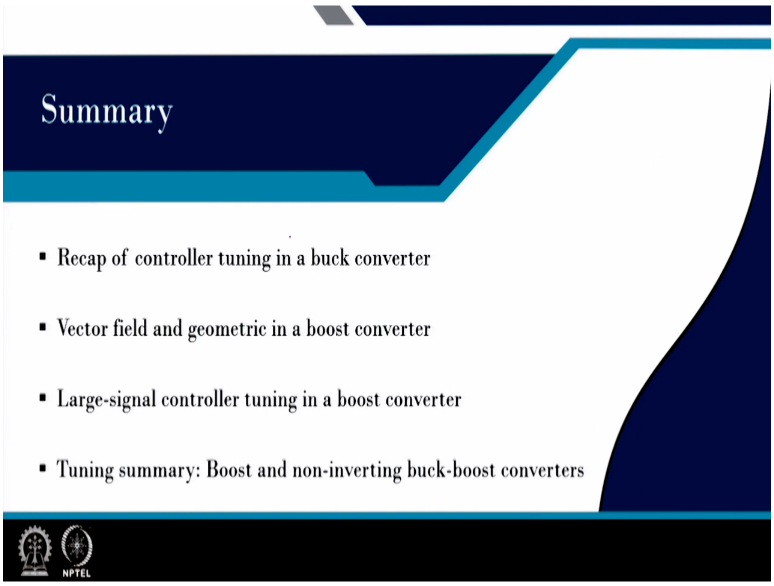

So, with this I summarize that we have recapitulate the controller tuning in a buck converter then we draw vector field and geometric aspect in a boost converter then we talked about large signal controller tuning in a boost converter and then we have summarize the formulation of the tuning parameters for boost and non-inverting buck-boost converter.

So, with this I will finish it here and we will discuss the MATLAB simulation case study in the last week. So, with this I finish it here.

Thank you very much.