Control and Tuning Methods in Switched Mode Power Converters

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Module - 12
Performance Comparison and Simulation
Lecture - 60
Course Summary, Key Takeaways, Few Emerging Applications and Future Scopes

Welcome, this is lecture number 60 perhaps this is the final lecture of this course. And in this lecture we want to summarize what are the concept that we have learned in this course, then what are the key takeaways. And then I also want to discuss Few Emerging Applications and some Future Scopes.

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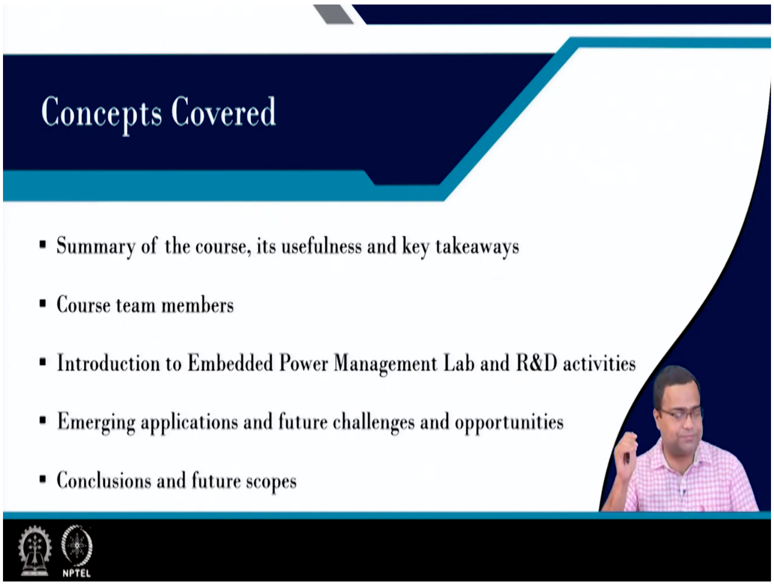

So, in this course we are going to talk about, we are going to summarize the concepts that we have learned and what why they are important and what are the usefulness. And, of course, some key takeaways. then I also want to introduce the course team members and I want to introduce embedded power management lab and some research and development activities.

Then I also want to show some emerging application and some future challenges as well as opportunities. And finally, I want to conclude along with some future scopes.

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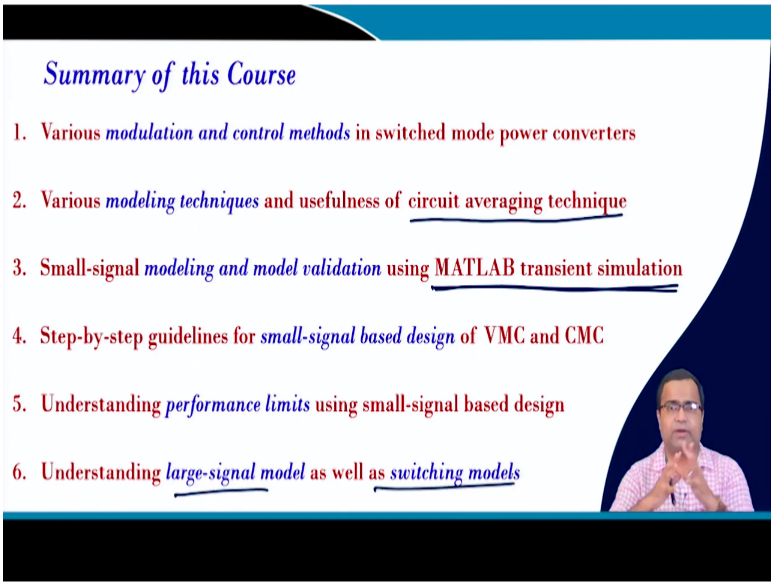

So, in this course we have learned many things like and as I said at the very beginning, this course is somewhat different from conventional switch mode power converter course. In this course, we have primarily you know focus on modeling, control then tuning, design modulation technique, variety of thing which are often very important for switch mode power converter. Though most of the example we have considered in buck and boost converters, in some cases cascaded converter.

You know this concept once you know one can understand the concept, then you can also try to apply to other converter like isolated converter topologies. In fact, some you know many of these concepts are equally applicable for a resonant kind of converter and so on.

So, first thing we have learnt various modulation and control method in switch mode power converter. We have seen that we have discussed like a fixed frequency modulation, variable frequency modulation we talked about linear control like a traditional current mode voltage mode control.

We talked about you know non-linear control like a sliding mode control, then boundary control like a switching surface based, time optimal control and all these are very important. Then we also discuss briefly about some modeling technique and we have considered primarily some of the small-signal modeling technique in detail. Because we have developed model and we have validated those models using AC MATLAB transient simulation. And we have checked that how far those models are valid.

And then we have realized that, what are the performance limit due to this small-signal model and how to go beyond that. And we have emphasized for most of the small-signal model using circuit averaging technique. And in this circuit averaging technique, one important point that I have I want to highlight that this technique gives us physical insight.

Because you know we have often talked about input impedance, output impedance audio susceptibility, then control to output transfer function. So, if you want to understand from the circuit point of view like you know how to shape the response, this circuit averaging technique as well as the equivalent circuit concept was very, very important.

Then we have derived various small-signal modeling like a we have introduced a small-signal modeling as well as derive small-signal transfer function. We have validated those transfer functions using MATLAB transient simulation, and this is one of the very important feature.

Because you know you want to understand whatever you have designed by means of transfer function, by means of compensator whether those models are really valid. Whether your design using the linear model by a closed loop simulator like a closed loop simulation is it going to match with the actual switch simulation?

If it does not match, then whatever effort we put during the design process that does not make much sense. Because unless we validate that our concept are applicable, they converge with the actual switch simulation, then whatever we do that has does not have much meaning.

Then we also discuss step-by-step design and this MATLAB transient simulation, actually I have demonstrated in multiple lectures to step by step. That means, you know like I have demonstrated the MATLAB code and I have also demonstrated how to plug in those transfer functions, obtain the step response and then how to add the offset point and how to compare with the actual switch simulation. So, these are very useful technique like a and also I have given a lot of resources for the MATLAB.

Then I have also discussed step-by-step guideline for small-signal based design and tuning of voltage mode control as well as current mode control. Then we understood what are the performance limit using small-signal based design right. Then I have also discussed some large-signal model as well as like a switching model, because the large-signal model actually considers both switching model and average non-linear model. So, it combines both together that also we have discussed.

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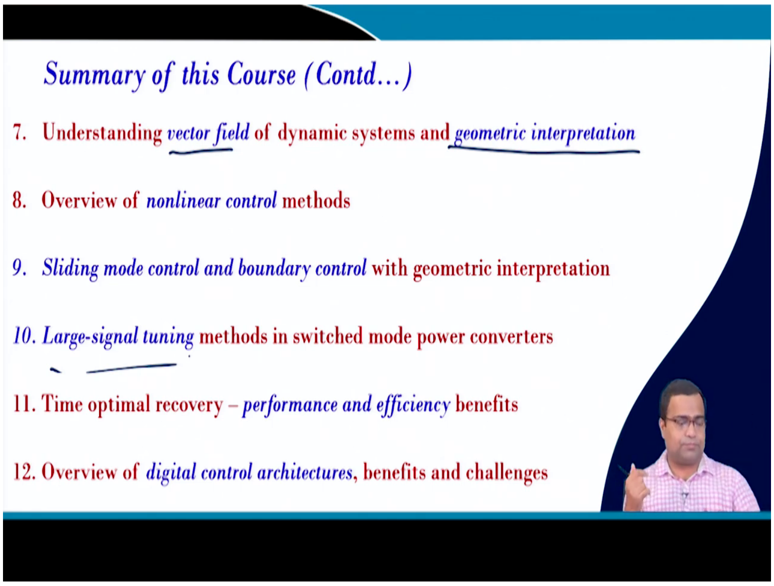

Then we have discussed you know vector field of dynamical system and its geometric interpretation. Because this particular is very important because we often talked about phase plane behaviour when you go for switching control like you know geometric control, boundary control, sliding mode control, we often try to design the switching surface.

But there we need to consider before we design any switching law we need to understand what is the phase plane geometry. That means, if we have a given sub systems we need to understand what is the trajectory of the subsystem on either sides of the switching surface. Then which side should we choose what kind of subsystem, so that it will converge to other switching side.

To understand the trajectory, it is very important to understand the vector field. That is how we have discussed vector field. And we have also demonstrated using MATLAB simulation, how to draw vector field using MATLAB as well as how to draw vector field using analytical solution. And how to interpret this vector field using eigenvalue eigenvector for the linear system.

Because we often talked about eigenvalues, eigenvector, but here in this presentation in some of the previous lecture I have shown that if you understand the vector field very well, then you can interpret physically, the geometric interpretation. How does the vector field look like, how does the eigenvector look like, what is the invariance property of the eigenvector?

Then what is the significance of eigenvalues and eigenvector and then what is the significance of eigenvalues and eigenvector in order to drive the trajectory towards the desired path that also we have discussed. Then we also discuss you know for you know if the system is non-linear, then you cannot talk about eigenvalues and eigenvector.

But the same vector field concept that you have learnt is equally applicable for a non-linear system that also we have discussed. We discussed smooth vector field. We also discussed nonsmooth vector field when there is discontinuity. And then how these vector fields with discontinuous vector field can be combined, and it takes the form of a variable structure system and can be combined into sliding mode control. And then how it can be extended to boundary control that also we have discussed.

Then I have given you know I have also provided the overview demonstrated the overview of non-linear control method. And we have categorized this non-linear control method based on three different models, the first model was linear parameter varying model. Because whatever switching converter transfer function we obtain those are basically obtain around some steady state equilibrium point.

That means, if the say operating point or the equilibrium point changes or the average quantity changes, then your transfer function parameters also change. And such transfer function are called linear parameter varying, represent linear parameter varying system where either transfer function or state space model whatever you say their parameters are operating point dependent.

Then we saw that how to apply gain scheduling technique in order to take the full advantage. So, gain scheduling is nothing short of tuning approach online tuning where we need to update the controller parameter as and when the operating point changes. Because then the transfer function location of poles and 0 may get affected and we need to update the controller parameter. So, that we can get the optimal at least the better performance than the design based on you know conventional design based on offline criteria.

In which we generally consider the worst-case scenario design the compensator based on worst case and then we plug in the controller value at the very beginning. As a result, such design when the controller does not operate like, when the system that because the system or the converter do not generally operate, you know the worst case, it is like worst case or rare cases. But when you do not operate in the worst case or you operate in nominal condition, then you lose a lot of performance due to this offline design.

And then we have discussed the online tuning or the gain scheduling technique tuning a class of gain scheduling technique tuning. This can be used to update the parameter to get a better response. But again these models since they had they have they are derived based on the small perturbation, they are not you know they do not give enough bandwidth or performance, because there is a model validity concept.

Then we discussed average non-linear model and we have talked about feedback linearization the exact linearization as well as we have also discussed the Lyapunov stability base criteria where we can use the same control. But extend the stability range by means of writing an energy function, energy like function where we need to prove the rate of change of energy where energy function consisting of error voltage and error current.

The rate of change of energy should be negative until all the error becomes 0. And that will ensure the asymptotic stability for the large-signal average model. Then we also discuss the switching model. Even the average model actually ignores the switching ripple information.

So, we cannot even further improve the performance and then we discuss if we incorporate the switching model, then we can go to the fastest response and achieve time optimal recovery. And which actually gives us the slew rate limit of the converter, so we can reach up to the slew rate limit.

Then I also talked about in detail like a sliding mode control and boundary control and their geometric interpretation. We have also simulated using MATLAB that you know first order switching sliding mode control with first order switching surface. We also talked about geometric control with the second order switching surface and you know their geometric interpretation. How does the switching surface look like.

And why we need to go for higher order switching surface to get you know the like that is the concept of boundary control where the switching surface we are trying to you know shape it in such a way it becomes a desired trajectory right. But there we found that if we go for a higher order switching surface, they have some kind of you know complex implementation architecture because of squaring block and all other block.

So, then we had talked about if we take just a first order switching surface and we can that can be framed into a PID controller or a PI controller for current mode control. And then we have to simply get the optimal gain of the proportional controller which decides the slope of the switching surface. And that can go to the fastest response of the close to time optimal response.

And that gives us what is called large-signal tuning that we will also discuss and that has a potential benefit of achieving fastest response, even using our existing current mode controller, voltage mode control to get the fastest response using by incorporating the current lipid.

Then we also you know understood the time optimal recovery that is the fastest recovery. And, this time optimal recovery not only improves that fast response, it also improves the energy efficiency. Because the number of switching it takes to reach from one operating point to the other operating point is just one switching action.

So, it reduces the number of switching. As a result, the switching loss can be improved and overall energy efficiency will improve when the converter undergoes frequent load step transient. And that also we have shown using experimental result. Then we also discuss an overview of some digital control architecture. Since this course is not for digital, but I have given some insight that whatever we learn, some of this can be implemented in digital control.

And some of the modulation technique that I have learnt, I have taught in this course trailing edge pulse width modulation, then constant on time constant off time as well as the hysteresis control. They can be very effectively implemented using digital platform using low resources small resources and they are useful for high frequency application. Then you also saw some benefit of digital control and as well as the challenges in terms of stability in terms of implementation and, so on.

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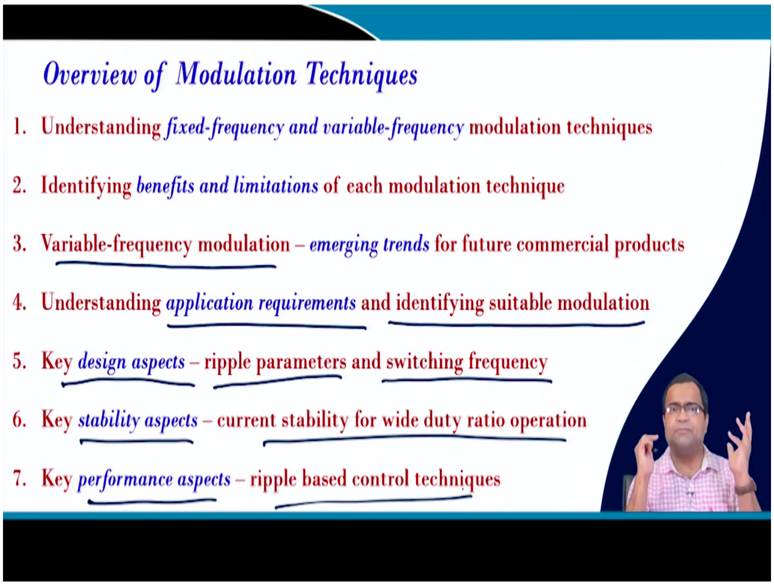

So, we have gone in depth about the modulation technique. In fact, first I would say first two techniques, first two like weeks first week, second week sorry, second week was completely like modulation technique ok. And there we understood fixed frequency variable frequency modulation technique. Then in the throughout the course we have understood the benefit as well as the limitation of each modulation technique.

For example, if you go for trailing edge modulation in current mode control, which is nothing but the peak current mode control. We saw there are stability issue, current loop stability issue beyond you know close to 0.5 duty ratio or that is the boundary line for both tailing edge and leading edge or basically peak current mode and valley current mode control. And there are each of them have limitation in terms of operating duty ratio.

Then we have also understood that variable frequency control such as constant on time constant off time even for voltage mode also they can be much faster than traditional voltage mode control. Also, in current mode control, the variable frequency current loop actually makes sure the current loop is inherently stable for the entire operating range.

So, they are very you know kind of emerging modulation technique for wide duty ratio operation and this kind of variable frequency control methods are the emerging trend in power management product. I mean power management product probably see more use of ripple based control like a constant on time constant off time, hysteresis control in the future.

It is already there, but a majority of the commercial products still dominated by fixed frequency current mode and voltage mode control, but in future the ripple based control will be dominated. I mean it will going to be useful. And using the digital control architecture, we can even make things much better, because one of the limitation of variable frequency control is to regulate the switching frequency. But once you go to digital control, then you can easily program the switching frequency inside the digital platform, because you have an inherent all digital PLL.

And we have also discussed that, in such cases, the event based sampling variable frequency control can offer significant stability and performance benefit over their fixed frequency counterparts. And that can be future commercial product point of view, they can be potential solution.

Then we understood you know different. I mean we need to understand the application requirement. And identify the suitable modulation technique, because after end of this course we should understand that when you want to select a suitable modulation technique.

As I said it need not to be always variable frequency, you still want to use fixed frequency for certain application. It is a kind of mandatory requirement. But that is why we need to first understand what is the application requirement, how much frequency variation is acceptable, what are the resource requirement, what is the switching frequency right, what is the EMI requirement.

So, keeping all this mind, we can decide that which modulation technique will be suitable and which will be best among what we learn. But otherwise you know in most of the cases we talk about only fixed frequency modulation, but this all this range of modulation technique that we have learned it will be useful to decide which one to be selected based on the application requirement.

Then we also learn about some key design aspect like you know and this design particularly when we select one modulation technique, then our next question will come how to design the power stage. Because we need to take care of the ripple aspect because this will be directly related to our you know the ripple specification as well as conduction loss right. We cannot have a very large ripple, then our conduction loss will increase or it may violate the ripple constant.

Similarly, we cannot have a very low ripple because that will increase the switching frequency and that may not be acceptable because the switching loss will dominate. So, from loss point of view, what is the optimal you know which modulation technique should be selected and how to design power stage and then how to regulate the frequency within certain bound. And certain switching frequency variation weather is it acceptable? If it is not, then we need to adapt a suitable mechanism to adjust the switching frequency.

Then we also learn about some stability aspect and these aspects are important to select the modulation technique. For example, if you go for variable frequency control, any of this variable frequency three control you have learned like a constant on time constant off time and hysteresis they do not have any current loop stability problem. So, they can be operated for wide duty ratio operation; whereas, in peak current mode control, we have real difficulty when you try to go for wide duty ratio operation because of the current loop stability.

And we often introduce you know RAM compensation and that makes the current loop bandwidth also lower and also in many precise applications where we need to track precisely the average current, we need to track precisely the ripple parameter. This ripple based control can be very useful where we may not need to use any ram compensation.

Another aspect is the performance aspect, even if we do current mode control fix frequency, but if we go for, let us say fixed frequency modulation if we go for small-signal based design. And we have discussed that this design inherently assumes that model is valid for one tenth of the switching frequency.

As a result, your compensator is designed like and it behaves like a low-pass filter. So, it attenuate the switching component frequency component and its harmonic. So, the ripples are not accessible to the loop and, as a result, your performance is limited.

But suppose the same modulation technique we have learned if we go for large-signal based tuning where we have incorporated the ripple information. Then we can keep we can use the same controller like a voltage mode or current mode control. And we can reach the performance up to the physical limit, which is a time optimal performance, and that is also possible. Similarly, we can implement ripple based control like controller of time hysteresis control to achieve very high performance.

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We also discussed you know various feedback feedforward control methods and. In fact, I think in lecture number 17 we have in fact talked about the combination of combined linear feedback and feedforward control. And in fact, in the subsequent lecture in the tuning we have discussed this combination can, because you know if you recall voltage mode control suffer from poor line regulation, current mode control suffer from poor load regulation.

So, you, in order to anticipate the voltage mode control, we need to consider input voltage feedforward. For current mode control, we need to consider load current feedforward. So, by this feedforward method we can achieve and we can make their performance very high, fast and we can make insensitive almost to the disturbance. Like it will have very high like a very good excellent disturbance rejection property and this can be very useful.

But you know that comes with the price because the load current feedforward is something is not very easy if you need to sense load current. But if we go for digital control, we can use a load estimator and there we do not need to sensor load current.

Then if you go for voltage mode and current mode control, these two techniques are still dominated in commercial power management products. But we will see increasing use of ripple based control, whereas I said there is no problem with the current loop stability and by virtue of the ripple information we can go the fastest response like a time optimal response.

But we can also use ripple base fixed frequency control where like a ripple like in the model we want to incorporate ripple I will not say ripple base, but we can incorporate ripple information into the tuning of the controller to get the performance up to the physical limit. And these are the potential they have the potential for future commercial product.

Then we also discuss briefly about the digital controller platform to implement advance control. But remember we should keep in mind if you go for any commercial product the algorithm has to be simple as well as it must resource aware, so that we can save the silicon area.

And, why you are talking silicon area? Because in future power electronics people are talking about power supply on chip or power supply on package where we may see more integration of power electronics and slowly it will become like an IC kind of form.

So, your controller as of now is IC, but in future along with the controller you know also we can consider the deviser also part of switch, but in case of a little bit high power application where we still use a bulky offset you know of the shelf component. But many of this can be combined to make IC to increase the power density and that is the future train.

Sometime you know people are now talking about integrated magnetics right in the PCB itself and you know. So, this kind of trend high frequency high power density we will we have to think about the PCB area, because the size the volume power density; that means, the weight of the power supply that has to be reduced.

And in terms of IC which are going to be more and more IC will see in future the silicon area also matters. So, you need to reduce it, so the algorithm has to be simple and resource aware. And what we saw as the large-signal tuning it simply uses our traditional current mode voltage mode or even constant on time off time and it can reach to the fastest response.

So, this can be very useful in terms of simplicity in terms of reduced resource utilization because it just use the existing architecture only you have to tune the gain properly. And the digital control solution they are very useful for high performance and efficiency and for reconfigurable solution because we talked about in digital control multimode solution right.

So, this multimode solution can be used to achieve high performance and efficiency for an entire operating range, for a very light load to very high load condition you have to retain.

Because, if you are talking about future smartphone, even the current smartphones they are like a computer right.

So, where the smartphone we want to still increase the extend the battery life; that means, it is most of the time it is idle mode or standby mode where we need to improve the high light load efficiency. Again, when it is running or you know you are you know you are actually attending video conferencing or you are doing some like or playing some games there also the high computational performance has to be very high. And your energy efficiency also has to be very high, so that you can also increase the battery lifetime.

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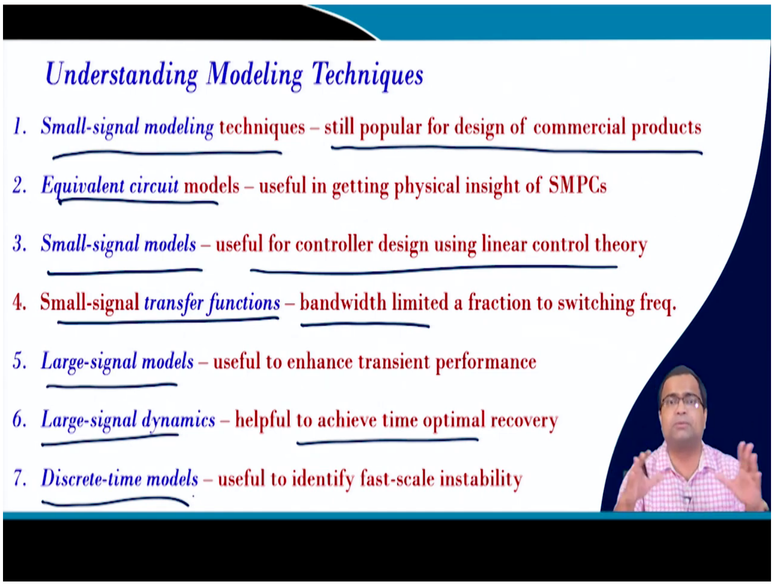

Then we learn in the modeling technique the small-signal modeling technique was the simplest one because that gives us the transfer function. And we have familiar with the different you know control to output transfer function impedance and this kind of concepts are still dominated in commercial product. And you will find lot of application nodes are available which use a transfer function base compensator design. And each industry provides this application node related to their product and you can learn from there.

But what we learn and there the equivalent circuit concept, model concept, was very useful that gives us physical insight in terms of output impedance, in terms of audio susceptibility input impedance. So, we can design as you know input filter for stable operation as well as high bandwidth operation. Then we can design output impedance in such a way closed loop, so that you can reduce the undershoot overshoot right and you can shape the transient performance or output impedance.

And these small-signal models are useful because you will get lot of control system tool, like frequency domain and time domain approaches. In frequency domain, we can use the Nyquist criteria, we can use Bode plot then we can use you know gain margin, phase margin criteria for the design in time domain you can use root locus criteria right.

So, there are like a transient analysis, so these are there are like a we have a rich tool, but such models this transfer functions often ignore the ripple information. As a result, they result in a bandwidth closed-loop bandwidth which is a small fraction of switching frequency. And such performance may not be enough for the to meet the future requirement right.

So, then we talked about large-signal model. This model can enhance the performance of the converter even though the controller is same, but when the small-signal validity will remain a concern. Then we can use a large-signal model to further increase and particularly large-signal average model you can go further up. So, that for wide duty ratio variation, this model can still work.

But if we want to incorporate the switching dynamics, then you will get the fastest response, which is the time optimal recovery. And that is what we want to achieve in the future, so that our power supply becomes extremely fast and very highly energy efficient and it can meet very increasing demand of the different site. So, that you can reduce the size of the capacitor and we have discussed that such fastest performance time optimal it also provide us to reduce the output capacitor to increase energy efficiency. So, your thermal overhead will come down.

And in future you will find the product coming without any heat sink because. In fact, the wide band gap device itself are very efficient and if you can make the controller also very effective and the power converter can be very efficient. So, you can reduce the heat sink size significantly. At the same time, you can also decrease the output capacitor. So, your power density can be increased.

And we have also learned the discrete time model which are useful to you know analyse fast scale instability to ensure that power supply is free of subharmonic oscillation.

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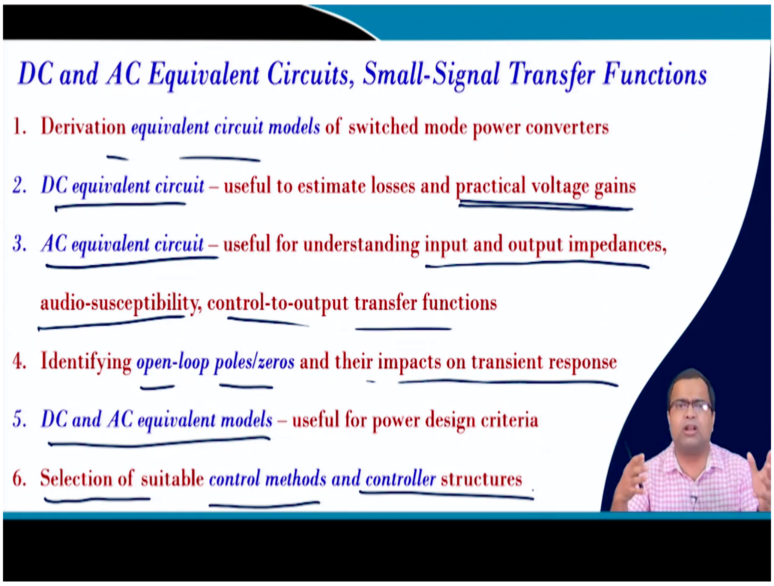

We have also discussed DC as well as AC equivalent circuit small-signal transfer function and we have derived the equivalent circuit model. And using DC equivalent circuit, we have shown how to estimate losses in some sense and then how to get the practical voltage gain. And these voltage gains are different from the ideal voltage gain because there will be a correction factor due to the parasitic.

Using AC equivalent circuit, we have derived various transfer functions like input output impedance, audio susceptibility, control to output transfer function. And we identified the open-loop poles and zeros and their impact on transient response. We saw that if the poles are complex conjugate, then that may lead to more you know oscillatory behaviour. And if you can separate two poles, then the response can be in terms of it become over damp, but we need to place properly, so that you do not lose the performance.

And we also saw the effect of a zero which can speed up the response, but at the same time it can result into higher overshoot. And we also discussed the right half plane zero, which will introduce an undershoot inverse response and that can significantly affect the closed loop performance. And we also discuss if the right half plane zero comes close to the imaginary axis, then your closed-loop bandwidth will be severely restricted because of the non-minimum phase behaviour.

Then we saw that AC and DC equivalent models are very useful for the power state design and that will also help that model to select the suitable control method as well as how to design the controller. Because we discussed for voltage mode control, we talked about PID controller tuning.

Then we saw the PID controller tuning even if we can try to achieve analytically first-order model for a bug converter, but our model validity remains a concern. So, then we consider type III compensator where we have considered one additional pole and that can increase the bandwidth with model validity that also we have discussed. And by that we can reach up to one tenth of the switching frequency.

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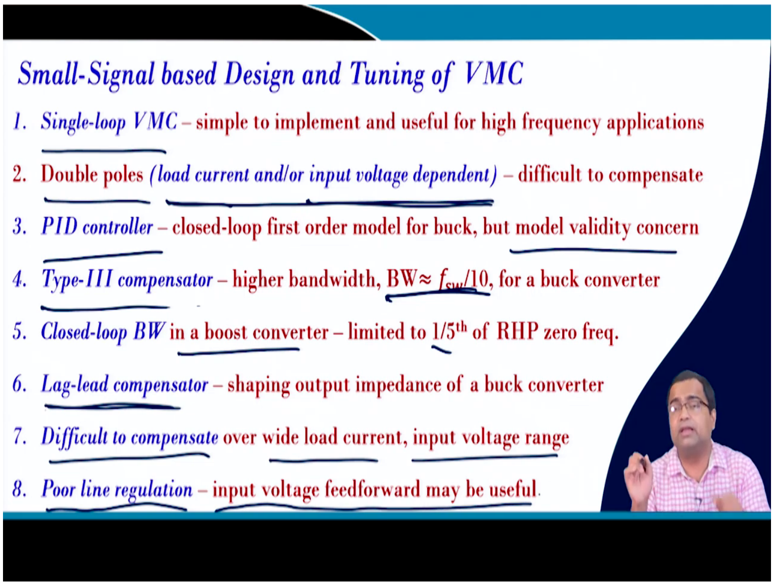

Then we discussed small-signal based design and tuning or voltage mode control. And the voltage mode control is a single loop control. It is very simple to implement and useful for high frequency application because there is no current sensing. But the problem is the double pole and the double poles are an often function of load resistance or the load current. And in case of input voltage sorry in boost converter and buck-boost converter, it is also a function of input voltage along with the load current.

And this makes it very difficult to compensate because the double pole moves in the complex you know plane and the location of the double pole and that makes it very difficult to compensate this double pole. Because you need to adaptively vary the controller zero and that is why offline base worst-case design will not be a good solution to achieve you know high bandwidth for the entire operating range.

Then we talked about a PID controller design in a voltage mode control and it was intended to achieve first-order model for a buck converter. And we could achieve that even for low bandwidth solution, but as we try to push bandwidth then the model validity was a concern.

Then we talked about a type-III compensator where we have introduced one additional pole and that gives us flexibility to independently adjust the crossover frequency and phase margin of a buck converter. And this can also push up or increase the bandwidth of the buck converter up to one tenth of the switching frequency with very good model validity.

But for the same type-III compensator for the boost converter it is limited to one fifth of the RHP zero, but if the RHP zero frequency is very far away you know when the load current decreases then again one tenth of the switching frequency is the limit. So, the model limit is minimum of one fifth of the RHP zero comma f s w by ten that is the limit of the boost converter closed-loop bandwidth in terms of model validity.

Then we talked about lag-lead compensator design that can be effective for load transient response for a buck converter, but a lag-lead compensator does not have an integrator. So, you need to take care about the steady state you know DC gain. So, that is why you know many commercial products they do not leave lag lead due to some steady state regulation problem.

So, such compensator difficult to compensate I mean make it difficult for the voltage mode control, for a wide load current input voltage. And you will really find voltage mode control solution for a boost converter for a wide range of input voltage and load current. Because it makes it extremely difficult because of this pole as well as the right of plane zero location because which is also a function of load resistance and input voltage.

And this voltage mode control also suffers from poor line regulation, but it offers very good excellent load regulation. And this poor load line regulation can be anticipated by means of input voltage feedforward, that also have discussed.

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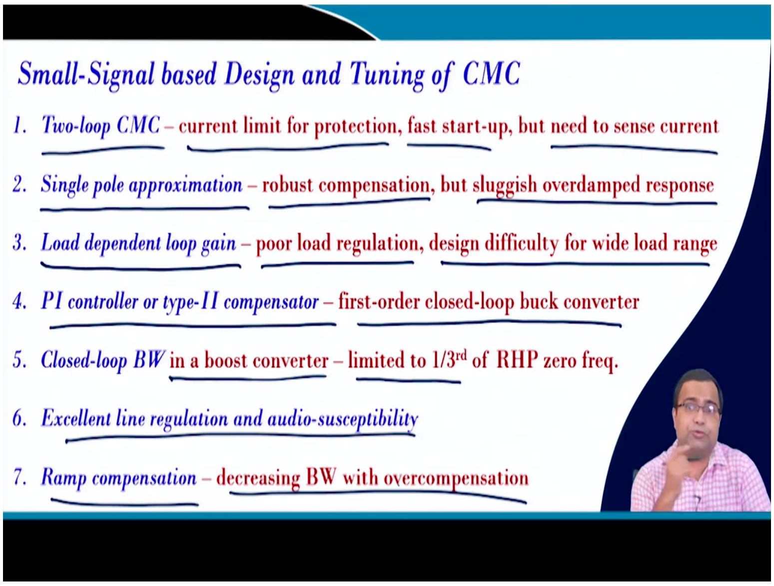

Then the small-signal based design and tuning of current mode control. Current mode control is a two-loop control. And it offers fast current limit a current limit and the start-up can be very fast and you, but you need to sense inductor current. But what is the major advantage because of the two loop control where the inner loop is much faster and the inner loop makes the whole system look like a single pole approximate system that is a first order system.

So, you can go for robust compensation because there is no double pole effect. There is no q peaking effect, but the response can be sluggish because of the overdamp. So, we need to properly design the compensator. The load dependent loop gain makes the current mode control poor load regulation, and it is also very difficult to design for a wide load current range. So, you often need to consider load current feedforward in order to anticipate that. But current mode control offers excellent line regulation and audio susceptibility.

So, in current mode control, we saw PI controller type-II compensator is enough and it tries to get first order response closed loop for the buck converter. And in case of boost converter we saw even with type-II compensator or PI controller we cannot achieve the bandwidth I mean, one third greater than one third of the switching frequency, because beyond that the model validity remains a concern right.

So, our close loop from model validity point of view the boost converter using current mode control can current mode control can offer either minimum of the one third of the RHP zero comma f s w by 10. Current mode control offers excellent line regulation audio susceptibility and the ram compensation in current mode control is required if you have a sub harmonic problem. And if you increase the ram slope, then the bandwidth can be it will decrease.

And if you go for worst case based design using offline current mode control design, we often need to consider the highest ram. Because in order to make sure the current loop is stable for the entire voltage range input voltage range and this over compensation can reduce the bandwidth.

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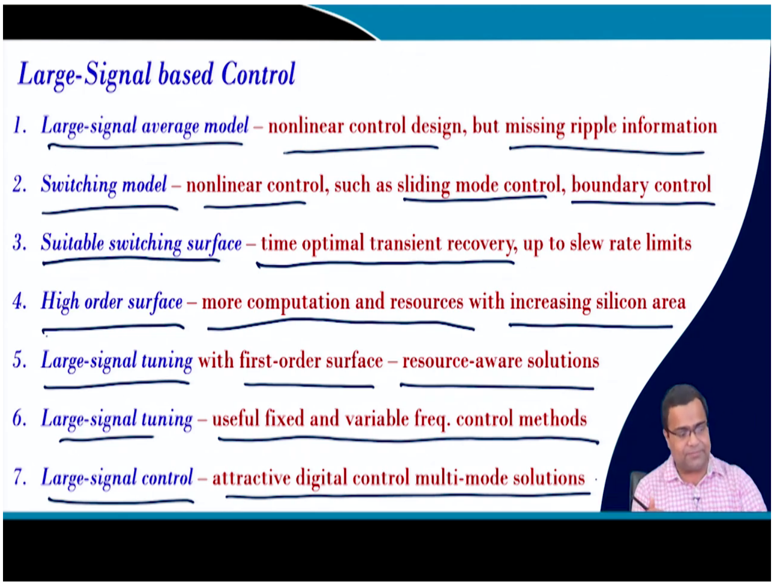

Then we discussed large-signal based control where initially we talked about the large-signal base average current average model based control where we talked about exact linearization we talked about Lyapunov based stability.

And we saw if you take a state feedback model state feedback control we can achieve higher you know faster response in case of boost converter over output feedback control. But the small-signal model validity due to that you cannot increase the bandwidth even beyond one half of the RHP 0.

But if we use a large single average model and use the Lyapunov stability, we can increase the bandwidth even because there is no bandwidth concept. So, you can further improve the performance and it can go close to time optimal, but not exactly because there is a limit on the duty ratio.

But it still misses the ripple information. So, the switching models actually we can use non-linear control such as sliding mode control boundary control and we can reach up to faster switching surface as for fastest control time optimal control. Then the suitable switching surface for such control is very important to achieve time optimal recovery up to the slew rate limit.

The high order switching surface tries to mimic the target trajectory. But this kind of higher switching, high order switching surface may be difficult because of computational and resource point of view. And in case of an integrated circuit that can occupy or require more silicon area whereas, if you go for large-signal tuning where it uses only first order switching surface and this can be resource aware and it can offer optimal solution.

So, and this tuning we saw you can apply for a fix as well as the variable frequency control and we have shown some say you know motivated experimental case study. And the large-signal based control is going to be the attractive solution for digital as well as multimode control. And many industries are coming with large-signal based control because they want to go beyond the performance using the conventional small-signal based design.

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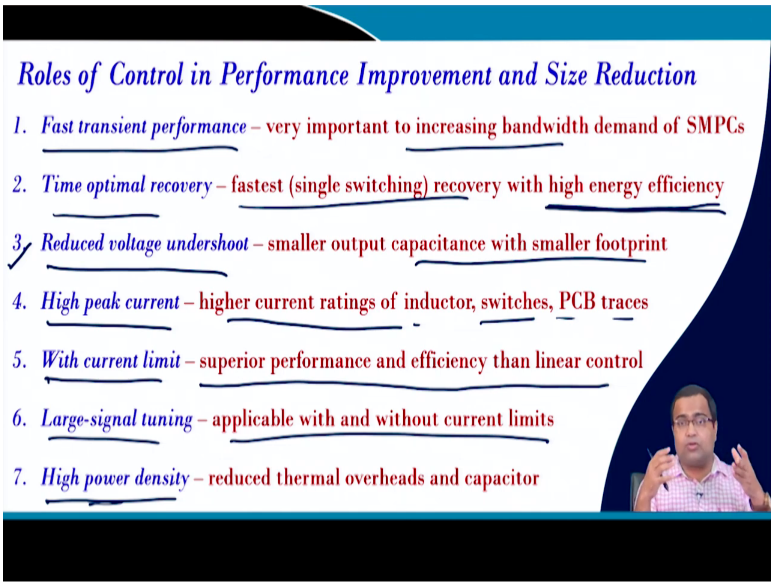

So, role of control in power converter role of control in performance improvement and the size reduction. If we can achieve very fast transient, response then we can meet increasing demand from the power bandwidth demand.

The time optimal recovery is the fastest transient with single switching it also offer higher energy efficiency over conventional control if the transient appear more frequently. And that is the case for many applications, particularly for data center application you know portable device applications where the computation is happening you know continuously right. So, we need to meet the demand.

Reduced output voltage actually offers I know if the output voltage undershoot can be reduced, then you can simply reduce the capacitor because you have certain noise margin or certain deviation limit is given. So, if you want to reach up to that level you can even reduce the output capacitor size.

So, it can improve or reduce the footprint. That means it will improve the power density. Then high peak current is one of the problem for such time optimal control. So, that requires higher current rating inductor switches and it can also increase the PCB traces current rating as well as if you go for IC the bond pad you know that has to carry the current.

But we can incorporate current ripple and we all we can also get much superior performance and efficiency than linear control even with current limit. Because here we are not considering the small-signal duty ratio variation, we are allowing the duty to saturate. The large-signal tuning is applicable with and without current limit that we have discussed and we have demonstrated using simulation as well as the experimental result.

And high power density is achievable because in this method, we can reduce the undershoot. So, as a result, the capacitor size can be reduced. We can impress the higher energy efficiency. So, the thermal overhead can be reduced. So, by that way, we can reduce the size of the converter for high power density. So, the control role or significant role sorry control can play a significant role in the size reduction, performance improvement, efficiency improvement.

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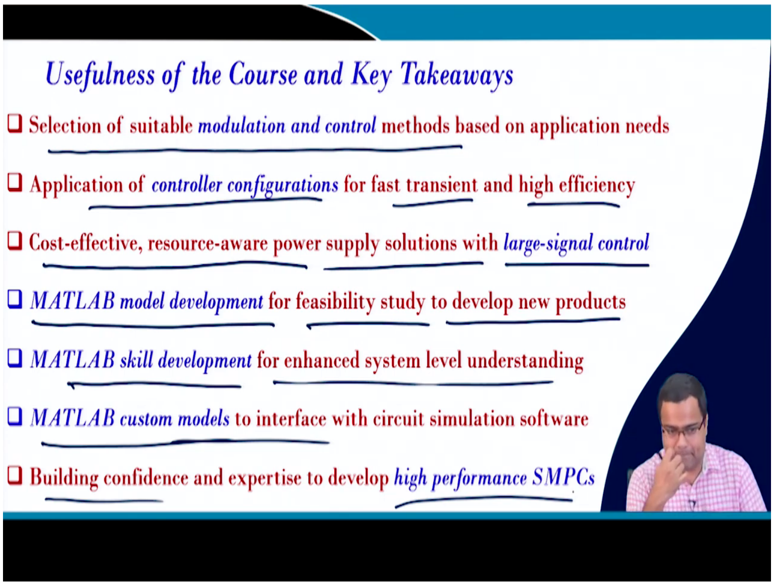

So, the usefulness of this course and the key takeaway, so now after this course I think we should be able to decide what suitable modulation and control method need to be selected for my application demand. And this is often like you know those who are working industry they need to meet certain demand for the customer and we tell we talk about customer means the end user right.

So, based on that demand, they want to come up with power management IC or product which can be you know smaller size, high efficiency and high performance. So, we need to select the suitable modulation and control method. But in some cases there can be a restriction in terms of sensing current may not be available, so we need to manage with voltage mode. But in some cases we may have restriction in terms of EMI, for example, in automotive and space application where EMI is a real concern. So, we may not be able to go for variable frequency or even if you go, we need to tightly regulate the switching frequency.

Then the application of a configurable controller, so we learn about how to configure the same resource can be used either in constant on time to constant off time trailing edge modulation with change in controller gain right to achieve fast response and high efficiency.

And how to achieve change between fixed frequency variable frequency or constant off time to constant on time to achieve high light load efficiency and high performance for high load condition. So, application of such a configurable controller will be useful. Then the cost effective research aware resource aware power supply solution using large-signal control and that is going to be a very effective for future application.

Then we also learn MATLAB model development. This model development will be useful for feasibility study to develop new product. Even this development concept can be extended for other power converter because we have already learned how to develop a model from the scratch and how to make the MATLAB model and how to develop interactive simulation. And this will help to do skill development for enhanced system level understanding.

And the MATLAB custom model will be very useful to interface suppose if you use a plex software with MATLAB and you can also try MATLAB interface with other whether it is possible to go for Simplis and other professional circuit simulation software. Or even you can have one custom model using MATLAB and you can compare that using, let us say simply simulation where you will have the component model like of spice simulation with the spice model of the, so you need to compare.

Because whenever you take spice model from the manufacturer, you may not know the exact model what is inside. So, if you want to go for some device level or more understanding of the model of the switches and the parasitic. Then you can develop MATLAB model and try to compare your model performance with the professional software simulation. So, this is also very important and finally, this course will try to build confidence and expert is to develop high performance switch mode power converter solution.

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So, this course the NPTEL team you know as I have been teaching, so you all know about me. And then we have teaching assistant you know Dipayan Chatterjee, Ruturaj Garnayak and Prantik Majumder and they are Ph.D. student and they have immensely helped. And you know they have been interacting throughout this NPTEL portal, you know the course online portal and they are you know trying to address all the query who are have been raising right.

So, that will be very helpful, you know, and I really want to appreciate. And also some of my other students as well as some supporting staff they have helped to make this course successful. I mean, I will say successfully complete this course. And we have whatever resource you know PPT and all these materials we got a lot of support from all the team members.

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And I also want to introduce our department of electrical engineering IIT Kharagpur. And in this department we have B. Tech undergraduate program, then joint M. Tech Ph.D. program, dual degree B. Tech M. Tech program M.S. by research program then Ph.D. in electrical engineering.

And we have multiple teaching and research laboratories. This is our electrical department, which started in 1951. And you know, the IIT Kharagpur was the first IIT among all the IIT chain. And it was started, the department started in the same year when the IIT started 1951. And we have in our department we have a, because in this IIT we have a separate electrical department, electronics department.

So, in our electrical department, we have the emphasis on core electrical engineering as well as the modern electrical courses. And we have multiple associations with leading industry in power electronics, power management, signal processing, and various other industries we have collaboration with our department. Presently, we have 35 faculty member, but very soon we are going to have more faculty members.

And, so far almost or more than 200 Ph.D. student have graduated. And our faculty members are very active in research and they have been serving as in the editorial team of I triple E leading journals. And for more information about the department, you can visit this website.

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Now, I want to just introduce our embedded power management lab, and this embedded power management lab was inaugurated on August 18, 2014. In fact, we have just finished 7 years of our existence. And we have industry collaboration with this you know embedded power management lab like STMicroelectronics, Qualcomm, NXP semiconductor, then GE Global Research, Texas Instrument, HCL Technology. And we have been associated with this industry either in terms of research project or consultancy project or training works force in digital power management solution.

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So, in this embedded power management lab we worked in multiple area. So, we have we can divide into two parts the technology vertical we work on digital and non-linear control, digital modulation technique. Then we develop a lot of modeling analysis and design tool for future power management solution. Then we work on gallium nitride and silicon carbide base prototype power converter development and control development.

Then we also work on very high power density topologies and these are for data center application, EV application as well as the charger applications, ADAS, automotive application. Application domain. We work on electric vehicle, charger, ADAS, drivetrain, data center, LED driver, IoT, power management for you know artificial intelligence as well as the ASIC that IC, power management IC, the mix signal IC.

Then we are also working on solar as well as DC micro grid control as well as some development, topological development and we also work on to some extent of modeling and a battery management system.

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Our ongoing research activity includes the data center and cloud computing and where we are trying to focus on high performance energy efficient digital power management solution as well as some you know hybrid topological development. We are working on GaN based power supply for charger, ADAS, multiphase and hybrid power converter solution. We are working on portable and mobile application for fast recovery energy efficient power supply solution.

In the automotive area where we are working both like white band gap based EV charger both using gallium nitride as well as silicon carbide. And here we are also working with STMicroelectronics in terms of charger solution, you know collaboration. And we are also working on auxiliary power supply for electric vehicle as well as the regular car. And also working on the ADAS solution for and because ADAS is going to be almost common for all car because of the safety point of view, advance driver assistant system.

Then we are also working on extensively on GaN based solar inverter, hybrid converter, model predictive control as well as digital control. And we will have you know energy efficient solution stable solution for the solar integrated renewable or microgrid.

We have also we have been working on analysis and design tools for digitally controlled high frequency converter. And we develop we have identified, and we have reported the first time that there are a lot of stability issue due to the current sampling effect in digital control. And we have also developed solution that how to overcome that and that may be useful for many other converted topology and control technique.

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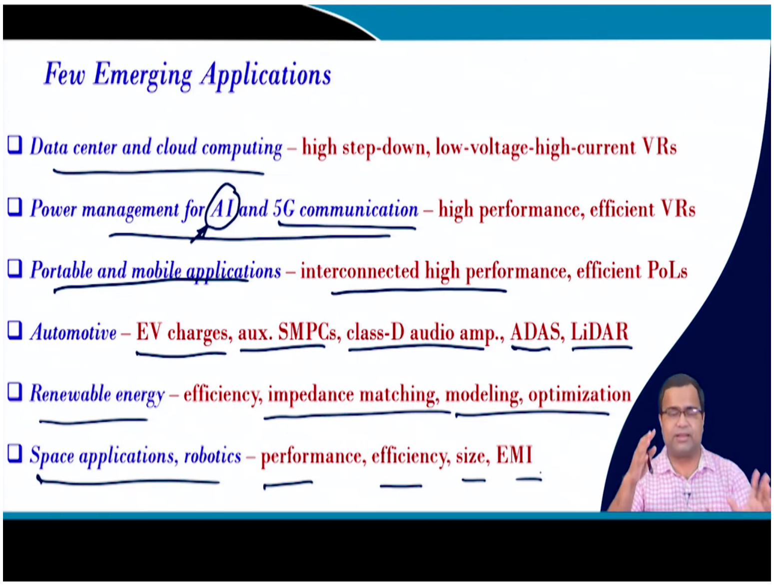

So, some of the few emerging applications like you know data center and cloud computing that are going to witness you know more and more. Because now everything we talking about cloud everything is our cloud server. So, and the cloud that computation current requirement can go above 1000 ampere and this is this will require multi core processor and multi core solution and that also we have been working here. So, this is also one of the big area upcoming area data center.

Then the power management for AI and 5G communication this is also very important. because you know we want to get like a 5G communication, the speed of communication should be extremely fast, but who is responsible for fast communication? So, who will provide power? So, it is a power converter right, so the power converter bandwidth has to be very fast. And you know there will be a lot of development in the area of dynamic voltage scaling as well as the envelope tracking power supply for this fast communication.

Then if you are talking about AI you know now if you talk about AI enable you know smart camera right for CCTV camera where you know we cannot simply take keep on taking image and storing data, because that data will be huge and that cannot be managed. Because there are so many surveillance cameras, so here using AI algorithm we can use smart camera. That means, it may not even store image unless it sees some abnormal behaviour, movement and based on that algorithm, it keeps on developing.

So; that means, such kind of processor the computation can vary from extremely low computation to extremely fast. And most of the cameras are located in remote location where it is run by battery. So, you need to have very highest performance and high efficiency ok.

Then if you go for portable and mobile application like now, the portable and mobile devices are common because you know like work from home. When you are traveling, the smartphone itself slowly becoming like a minicomputer. So, for such a system, you know there are multiple power management converter and each will have their different voltage current requirement.

And they can be operating either standby mode extremely low power, where you need to save energy, as well as they can operate to its full capacity, where the processing requirement can be very far high. And power supply has to meet the demand for both dynamic voltage scaling like a voltage difference as well as current difference. So, we need a very interconnected high performance PoL solution.

For automotive EV charges now there are like many industries, many academic institutes are working on EV charger, but in most of the EV charger the challenges will come you know when you are talking about. So, it is of course, the hardware development itself is a challenge using wide band gap devices where the topology, your packaging, you know then thermal these aspects are very crucial. Along with this active EMI control then active I would say that power converter control, because we need to achieve also high efficiency right.

Then the auxiliary power supply in car those are very important, because they have to like this auxiliary power supply can be used to cater the requirement of let us say dashboard where we will see increasing use of electronic gadget right. Class D audio amplifier that is all one of the big area where GaN devices are coming and where we need to achieve high fidelity that audio amplifier you know, where the audio amplifier should have extremely high you know kind of very low distortion right.

ADAS is also very big area where you need you know in ADAS there are radar right and you need an envelope power amplifier for first real time communication, first communication. Then the camera has to be extremely fast and then your electronic control unit and there are many processors. So, all these require multiple power supply with high computational capability. So, you need a very high end power supply and LiDAR is also very important here.

Then renewable energy that is also you know when you are talking about multiple solar energy are integrated and lot of research is going they are already happening and already have developed a lot of technology. So, we need to do impedance matching, model optimization. So, people are now going to MPC; model predictive control where the digital control can be very effective.

The space application robotics, more electric aircraft, etc. where performance, efficiency, size and EMI they are very, very important. Because the power supply size has to be, it should be lightweight, smaller size, highly efficient, low EMI. Because ultimately the power converter will be plugged in into the spacecraft and it has to, you know, fly right. So, you need to reduce the overhead due to the power converter weight and other thing.

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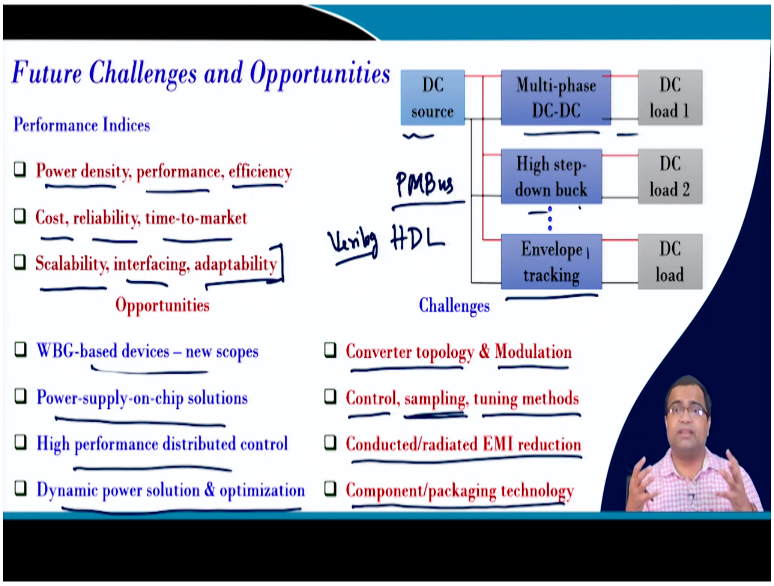

So, the future challenges you will see more complex network. I mean the power converter will have interconnected power converter. For example, in a battery you may have only one source, but multiple processing element where you may need single buck converter.

So, single, DC-DC or multiphase you know multiple step down converter, envelope tracking for power amplifier of your mobile phone, smartphone. So, such complex architecture if you are talking about and this power management occupies almost more than 50 percent of the space.

So, one of the performance indices, the power density; that means, we have to reduce the size; the performance has to be high. So, the thermal overhead can be reduced by increasing the efficiency right and it needs to perform high. You need to offer high performance because even the computational requirement is very high.

Then we need to have a low cost reliable and the solution should be very fast time to market. And the solution should be scalable and it should be interfaced with the surrounding devices. Because, now we are talking about PM Bus where, it will communicate with surrounding devices, multiple devices by sharing clocks and data.

And then adaptability because the processor technology can change, but our control algorithm should not change or it should not drastically change because if we are going for digital control we can write our algorithm in HDL like you know you can say Verilog HDL or you can say VHDL language you can say Verilog or even VHDL.

So, this HDL language is basically platform independent. So, you can use this HDL language and you can develop your controller, you can prototype using a PGA, but this HDL language when if these are tested fine this can be synthesized by any professional circuits say simulator tool software like a cadence, synopsys. And then you can synthesize or basically the particular digital circuit using the process technology that you are going to use ok. So, these are it should be adaptive solution ok.

And the opportunity we are talking about wide band gap devices offers new opportunity for further size reaction, higher power density, higher efficiency. And as I said that we are going to witness more use of power supply on the chip, the whole power supply size will come down in near future.

And we need a very high performance and distributed control because there will be more interconnected converter. And the dynamic power solution optimization we talked about DVS where the power supply voltage of the processor has to be adjusted according to the computational demand.

So, that we will reduce the dynamic power to save energy without violating the real time constraint right. And the challenges are developing suitable converted topology modulation technique may be the digital modulation technique. Then control technique, sampling method and tuning method those are very important, like we talk about event based sampling. So, if you are changing topology, then what kind of variable frequency control are you going to talk about, then what should be the event that will make sure the controller is stable.

Whether should we go for fixed frequency control, like a tuning method, then the conducted EMI, and radiate like we need to go for active EMI control. That means, the digital control should also take care about the active EMI reduction by means of control. And finally, component packaging and technology are also going to a very important for future.

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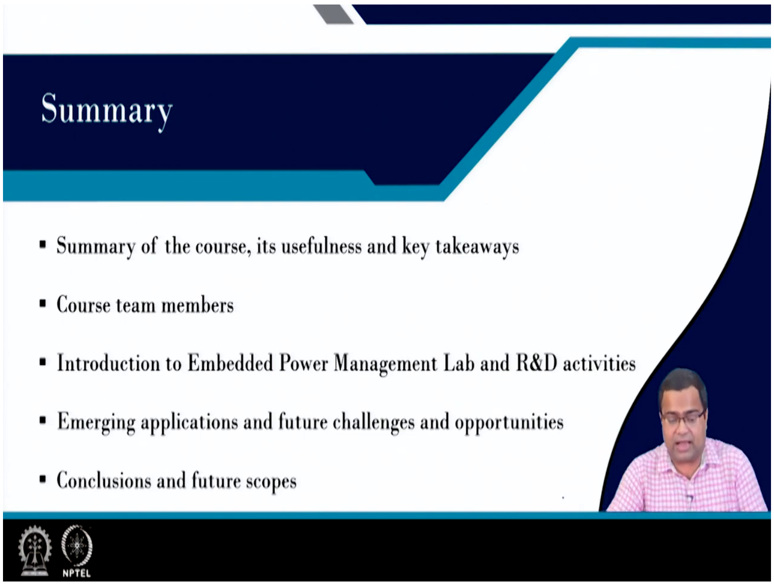

So, with this I want to summarize that we have discussed the summary of this course, its usefulness and key takeaways. We have introduced the team member of this course teaching assistance as well, the introduction to our embedded power management lab and our research and development activities. We also talk about free emerging application future challenges and opportunities and conclusion as well as the future scopes.

So, with this today, it is the final lecture or the conclusion of this course. And I would like to thank all the teaching assistant team member you know our supporting member they have helped immensely to complete successfully this course.

And I hope this course should be useful and it will be a complimentary course along with the traditional switch mode power converter where we learn about a lot of topology another thing. And where we can apply many of this control and try to develop models, we can develop you know control algorithm and so on.

So, with this I think you know and what I could not show in this so course you know thought of adding some hardware experiment. But I could not add because of this you know pandemic situation, our lab activities are not in running in full swing. But I hope we can add some supplementary video in the future, you know and that is it.

Thank you very much, yeah.