Control and Tuning Methods in Switched Mode Power Converters
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Module - 12
Performance Comparison and Stimulation
Lecture - 56
Performance Improvement and Size Reduction Using Large - Signal Based Control

Welcome this is lecture number 56. In this lecture, we are going to talk about Performance Improvement and Size Reduction using Large-Signal Based Control.

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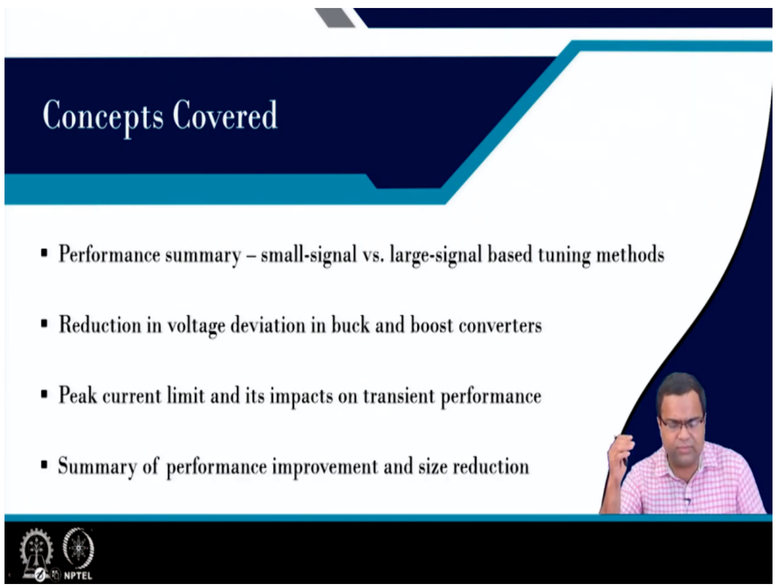

So, in this lecture we will first summarize small-signal versus large-signal based tuning; performance summary and we will initially show simulation result using load transient for load transient as well as a reference transient for a buck converter using voltage mode as well as current mode control.

Then I will talk about the reference transient of a boost converter using current mode control that comparison and then finally, I want to show an experimental result of some fixed frequency as well as the variable frequency small-signal and large-signal tuning, ok.

So, then I want to show the reduction in voltage deviation and voltage in deviation in buck and boost converter, then peak current limit if we impose, then what is the impact on the transient response because we need to achieve time optimal recovery using large-signal transient or large-signal tuning. But, that will come with the price of somewhat higher current overshoot, but if you impose a current limit, then we want to see what is the performance with then current limit. Then we want to summarize the performance improvement and size reduction.

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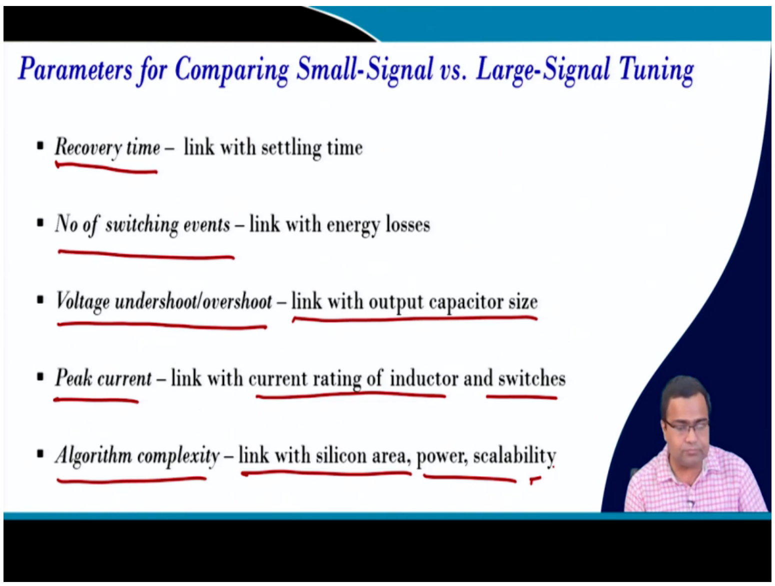

So, the parameter for comparison first we want to talk about recovery time because this is very important this recovery time because it represent the speed of the response and this is somewhat similar to settling time because if that can be reduced, then the converter can respond to frequent load or reference transient ok. So, that is the requirement from the application end.

Then the number of switching event during a large-signal recovery: so, if you can reduce the number of switching event then we can even reduce the switching losses right, because the driver loss and switching loss and by that way we can in fact, save or you can improve the energy efficiency.

Then we can also improve or reduce the voltage understood and overshoot and which is linked with the output capacitor. So, if we can reduce the voltage undershoot or overshoot either you know within the acceptable range, we may have freedom to reduce further reduce the capacitor.

Because suppose if your specification is let us say 200 millivolt for 1 volt power supply and suppose if we could achieve up to 100 millivolt reduction like an undershoot then we can further reduce the capacitor by almost half. So, that will increase the power density.

The peak current sometime will see that is another factor because in this large-signal tuning since it is going for time optimal control, you may have a high peak current and that we should you know that may require higher rating of the inductor and the switches.

But if we incorporate the current limit, then you do not need to bother, because if you are talking about current mode control you can always put a current limit. This current limit will try to extract the best performance within the range of current bound, which can be achieved using our optimal tuning. Finally, we want to evaluate what is the complexity of the solution because that is linked with silicon area power you know power budget as well as the scalability, ok.

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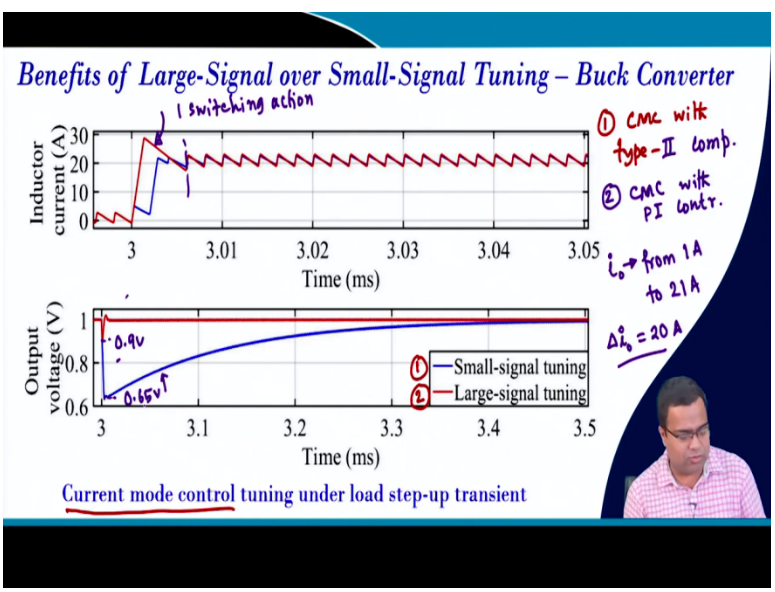

Now, we want to show the benefit of large-signal tuning over small-signal tuning. Here we are talking about current mode control. It is mentioned here you know we are talking about current mode control for both cases, but in large-signal tuning we have computed and in current mode control; that means, for let us say this is our 1 case and this is number 2.

So, for case 1 we are taking current mode control with type 2 compensator whereas the 2nd case we are talking about current mode control with PI controller and the load current is going from changing from it changes from 1 ampere to 21 ampere sorry, 21 ampere. So, our load step size for all the case studies that we are going to show for buck converter loads transient is the 20 ampere load step size.

You can see the optimal large-signal tuning is achieved. It can achieve 1 switching action; 1 switching action it reaches here right whereas, in case of current mode control regular, it takes multiple switching cycles. The output voltage comes up to 0.9 volt for the large-signal tuning and this it can come up to 0.65 volt; that means, the undershoot for this case, the undershoot will be 0.1 volt and here it will be 0.35 volt ok.

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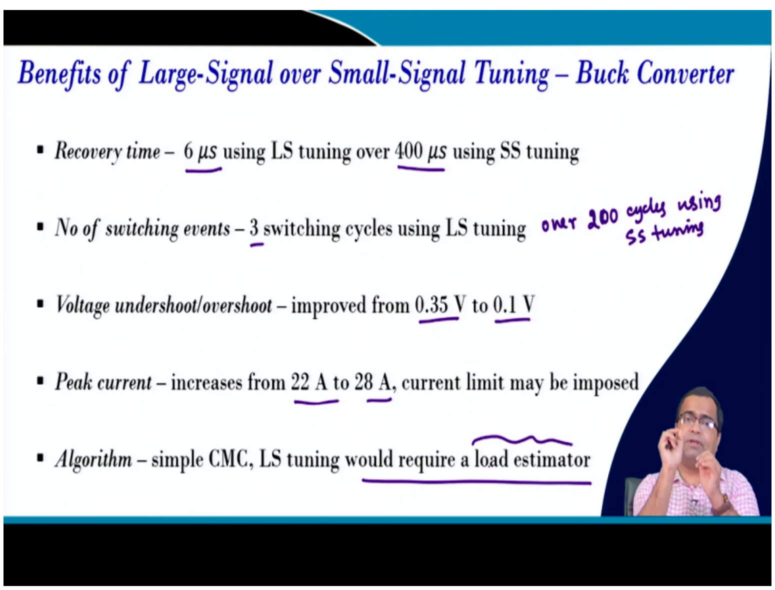

Now, if you summarize the performance, the recovery time for large-signal tuning is 6 micro second over 400 micro second means small-signal tuning number of switching cycle is a 3 switching cycle using large-signal tuning and because that and here it will be because 2 micro second is my time period. So, in this case, it will be over. You can say 100 200 cycle using small-signal tuning ok.

Voltage undershoot is improved by from 0.35 volt to 0.1 volt and there, but the peak current increases from 22 ampere to 28 ampere. So, you may put a current limit and then the algorithm in regular like a for the large-signal tuning. We are using a load current feed forward whereas, the small-signal tuning we are not using any load current; it is a traditional current mode control.

So, this load current you may either require to sense load current, which is not recommended, or you can use a load estimator and that if you go for digital control, that load estimator you can put an algorithm to estimate load. In fact, you know if you are talking about the power supply for processor if you use a digital control platform.

And if you can interact or interface with the power supply and the processor and if there is a task scheduler which can give a priori information that a new task is coming with this much of energy requirement voltage and current requirement. So, then you can extract what will be my load step transient that is going to come. So, that estimation that load information also can be extracted indirectly from the processor, but otherwise you can put a load estimator.

In case of LED driving application you can get this load information from if you using a PWM dimming, each of this you know LED string will have their nominal current. So, once you turn on that string, then you know the nominal current is my required current. So, that can be indirectly obtained by looking at the switching status of the particular string and there that load estimation can be done very easily.

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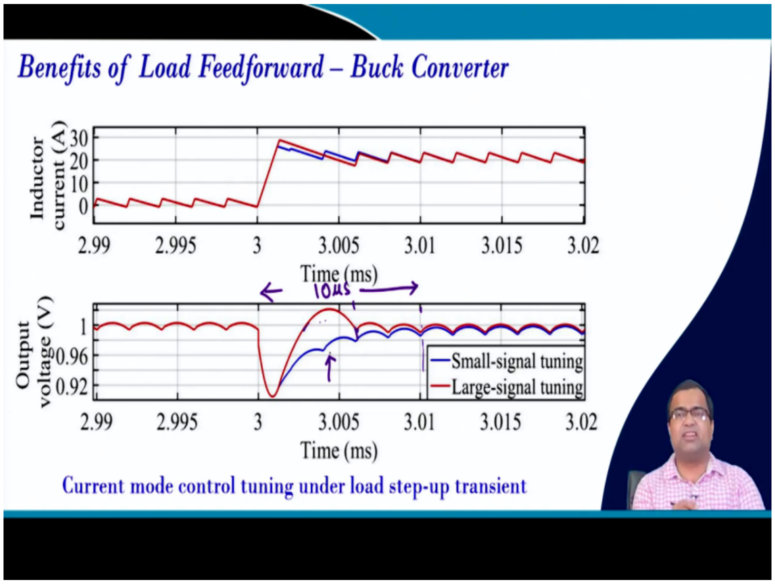

But, if you incorporate load current feed forward in regular current mode control and tuning optimal tuning already it is you know I would say it is already load feed forward is there, but you see this small you know an overshoot came in that time optimal tuning because we are using a fixed frequency modulator, right? So, the fixed frequency modulator we have a time constraint because it has to be again turned on when the next clock is come.

So, due to this time constraint of the modulator it may not be exactly optimal it is something called proximate time optimum, but now you can look at the load feed forward using current mode it is fast, but it require multiple switching action and the voltage comes close to steady state here. So, this is our recovery time. it is like almost 10 micro second for the conventional current mode controlling using small-signal model design, but with load feed forward.

And, because of this multiple switching action, you may end up with little more switching loss during the transient recovery. But if you are going for different load step size, different input voltage conditions, then these two responses will diverge. We will see this. We have seen earlier that if your input voltage decreases, then simple load feed forward in current mode control may not give this kind of response because then your optimal tuning can achieve really fast transient response.

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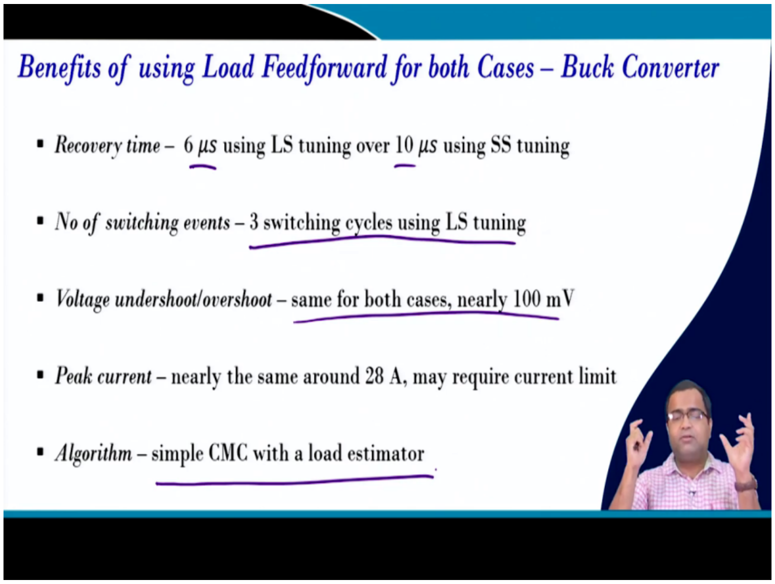

So, the benefit of load feed forward in this case 6 micro second over 10 micro second that is improved. Large-signal tuning only takes 3 switching cycle; the voltage undershoot is same it is 0.1 volt; peak current nearly the same 25 28 ampere and here we can use a load estimator for each case, but we can put a peak current limit and see what is the performance.

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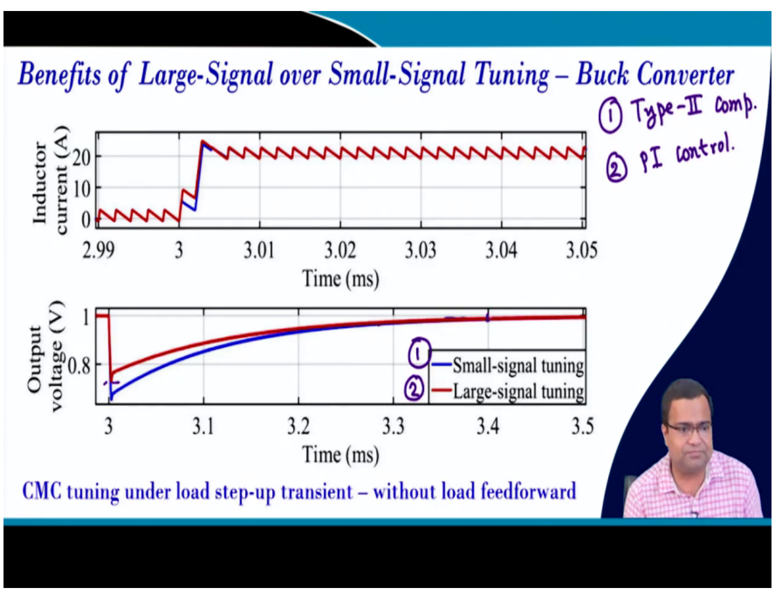

Now, if we remove load feed forward for both the cases. So, it is current mode control. In the first case when you are using conventional tuning, we are using type 2; that means, number 1 number 2, number 1 we are using type 2 compensator and number 2 we are using simply PI controller. Then you can see that PI controller with optimal T given because if optimal gain we obtain incorporating load feed forward.

But, suppose we retain the gain and we remove the load feed forward. You can see the undershoot is reduced I mean it is reduced by almost 100 millivolt; that means, both without load feed forward and both cases recovery time more or less same is like they are almost reaching 1 volt after this much time.

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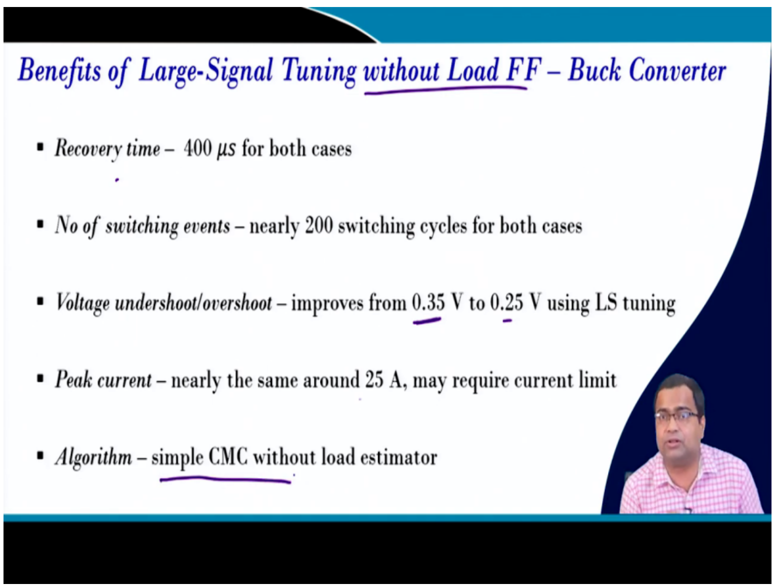

But, number of switching cycles are also same, but the voltage undershoot improved from 0.25 to point sorry, 0.35 to 0.25 so that can be reduced. So, that means this tuning can be used to even improve the performance of current mode control even there is no load feed forward.

And, the peak currents are nearly same around 25 ampere if you go back they are almost same like a 25 ampere, ok and you can also require current limit if you want to impose, but 25 ampere for 21 ampere nominal current is acceptable is much within the limit. And, as the algorithm both are using simple current mode, there is no load feed forward.

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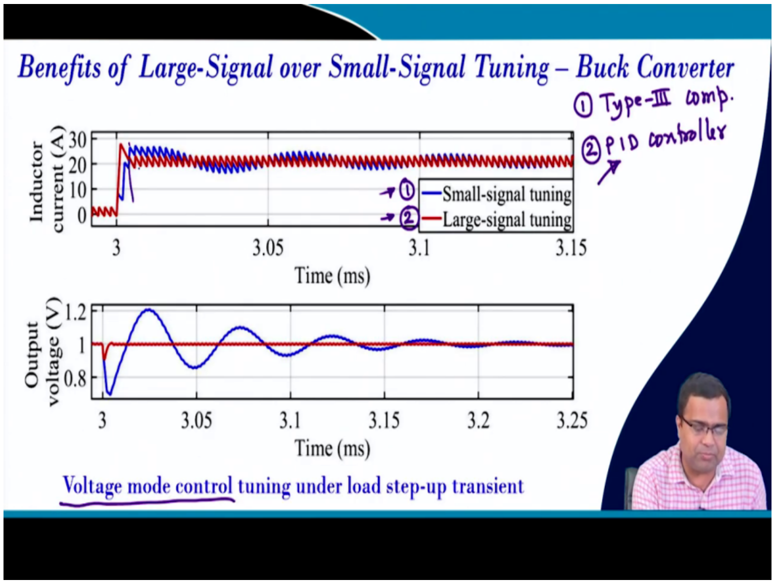

Now, if you are comparing want to compare voltage mode control. So, this is under voltage mode control where both proposed tuning; that means, large-signal tuning. I would say this is a large-signal, and this is a large-signal. This is small-signal tuning, and this is large-signal tuning.

So, for case 1, we are using type 3 compensator because we have discussed a type 3 compensator can achieve fast transient for a voltage mode control, whereas it is better than PID controller. It is because of the additional pole that we have discussed and I think this part was covered in lecture number 35 where you saw in 34 we use a PID controller there is a model validity issue and using type 3 compensator we can speed up the response.

But, with this, but now in the second case we are using a simple PID controller; that means, in small-signal model we saw PID controller was not good enough. We go for type III compensator, but when you come to large-signal model the PID controller itself is enough and it results into time optimal recovery. You see it is just it is reaching in two switching cycle just two switching cycle it speed up, very fast transient response whereas, the voltage mode control take lot of time because in the load transient response you know the output impedance has a problem here, right.

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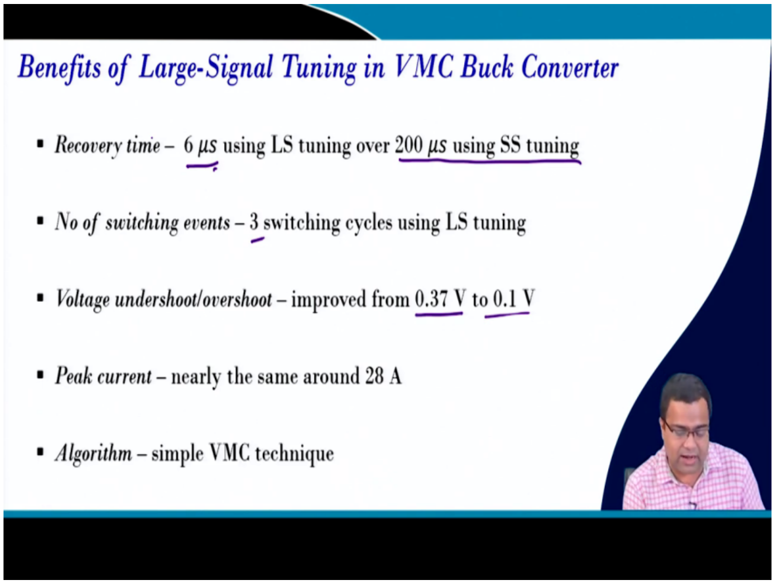

So, in proposed tuning, both are under voltage mode. It takes only 6 micro second perhaps it could be 4 because you know maybe if we include this 6 micro second using large-signal over 200 micro second using small-signal tuning. So, it is a significant improvement..

And, the large-signal tuning only takes 3 switching cycle, and the overshoot is drastically reduced from 370 millivolt to 100 millivolt and the peak current in both cases is more or less same. If you go back, their peak current are more or less same around 28 ampere, but since there is no current sensor here so, you cannot impose any current limit and algorithm. It is a simple voltage mode control nothing.

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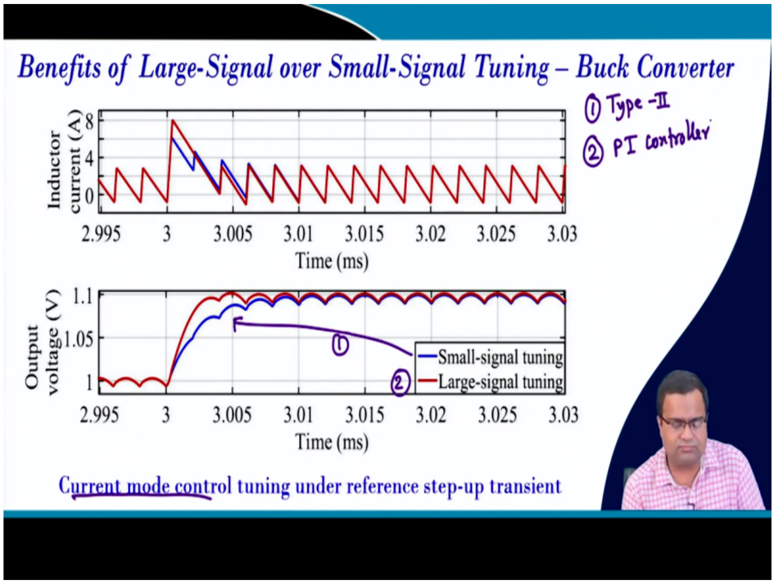

Then, if you go for a reference transient using current mode control, so, this is using because here there is no role in feed forward load feed forward because it is a reference transient, there is no change in the load current. Here, in case of traditional current mode control, where we consider one tenth of the switching frequency, this is number 1 and number 2 here you are using optimal tuning. So, again, for the first case we are using type 2 compensator because it is current mode control it is current mode control and number 2 we are using just PI controller with optimal gain and we achieve the response much faster.

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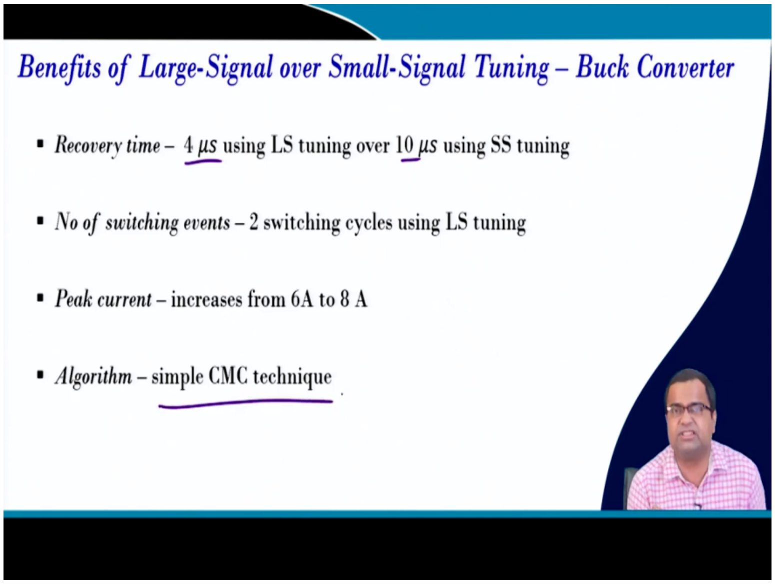

That means 4 micro seconds using small say large-signals tuning over 10 micro second, the number of switching is just 2 cycle it recovers. But peak current increases from 6 amperes to 8 ampere that can be reduced by putting a current limit and in both cases using simple current mode control technique, there is no load feed forward.

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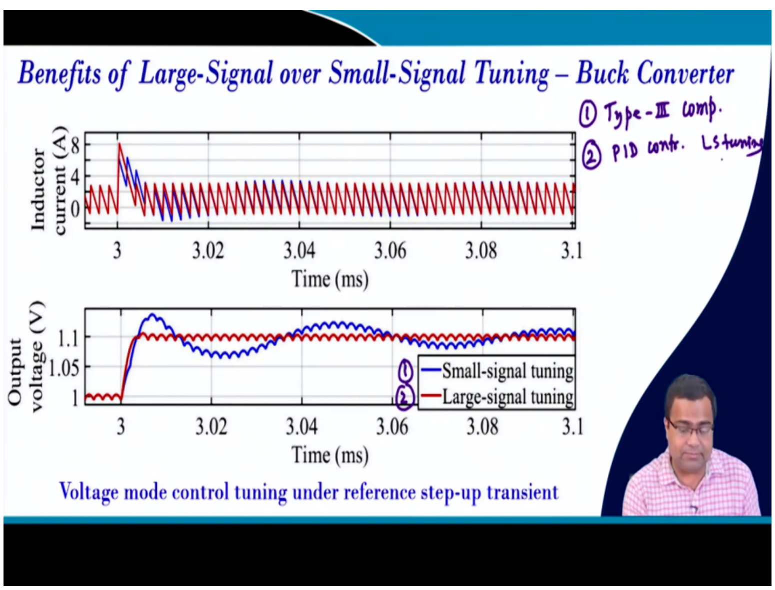

Now, if we go for voltage mode control reference transient so, here the voltage mode control you know in the first case; that means, this is number 1, number 2; we are using type 3 compensator because we saw type 3 compensator can achieve better bandwidth with one tenth of the switching frequency with model matching.

And, here it is simply PID controller and you see the PID controller with optimal large-signal tuning large-signal tuning can achieve optimal recovery and it just reaches in 4 microsecond whereas, this the other one that small-signal model based voltage mode it takes 400 micro second.

So, recovery time is just 2 switching cycle and, but the peak current increases from 6 to 8 ampere. I think that is not significant because you know we have a higher current rating, let us say it is a 30 ampere rating then algorithm is simple voltage mode control. So, the bottom line is this: you can improve the performance significantly.

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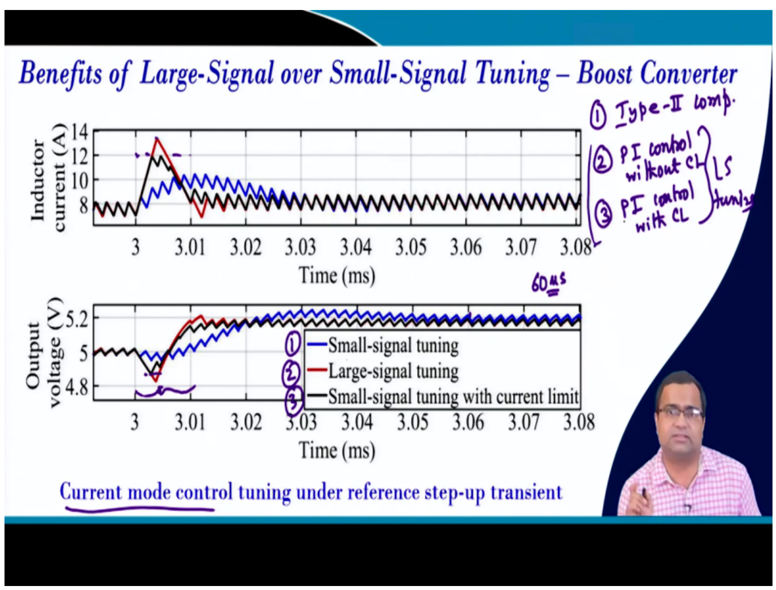

Now, if you take a boost converter, you know the boost converter. This is number 1, and this is number 2, this is number 3. In number 1 we are using it is current mode control only we are using type 2 compensator; type 2 compensator; number 2 we are using simple PI control without current limit and 3 PI control with current limit and both using large-signal tuning.

And, you can see the red one which is the optimal tuning with no current limit it is giving time optimal recovery and it is recovering in 5 switching cycles and our traditional current mode control it is taking almost you know close to I would say 0.6; that means, here. So, it is like a zero point; that means, 60 micro second, which is like 30 cycles.

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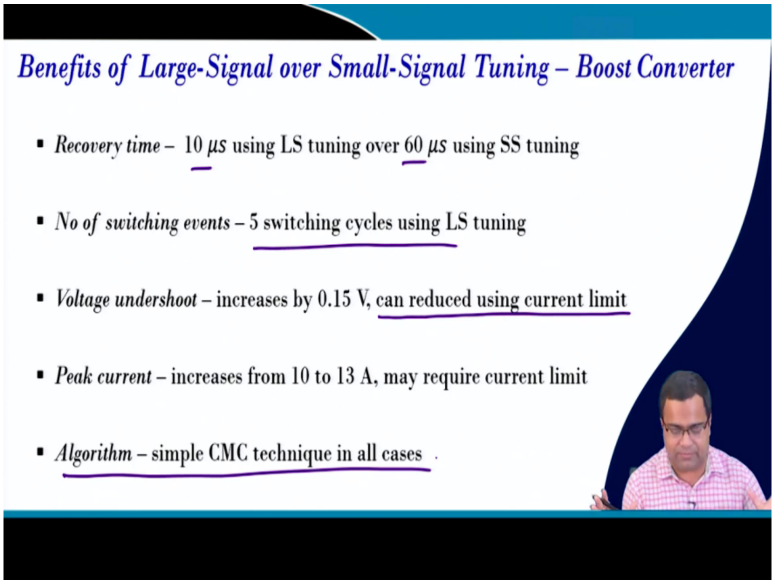

So, it is like a 60 micro second in 30 cycles. So, it improves by 6 time, it just recovers in 5 switching cycles. So, you can improve the energy efficiency and the voltage undershoot reduces because in the time interval control since the duty ratio is allowed to saturate and it is increasing and you know during the on time actually your output capacitor discharges.

And, if you continue to turn on the switch for a longer duration, the output voltage will further fall. So, as a result, this is in contrast to buck converter in which the time optimal control also ensures the minimum voltage undershoot, but in boost converter the time interval control actually results into a larger voltage undershoot because of the non-minimum phase behaviour.

And, that can be reduced and also the peak current can be reduced by putting a simple current limit and that exactly I did I just put a 12 ampere current limit in the third case and you see the third case the voltage understood is reduced and over the actual optimal where there is no current limit, ok. So, it is reduced.

And, it can be reduced, and it is reduced by almost here it is 0.1. So, that means, almost 50 milli volt is reduced and the peak current increases from 10 to 13 ampere from it is going up to 13 ampere and that can be reduced by putting a current limit that we have discussed shown here.

But, in this algorithm it is all under current mode control there is no lead load feed forward nothing and only thing we have discussed that we have use a type 2 compensator for regular current mode control and the current mode control with PI controller using large-signal tuning.

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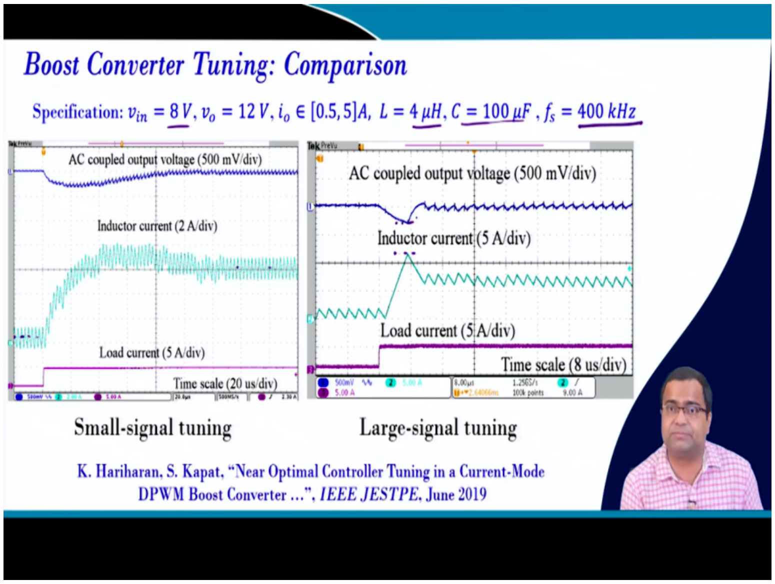

Now, I want to show some boost converter experimental result. So, it is under 400 switching kilohertz switching frequency, 100 micro farad capacitor 4 micro Henry inductor. And 8V input and 12 volt output, we are using small-signal tuning in current mode control where your load current increases from 0.5. That means it is changing from here to here. This is the inductor current. Remember average inductor current it is undergoing load step transient.

And the time of dual recovery it reaches so fast, but there is a current limit and also the voltage undershoot may be large. So, this is already you know these results are taken from this paper in our paper so where we have talked about large-signal tuning of voltage mode boost converter in current mode control.

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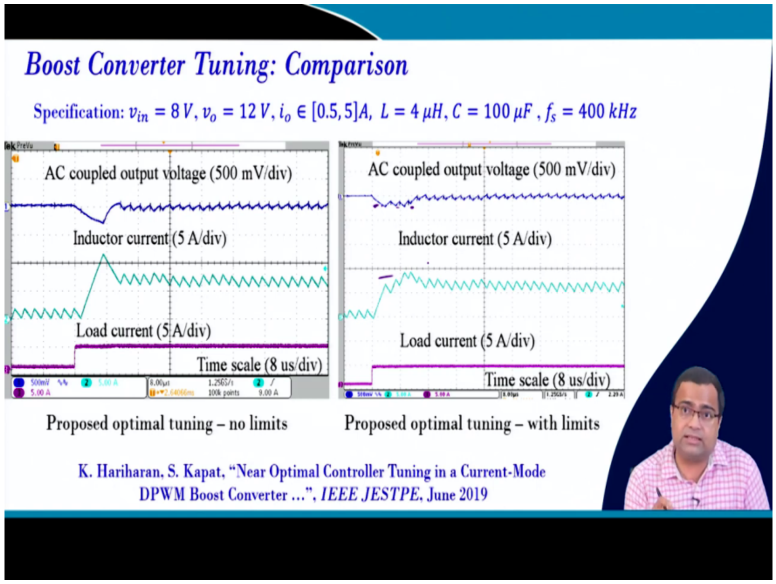

Now, if we impose a current and voltage limit, then you can drastically reduce the voltage undershoot because just now we discuss in a boost converter if you want to achieve time optimal control it will undergo larger voltage undershoot, but if you impose a voltage undershoot and the current limit, then you can drastically reduce it.

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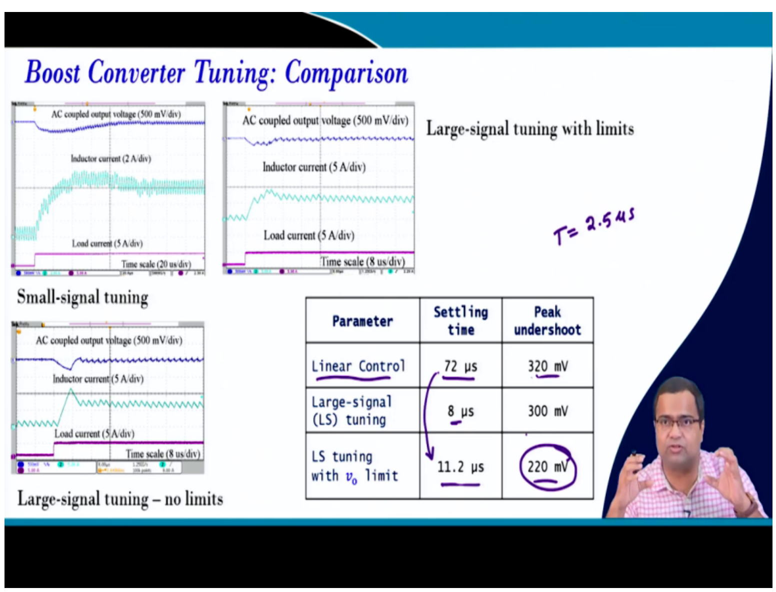

And, this is much faster than linear control and that can be shown using this table. So, linear control takes 72 microsecond whereas, the 400 kilohertz of switching frequency. So, our time period is 2.5 micro second is our time period, ok and large-signal tuning is just taking 8 micro second and if we put some current and voltage limit, it is just taking 11.2 microseconds. So, it is almost more than 6 time improvement even with reduce undershoot because a voltage undershoot can be reduced by putting imposing a voltage constant as well as current constant.

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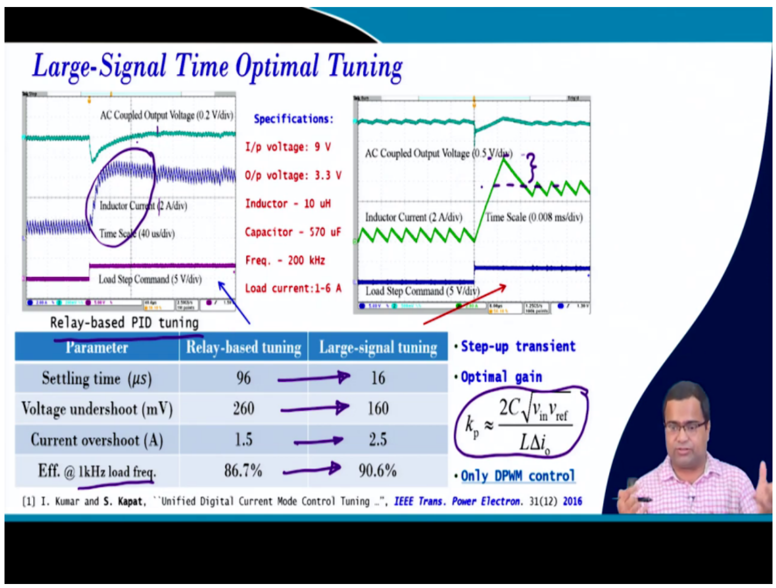

We have actually initially applied to a buck converter where we have compared if we take a relay based PID tuning that is a traditionally used and we have discussed this relay based tuning in lecture number 34 in a buck converter. And, if we use our tuning method where the optimal gain can be very easily frame using current mode control..

So, you can improve the settling time or the recovery time by 6 times 6 fold, and the voltage undershoot is also reduced from 260 millivolt to 160 millivolt. So, this will enable. This enables us to further reduce the capacitor, right? But the current overshoot increases, which we can also reduce as I told. So, the current overshoot means we are measuring the current from here to here..

So, this we call as a current overshoot. So, this is increased from 1.5 ampere to you know 2.5 ampere. If it is within limit fine, but if it is going beyond limit, then we need to put a current limit and we saw that with current limit also we get very good response.

And, another interesting point we have improved the energy efficiency because we have considered 1 kilohertz load frequency. That means the load step is happening at the rate of 1 kilohertz switching frequency periodically varying and this load step up straight down it is happening and under such condition we got improvement in efficiency almost more than 4 percent and that I saw.

I told because you see, during this recovery process, you have so many cycle turn on turn off number of switching that also increases switching losses and driver loss. It is only one switching action, and this is results are taken from this paper and where we have discussed in detail.

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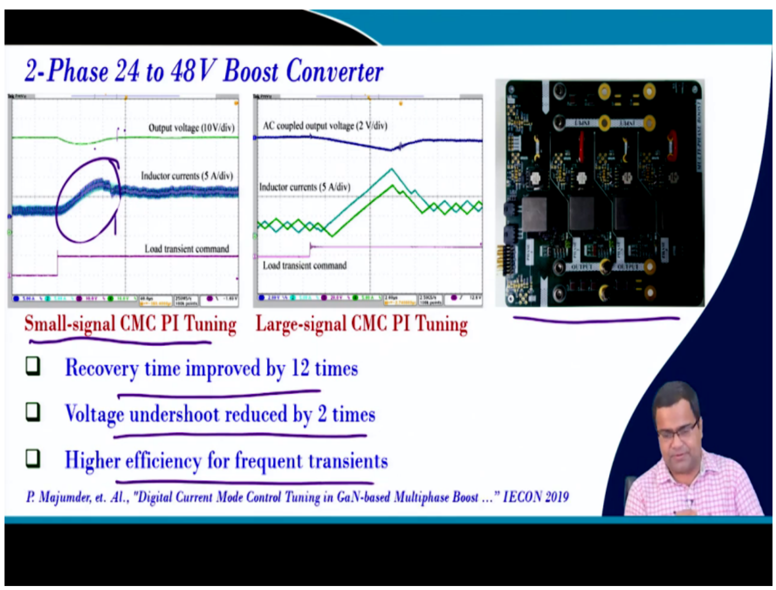

We have applied this tuning also for a boost 2-phase boost converter, where we have designed a current mode control and this is using a gain based architecture where we have operated close to 500 kilowatt switching frequency. And, if we go for large-signal to using in 2-phase boost converter we got almost optimal recovery. Near to optimal recovery and where the recovery time we improve by 12 time voltage understood is reduced by 2 times and the energy efficiency we got higher energy efficiency.

Here the number of switching happening because there are a number of phases are more, right? So, here two phases mean both the switches will be turned on and off multiple time. So, you can get even more benefit when you go for such large-signal control for multiphase where the number of phase increases because all the phases the number of switching even can be drastically reduced by this large-signal tuning and this has been reported in multiphase in our paper.

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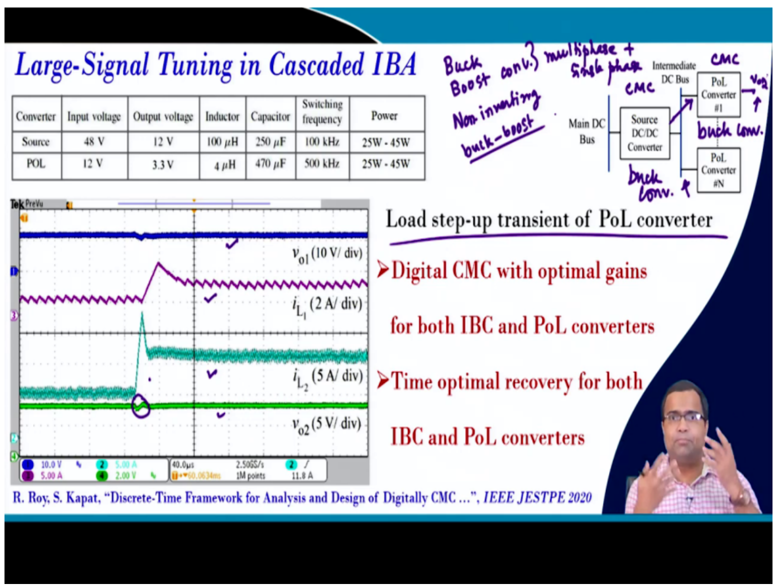

So, the large-signal tuning we also applied in cascade because we discussed if we take 2 and here it is a buck converter we have considered here also we consider it PoL buck converter, ok. So, two stages we have considered only these two stages may be, but there can be n number stages and this method can be extended.

So, this waveform shows the inductor current in the first stage. This waveform shows the inductor current of the second stage and this is the output voltage of the intermediate bus; that means, I am talking about this bus and this is an output voltage of the PoL; that means, it is output voltage where it is connected to the load.

The response is extremely fast. There is a power step transient or a load step transient at this second stage. We are applying a load step transient. We have discussed in the earlier lecture that both are operating under current mode control, but digital current mode control, where we have used PI controller for both the cases. The PI controller gains are optimally tuned. We have discussed in the previous lecture for a cascaded converter.

And, if we plug in those PI controller then we can achieve you know first optimal recovery for both the stages and it can really speed up the recovery and it is the fastest response that we can achieve in this two-stage architecture. So, time optimal recovery for both IBC and PoL, and this has been reported in this paper.

So, we have experimentally showed for a wide range. We have tested this for our normal buck converter. We have tested for boost converter and we have tested for multi phase also multi phase plus single phase then we have considered non-inverting buck boost, where you know in this APEC, 2021 we have published that non inverting buck boost. We can change mode from buck to boost to buck or buck boost by optimal tuning. You can apply just by simply changing the gain and current mode control we need to update the proportional gain.

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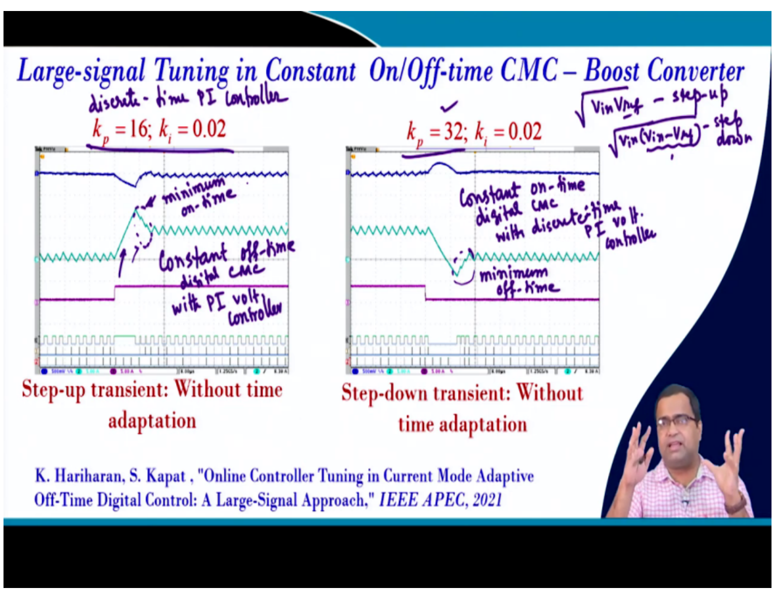

So, and then we have extended as I said that it can be applied for variable frequency control. So, here if we take a constant here, it is like a constant off time control constant of time control. Here we are using a with PI voltage controller and we are using the discrete time. It is like a discrete time is a discrete time PI because it is digital current mode control.

See, in constant of time we know that there is a problem in the step down or basically off time. There is a minimum on time that you have to provide and that is somewhat slowed down the response. Otherwise, while it is going up it is very fast extremely fast and there is an optimal solution.

But, some non-optimality or few more switching can come due to that minimum on time because we are not adopting the on time, but I will show you if you adopt this on time, then it is possible to actually make this transition fast. Another way if we go first step down transient and it is constant on time, this is all digital. I would say digital current mode control here also with discrete time PI voltage controller.

Here also we have some sort of minimum you can see minimum on off-time that is probably provided when constant on time and this is also minimum off-time on time that is provided in constant off time current mode control. And, because of that there is a slight you know degradation in the response, but it is ok.

So, this also these results are taken from this APEC paper we have presented here that our optimal tuning can be applied to variable frequency control constant on time of time even we can we have also applied in hysteresis control, but I am not going to show all the results.

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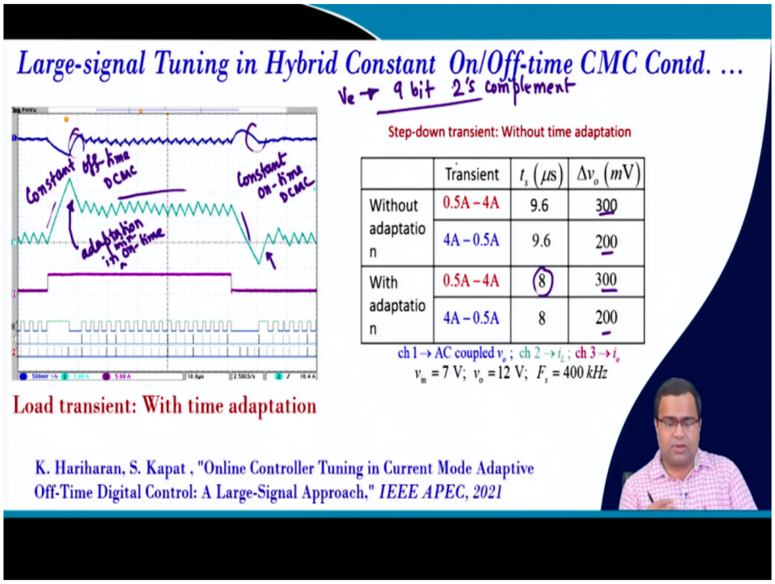

Then, if we hybridize, that means, if we take even with time adaptation; that means, if we take constant off-time you know a digital current mode control here and here if you take constant on-time digital current mode control, but you see we have removed the minimum on-time part here. So, we meet some adaptation in on-time I would say minimum on-time because we have simply disabled the minimum on-time operation during the transient recovery, but yes it is restored near the steady state.

Now, you may ask me how do you identify transient and steady state because when you go for digital control, we generally take the sample output voltage. Then we take inside the digital platform. We subtract that output voltage from the reference voltage and the error voltage will provide some quantized value; that means, if you take the error voltage, error voltage let us say it is 9 bit 2's complement format.

Now, by looking into the lower bit, you can identify whether you know it is the error is large or small. If the error is large, then you can identify there is a large tangent, the error is small and you wait for some few cycle then you can identify it is steady state and then you can restore this on time again.

And, here also we have eliminated the minimum off time. As a result we are getting time optimal recovery is in tangent and we got you know without adaptation we got 300 and 200 millivolt response time. So, the output undershoot does not change because in both cases this is fast very fast.

But, with the adaptation, we got some improvement in the settling time because this part can be improved compared to our previous case where we got some slow recovery due to some additional switching. So, that can be reduced and also you can further reduce the losses during this small part, where the switching even can be avoided and this also results we have taken from this APEC paper.

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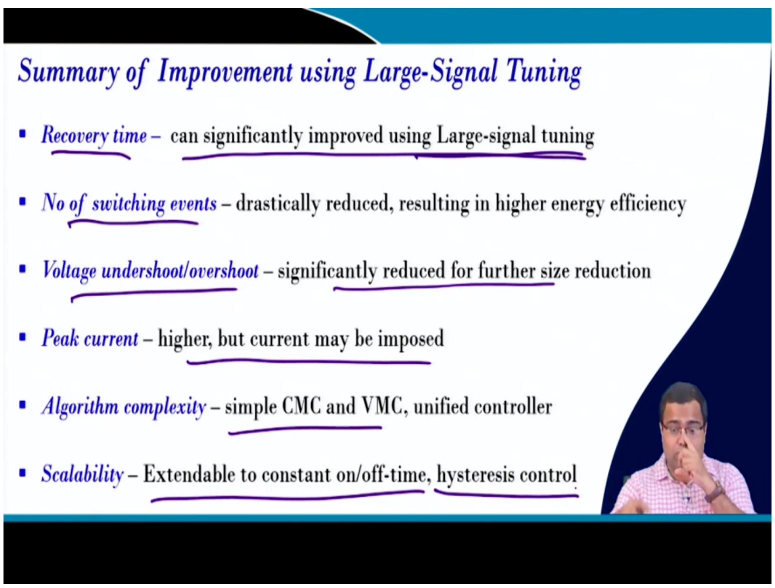

So, summary of improvement using large-signal tuning. We can improve the recovery time and by that way we can significantly reduce the recovery time and. So, number of cycles can be reduced. As a result the speed of the converter or you can think of in terms of bandwidth because it is not applicable it is a non-linear switching model the recovery time is very fast.

So, this converter can handle more frequent transient. Since the number of switching event was drastically reduced, so, you can save you can achieve a higher energy efficiency so that under frequent load transient your converter efficiency can be improved over a conventional linear control.

Voltage undershoot overshoot can be reduced. We have discussed in buck converter in boost we can put a current limit. This reduction allows us to further reduce the capacitor. In a majority of the commercial products, as per the recent trend in power management product to cope up with the performance requirement, they use two different controllers.

One is small-signal controller during steady state and large-signal controller during transient, because the large-signal controller mainly is of variable frequency control. They do not want to operate variable frequency under steady state. So, they integrate and that increases the size silicon area and the complexity and it may lead to some controller transition problem and all. But, here, the large-signal tuning is a single controller, it is either current mode or voltage, it is a single controller there is no separate requirement for additional controller.

But, you can configure this controller by using the same resource just by changing the modulation like we can change it from constant off time to constant on time and so on because your controller is common; that means, your control voltage is common or con reference current is common. And only the change in modulator will not make the system because there is something called wind up problem.

When there is a change in controller; suppose you are going for large-signal control to small-signal suddenly you enable, the integrator error can become very large. It can even make the additional transient due to the controller change, but here such problem will not happen because it is a single controller and where either we can initiate the integral action throughout or in some cases, we can stop you know incrementing during the recovery process.

Peak current was higher, but we have shown that by putting a peak current limit we can get close to near optimal recovery subject to the current limit that is simply, but the gain will remain same. So, that is the beauty here. And, the algorithm this is a simple current mode and voltage mode control. We can apply this tuning method. So, there is no additional complexity, there is no additional large-signal small-signal combination and this itself will act like a multi mode controller.

And, this technique is scalable because since we are just changing the gain it is just the view point change of the controller tuning instead of using small-signal linear model we are going for large-signal model and that can take into account the performance ripple information and you can push the performance up the slew rate limit.

And, we have shown this can be extended to constant on off time control, it we have shown also earlier. Although not demonstrated in this lecture, but in our research paper that this can be easily applied to hysteresis control. In fact, the switching control you started with in the hysteresis control, where we have formulated the gain. So, naturally this can be applied to hysteresis control.

So, this technique is scalable. You know you can go to any modulation or control strategy and you do not need to make any additional changes. Only you need to keep a set of gains for different operating condition and that is what we do even for regular small-signal model where we up we load some parameter value from a lookup table same thing can be done, but this can achieve very fast transient and high energy efficiency with smaller size capacitor.

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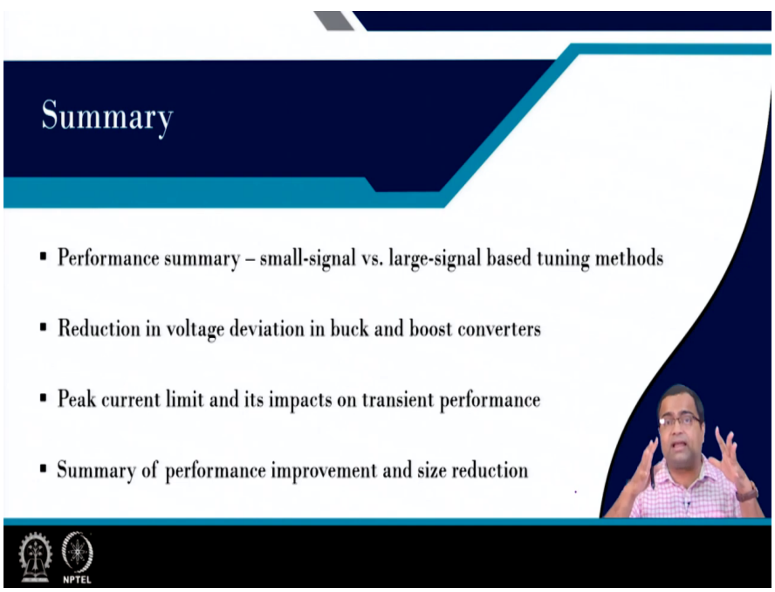

So, in summary, we discussed the small-signal versus large-signal based tuning method. We show we have shown that the reduction in voltage deviation in buck and boost converter can be achieved and there is a peak current limit. We can impose and we still can achieve very fast transient subject to the current limit..

And we have summarized the performance improvement as well as the size reduction. And, this can be useful for achieving higher efficiency, faster recovery and smaller size power converter for future power management solution. So, with this I want to finish it here..

Thank you very much.