Control and Tuning Methods in Switched Mode Power Converters
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Module - 01
Switched Mode Power Converters and Simulation
Lecture - 01
DC Power Conversion Systems - Introduction

Welcome to the NPTEL Online Certification Course. The title of this course is Control and Tuning Methods in Switched Mode Power Converter. I am Dr. Santanu Kapat, an Associate Professor in the Department of Electrical Engineering, IIT, Kharagpur. In this course, we are going to primarily consider the control and tuning methods in switch mode power converters.

This course is somewhat different from a conventional switch mode power converter course. Here, we are going to cover a wider range of modulation, control, tuning methods and some aspects of modeling techniques. I would also like to show what are the modern trends in power electronics. This is an introductory course. This a 12 weeks course.

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I want to show some recent trends in power electronics with few emerging applications and the challenges. Then, I want to demonstrate a DC power conversion system, primary blocks as well as the key objectives of voltage and current regulators. Then, I want to present the overview of this course and the reference resources for this course.

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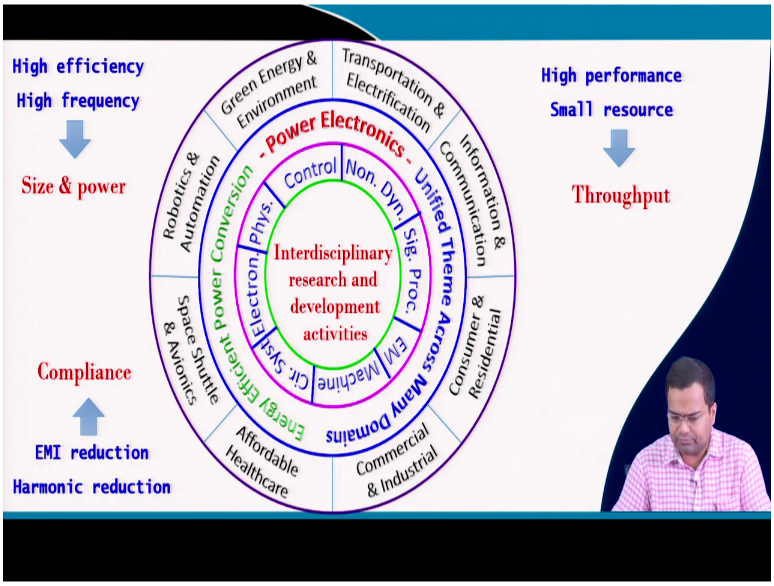

If you look at transportation and electrification, information and communication technology, consumer electronics, healthcare, space application, robotics, renewable, etc., everywhere we will find power electronics. This is used for energy efficient power conversion, which acts as an unified theme across many domains.

Power electronics actually touch upon various domains which include circuit system, electronics, physics, control system, nonlinear dynamics, electromagnetic, signal processing and so on. This constitutes interdisciplinary research and development activities.

The power electronics is going through a transformational chain where we are going to witness the increasing use of wide bandgap devices. Primary objective is to operate power electronics converters at higher switching frequency, so that the size of the converter can be reduced.

Another objective is to achieve high efficiency, so that the thermal overhead can be reduced. In a way we are trying to operate at a higher frequency to reduce size at the same time to reduce thermal overhead, so the whole the overall power electronic system and the subsystem in a particular application can be reduced.

It is also important to meet various stringent performance requirements. So, we need to achieve high performance. Since, we are trying to operate at a higher switching frequency, so we have limited time along with limited resources. So, we have a constraint on the resource as well as time. Thus, we need to use smaller resources yet to achieve high performance. So, we need to achieve a higher throughput.

Switch mode power converters are also sources of electromagnetic interference. So, we need to meet certain EMI compliance and harmonic requirements for various application. For example, in automotive and space applications, we need to meet stringent EMI compliance, and also we need to reduce the harmonic content.

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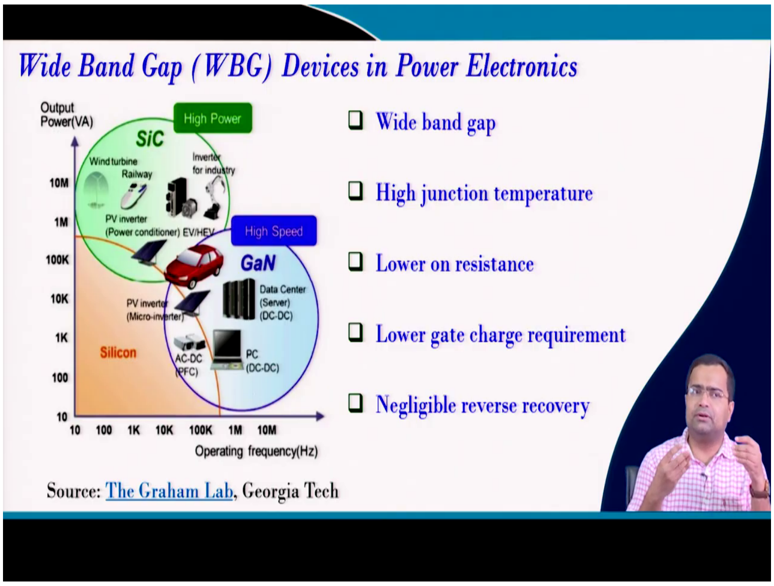

As I said the power electronics, we are going to witness increasing use of wide band gap devices. Two major wide bandgap devices are gallium nitride (GaN) and silicon carbide (SiC) devices which are slowly becoming more and more predominant in power electronics. GaN devices are more popular for low power high frequency applications, whereas SiC devices are more popular in high power low frequency applications.

Power converters using GaN devices can be operated at a much higher switching frequency in terms of few 100s of kilohertz to few megahertz or even few 10s to 100s of megahertz. In high power applications, we are going to witness more use of silicon carbide devices. These two devices are wide band gap devices, which mean that they can withstand a higher breakdown voltage.

Their junction temperature is very high, so that they can operate at a higher ambient temperature. Also they offer a lower R_ds(on), the on time resistance of the switch. So, the conduction loss can be reduced. And another important factor is that lower gate charge requirement. If we look at the silicon devices. We know about the figure of merit which is generally considered to be the product of R_ds(on) and Q_G (gate charge).

So, if you want to reduce R_ds(on) on then Q_G goes up, if you want to reduce QG then RDS on goes up. But, wideband gap devices offer a unique opportunity to reduce both R_ds(on) and Q_G, so they can be operated at a high switching frequency. At the same time, a smaller R_ds(on) can also reduce the conduction losses. So, we can reduce both conduction and switching losses.

Wide bandgap devices also offer negligible a reverse recovery problem which is another major drawback in silicon devices, in which there are body diodes. If we use a synchronous converter, only active switching (MOSFET) devices are used, and we need to provide some dead time. If the dead time is large, the body diode becomes operational. The use of a diode in a MOSFET leads to reverse recovery problem, whereas wide band gap devices offer reduced reverse recovery problems. In low power applications, such as data center, class-G audio amplifier, charger applications, GaN devices are now becoming an attractive solution.

Similarly, if we go for high power application, for example, the charging infrastructure, railway application, distribution power electronics or even battery charger, we can see increasing use of silicon carbide devices.

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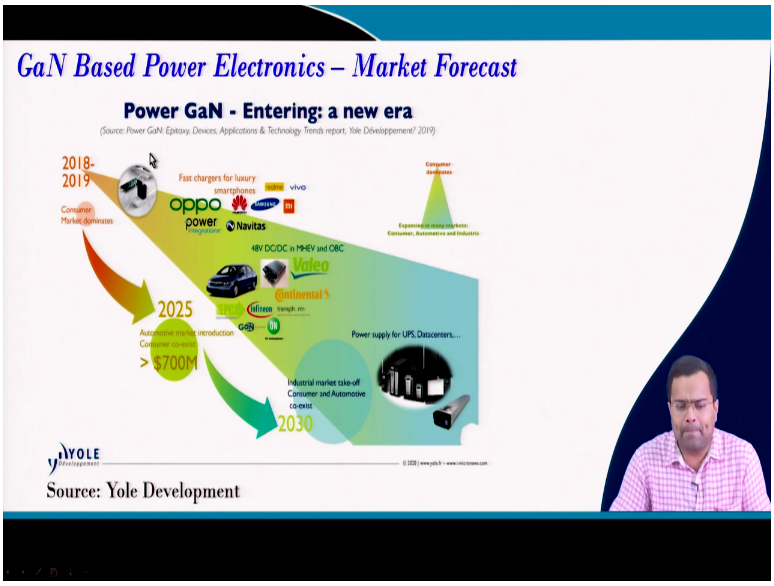

GaN power devices are now entering into a new era. And if we look at the growth projection, which is taken from the Yole Development, it shows excellent growth opportunity of GaN devices, and their market value can reach up to billion dollars or even more.

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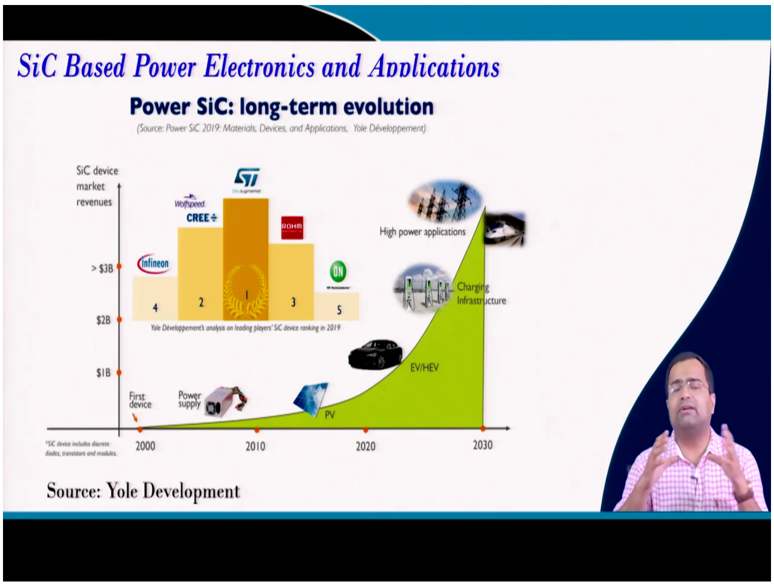

If we look at silicon carbide devices, their applications are more towards higher power than gallium nitride devices, because the former may not be able to operate at a high switching frequency like the latter. Applications of silicon carbide devices include solar renewable, hybrid and electric vehicles, charging infrastructure, distribution system, etc.

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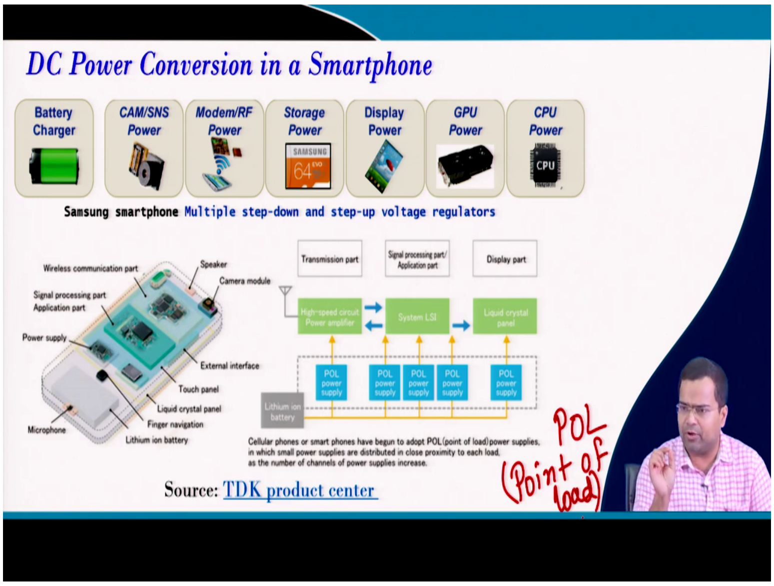

The use of such devices is becoming more and more attractive, and this trend is going up. I want to show one example of a DC distribution power conversion system in a smartphone. As we know, the smartphone is now common for almost many people, particularly for a post-COVID scenario.

In a smartphone, you have many features which include camera, RF module for wireless communication, storage devices, display devices, GPU (graphical processor unit), CPU (central processing unit), etc., but there is only one battery source.

So, we need to generate so many voltage levels, we need to drive so many applications which require power, but the source is only the battery. And if we try to you know what are inside a smartphone, there is one battery in all smartphone. In fact, nowadays hybrid battery technologies are coming. There are multiple applications for transmission, signal processing, displaying, which require various subsystems, and various subsystems require various voltage and current levels. Since there is only one battery, we need multiple point-of-loads (PoLs).

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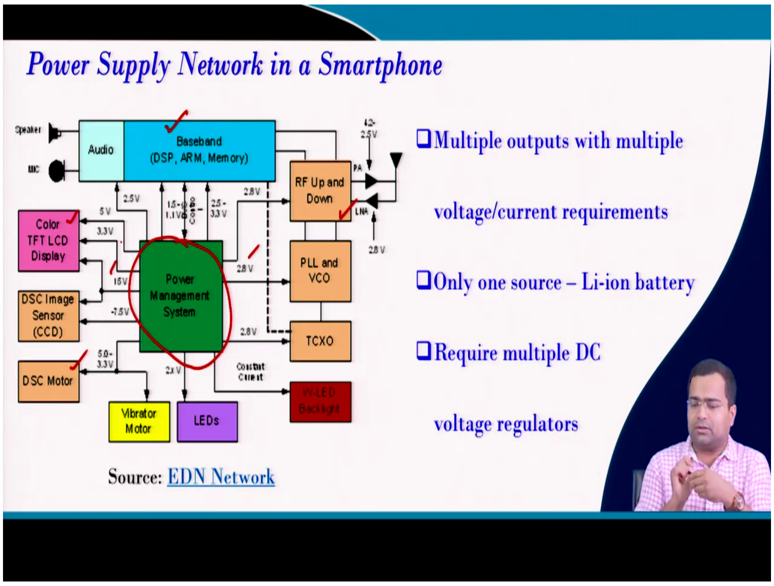

So, the point of load (PoL) power supply directly supplies a load. If we try to visualize what are there in power supply network in a smartphone, it requires multiple voltage and current levels for multiple applications. We need to generate all these voltage/current levels from the battery source.

So, there are various units with multiple voltages and current levels, which require multiple power converters with multiple voltage and current ratings. While the requirements are different, there is only one source that is a lithium-ion battery.

In modern smartphones, a single (lithium-ion) battery technology is not sufficient, which would require a combination of lithium-ion and some other battery technologies, because we need both high power density as well as high energy density.

That means, the battery has to store more charge for longer duration to increases lifetime. At the same time, it has to meet the stringent requirement to cater a high computational need. For example, if you want to see a movie, or if you want to talk, or if you want to attend a video conferencing, all these require fast transient response for frequent transients with large step sizes. So, the power supply requirement needs to cater fast dynamic loads as well as slow steady loads, which require both high power and high energy density battery technologies.

In majority of the time, smartphones operate in standby mode. You know, you want to use nominal applications, and you need high energy efficiency, such that the battery life can be sustained over a long time. But, all these require multiple DC voltage regulators in order to meet different application requirements.

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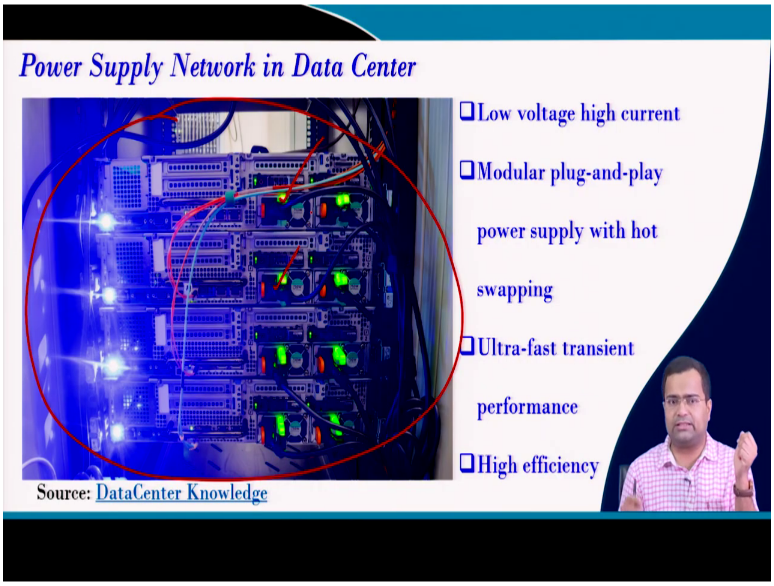

Now, if we look at data center application, data centers are common because everything we talk about cloud, even we want to store data in cloud, so it is a cloud server, like the cloud storage. We want to run certain applications in cloud where the actual server is sitting somewhere else.

We are browsing so many internet, we are accessing so many storage, you know for example, in Google storage, Microsoft storage, so most of these storage devices are sitting in a some data center. This means that such data centers require high computation and high bandwidth with large storage capacity.

So, all these require power and very stringent power. Most of the applications require very low voltage high current. For example, for processor application like a cloud server, the voltage can be 1 volt, 1.8 Volt close to that or even less than 1 volt, but the current can be 100s of ampere.

In fact, in future cloud servers, we may see 100s of ampere, or it may be more than 1000 ampere. So, for such applications, we need extremely high current demand with low voltage. So, power supplies require to meet stringent performance requirements to cater high computational requirements.

If you see the picture of this cloud server you can see, it is like a rack with multiple power supplies using some kinds of racks. So, it is a plug and play, you can take one then put another. So, they are arranged in a kind of a plug and play module.

So, these are module plug and play power supplies, and there should be a feature of hot swapping. Hot swapping means when other modules are active, if you want to interchange one module due to failure or something else or you want to replace, you can simply take it out and plug in another module without disturbing the overall power supply network.

Data center power supplies require fast transient response as well as high efficiency, because the current is in the order of 100s of ampere, and it changes in step. The current can change from 1 ampere to 10s of ampere or even 100s of ampere with the slew rate of 100s of ampere per microsecond. So, you know, this kind of application requires stringent performance requirement with high efficiency.

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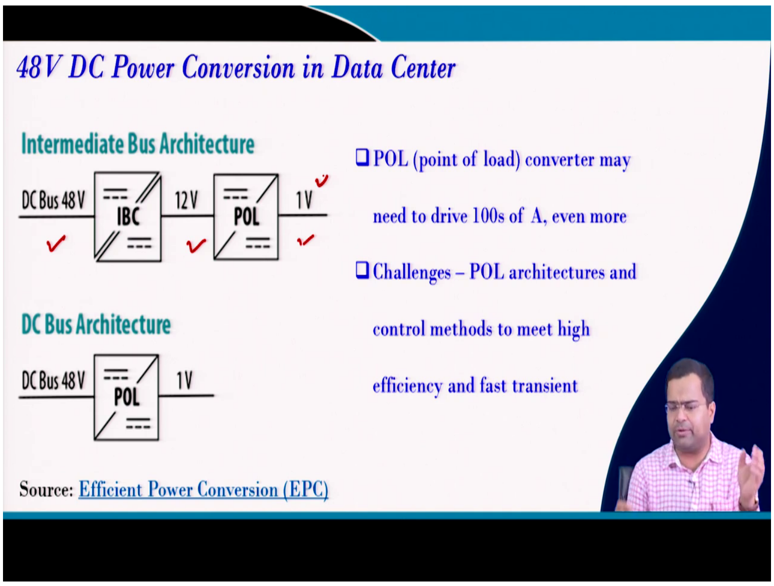

The present trend of data center they requires 48 Volt compared to earlier trend of different voltage levels, starting from the AC distribution network, conversion from AC to DC using multiple stages. Finally, when it comes to the processor, stage architectures were used earlier using an intermediate bus architecture, where we convert 48 to 12 Volt and then 12 to 1 Volt.

But now, actually we are trying to reduce the size of the converter because if there are two stages the efficiency of the overall converter will be product of these two. So, in order to improve efficiency and reduce size you know the present trend, there is a lot of research going on in various academic institute and also you know various industry where it is like a high power density power supply for 48 to 1 Volt application.

So, sometime this uses transformer based solutions, sometime you know we use hybrid DC-DC converter. So, in this course, I will briefly touch upon a little bit about this hybrid switch cap architecture, and then we will primarily go to traditional switch mode power converters.

So, in such application the output side which is 1 Volt it is a low voltage high current and it has to drive a server or a processor which may require few 10s ampere, even 100s of ampere. So, in the output side, we generally use a multi-phase converter. So, the current transient step size is pretty large, and we need to meet such stringent performance requirement and also to achieve high efficiency.

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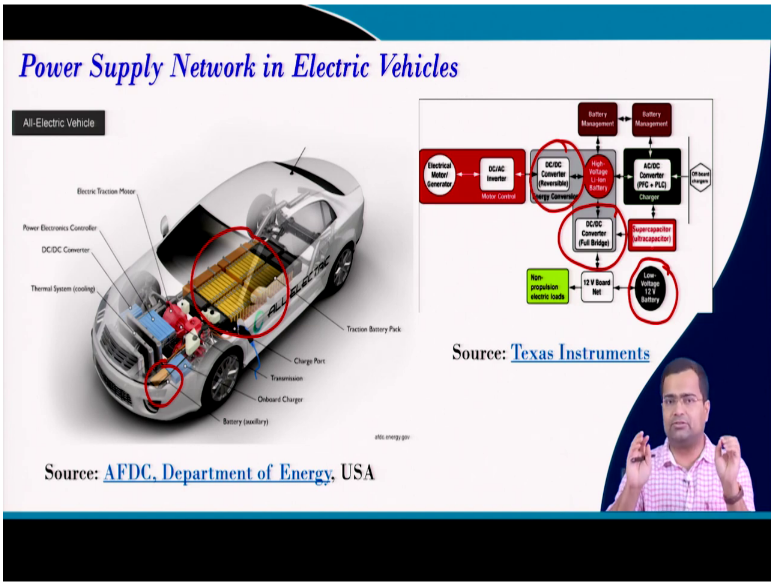

Now, if we look at power supply network in electric vehicle. Electric vehicle is another very upcoming area and in fact, many commercial electric cars are now available. Many manufactures are actually, you know, trying to upgrade the electric vehicle by modernizing their power supply network, particularly using wide band gap devices.

In electric vehicle, we have two type of battery, one high voltage battery and the other low voltage battery, similar to that in a traditional car using a 12 Volt battery. So, high voltage battery is used to supply the powertrain for powering drivetrain motor for propulsion applications.

So, we need this high voltage as well as low voltage batteries. And, there are many architecture like a power converter like a DC to DC converters, here high voltage to low voltage, so multiple DC-DC converters are required. And this 12 Volt, actually this 12 Volt battery supply majority of the electronic load in a car which is common irrespective of whether it is hybrid, plug-in hybrid, fully electric or even conventional car.

We have an informant system in the dashboard, where a lot of electronic gadgets are driven by this 12 Volt battery. This means we need multiple DC-DC converters with some common objectives in terms of performance, efficiency as well as power density size.

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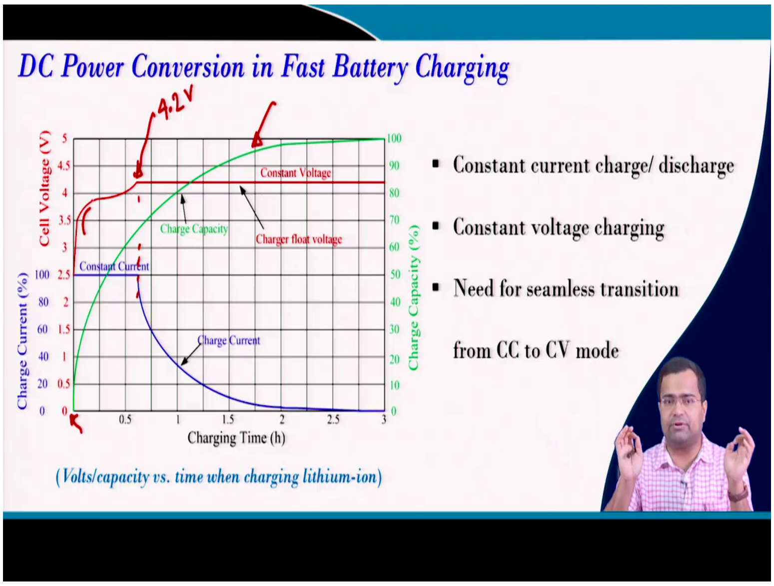

Another application is the fast battery charging that is also a very upcoming, you know. People are talking about fast battery charger, but for this fast battery charger, we need to consider various aspects. First of all, in a battery, whether it is a fast or slow charger, whenever the battery is fully charged, you see the green line here, which shows the capacity of the battery.

If the capacity is very low, its starting from almost fully discharged state. You may find some terminal voltages related to various products when a battery is fully discharged. They provide in their datasheets what is the voltage level corresponds to the discharge state of the battery, the capacity almost close to zero. Once the terminal voltage reaches to that level, we should not discharge further because there are certain constraints, and the battery life will be totally get degraded. So, once we let we come to the limit then we need to charge the battery because we cannot use it. So, when we start charging the battery up to certain level of voltage, and in majority of the lithium ion voltage you know they talk about 4.2 Volt.

So, when you start charging the battery you see the voltage is actually increasing, but initially we generally use a constant current charging, up to the voltage level of 4.2 Volt. And, this constant current charging is the amount of current that should be used to charge the battery. For example, in most of the mobile phones, the charger one of the terminals is the USB terminal, which we can put it into our plug adaptor or we can also connect to our computer. So, in both cases mobile will be charged either through adaptor or through our laptop. But you will find different charging times.

In an adaptor, it takes shorter duration, and in our laptop it takes longer duration. So, this is because of how much current you are using to charge. If you uses lower current, the battery will take longer duration to charge. For higher current, the battery will gets charged faster, but for faster charging, you have to pay penalty because the battery may get heated up. In fact, we need to check whether battery technology will support such fast current charging or not. So, there are scopes for optimization, thermal, other aspects.

But when battery reaches 4.2 Volt we need to go for constant voltage charging. This means that we need seamless transition between constant current and constant voltage charging, and the power converter has to meet certain constant current and constant voltage charging configurations.

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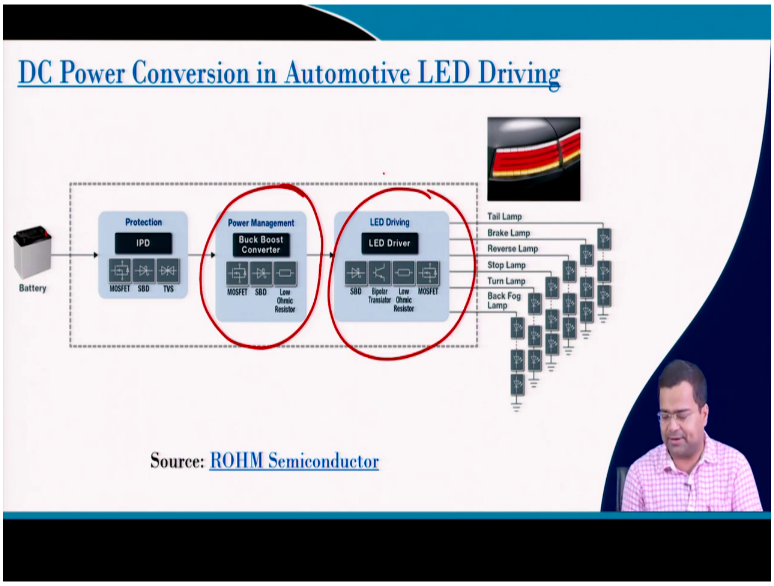

If we consider automotive LED, like a lighting system which is now going to be LED. So, if you take headlight, fog light, tail light, everywhere you will find increasing use of LED. And these LEDs are semi-conductor device and they directly operate using a DC voltage.

But, we cannot connect such LEDs directly to the battery because a LED requires certain current regulation. You need to ensure that the current through the LED is going through a controlled manner, which requires a power management circuit, mainly DC-DC converter based voltage and current regulators.

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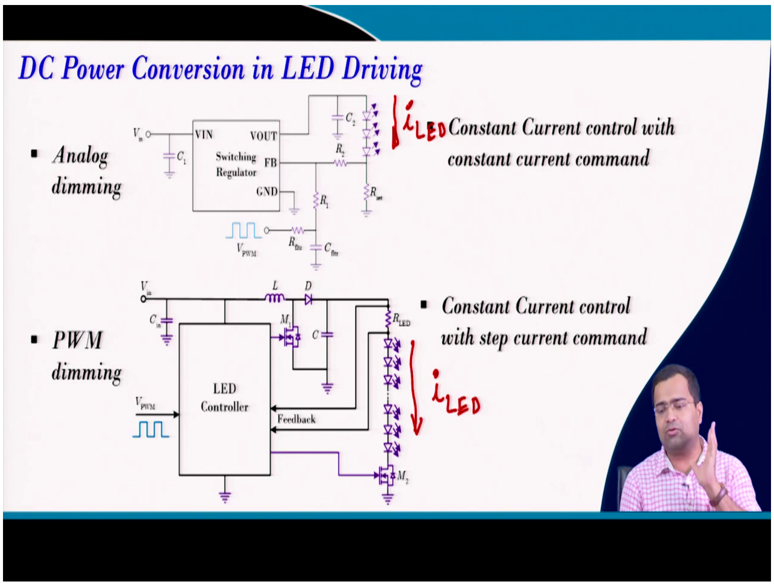

So, if you consider the brightness control in LED, we need to control the current through it, and a LED has some IV characteristic. So, one way to control the brightness of the LED by controlling the current in a continuous fashion, which means, if we reduce the current the brightness will get reduced, if we increase the current. This requires a constant current control based on current command which you are sending. This is analog dimming where we are strictly maintaining the constant current.

The another dimming technique is called PWM dimming, where the LED current is changed from its nominal current to zero current. That means, in unlike in previous cases where the current can be adjusted in between its nominal value to 0 value, in this case the current is used either 0 or full value a nominal value.

Then, if we use let us say you know 1 second fully on LED and 1 second fully off, so over 2 second duration we will get 1 second on, 1 second off. Now, if we this ratio if we keep 50 percent like 1 second on, 1 second off. Now if we make it 1 millisecond on, 1 millisecond off, the ratio remains same, but the time duration is reduced.

So, if you use such a faster change in current then our eye cannot see the transient effects of the current as if there is a low pass filter. So, we will see the average value of the current. This means 50 percent brightness of the LED. Since LEDs are semiconductor devices, we can turn on and off very fast.

But, from the human eye perception point of view, the LED can be turn on and off at a faster rate and if we adjust the duty ratio of the on and off time then we can adjust the brightness. So, this is another application where we are using constant current with a step command.

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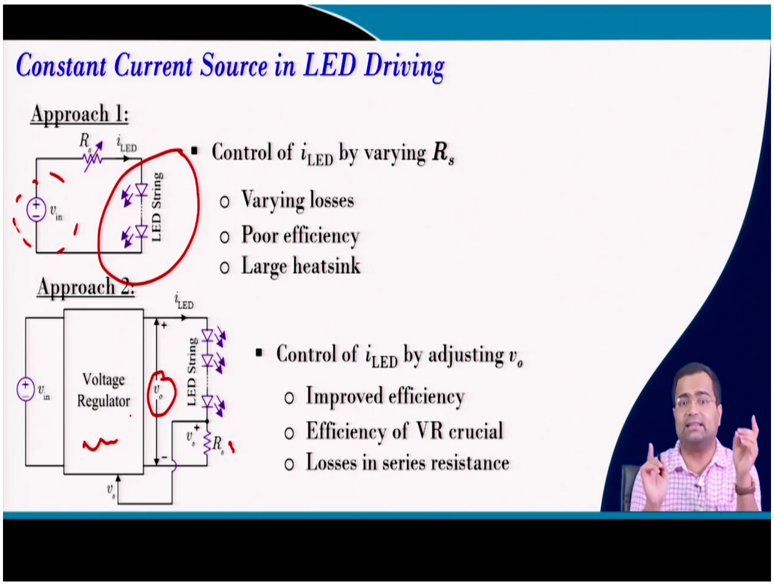

Now, in LED driving, either we can control this LED current connected in a string. So, for driving LED strings using a power supply, we can connect a series resistance to adjust the LED current. But, this is not a good way because this change in resistance actually is used to reduce the drop, voltage drop in order to maintain the voltage across LED as well as the current through the LED. So, this way majority of the losses happen through this variable resistance. Since, it is lossy, efficiency is poor, and we need a bulky heat sink.

As an alternative approach, we can use a voltage regulator in which the output voltage can be adjusted. Now, the series resistance is constant unlike in the previous case, but the voltage is adjusted. This means, we are trying to control the voltage using a voltage regulator. This approach is better than previous, but the efficiency still depends on the voltage regulator. And also, the loss in the R s is still there.

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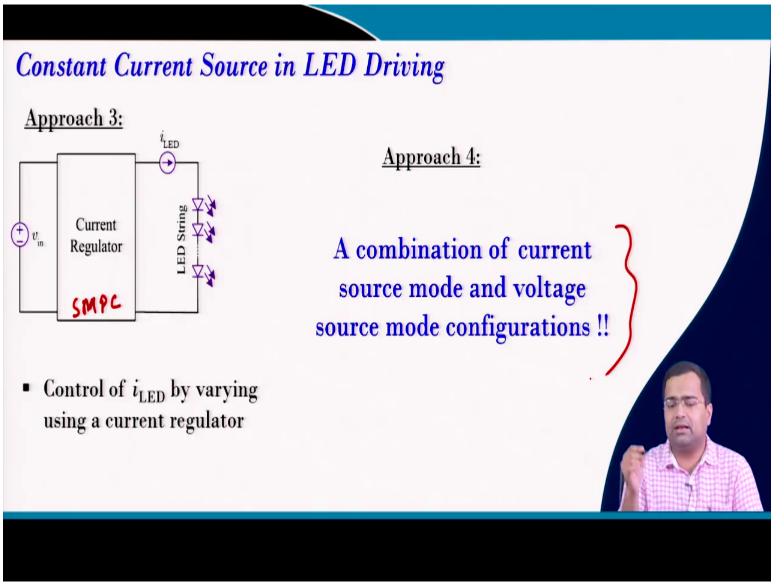

The 3rd approach: We can directly use a current regulator, and the power converter can be used as a current regulator, in which the output current is directly controlled. So, we do not need to use any resistance here, because we do not need to create a drop. So, we can control current this why you can achieve higher efficiency. Perhaps, a combination of voltage and current regulation configurations may be a better choice to reduce flickering effects particularly when series/parallel LED strings are used.

So, if you take care, combine these two technique because the practical current regulator cannot have you know, cannot have a pure current constant current during transient also. So, if we use these two combination probably we can reduce various drawback of either configuration and we can take the best combination in this approach.

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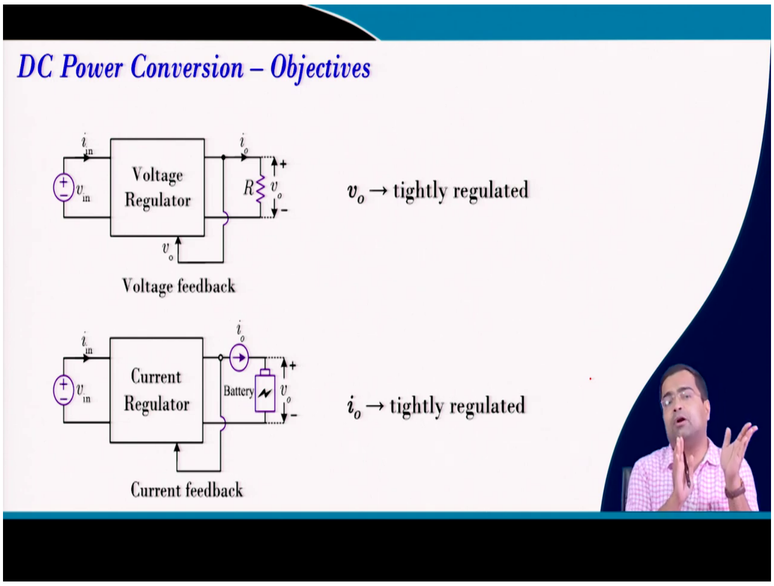

So, the DC power conversion objective, either we need voltage regulator where we need to regulate the output voltage or we need a current regulator where you need to regulate the load current or the output current.

So, that means, we need either voltage or current regulator. In voltage regulator, the output voltage may also need to track an envelope, for example in power amplifier. Thus, voltage regulators are power converter which can be used for tracking application as well.

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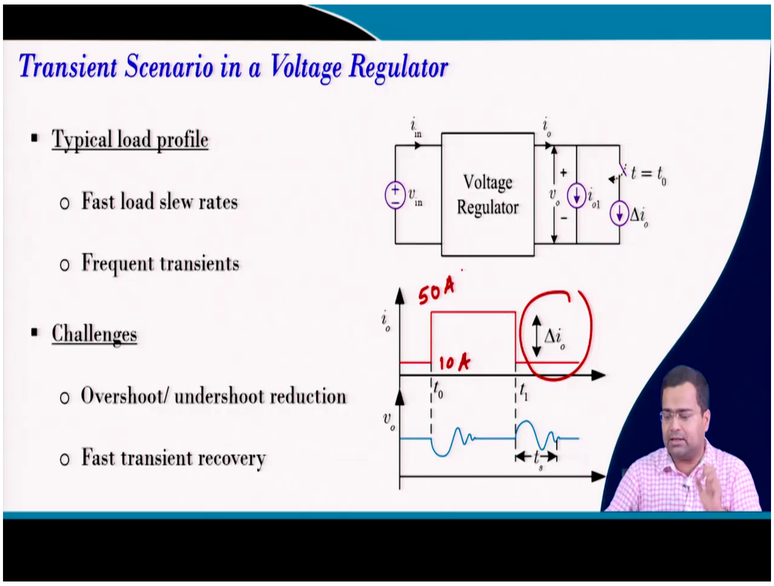

In a transient scenario, I talked about low voltage high current application, where the load step size can be a few 10s to 100s of ampere. For such load steps, the converter can actually undergoes large undershoot/overshoot during step-up/down transients. So, the typical load profile changes very fast, and the slew rate can be a few 100s of ampere per microsecond.

This transient can appear frequently because if you use a computational load, at the instant of computation, the load current can drastically change, so the transient can happen frequently. And we need to reduce this overshoot and undershoot, because there is a stringent requirement in terms of noise margin of the voltage because this power supply is used as a Vdd of a digital processor.

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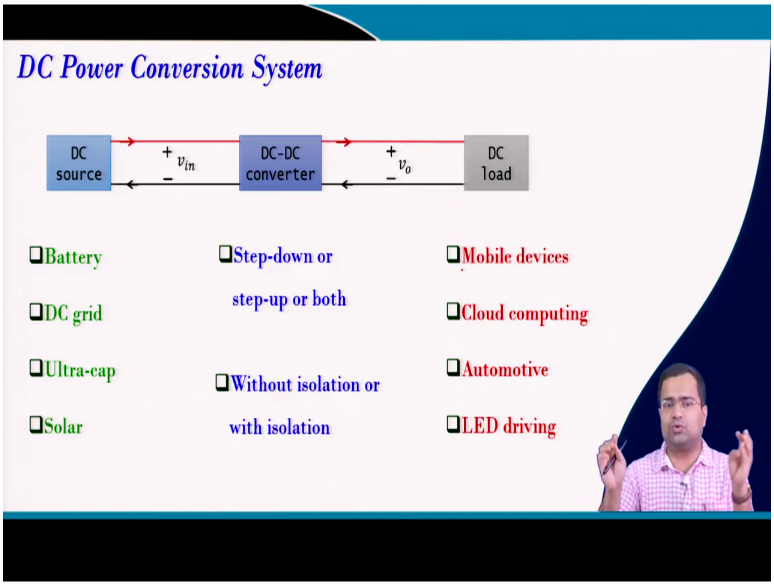

And we also want to reduce the transient time. This means that we need to speed up this transient. So, the primary objective of a DC-DC, this course we are trying to particularly focus on DC power conversion system where we have a DC source and one or more DC loads, but we are talking about a single source. Even in some cases there can be multiple sources, which can be battery, grid, ultra-cap, solar. The load can be of various types depending on applications, such as mobile phone, cloud computing, automotive. We need to step-up from source to load or we need to step-down or it can be close to input output voltage can be close to each other. Either, we need to isolate the ground between DC source and DC load and in some cases we do not require isolation.

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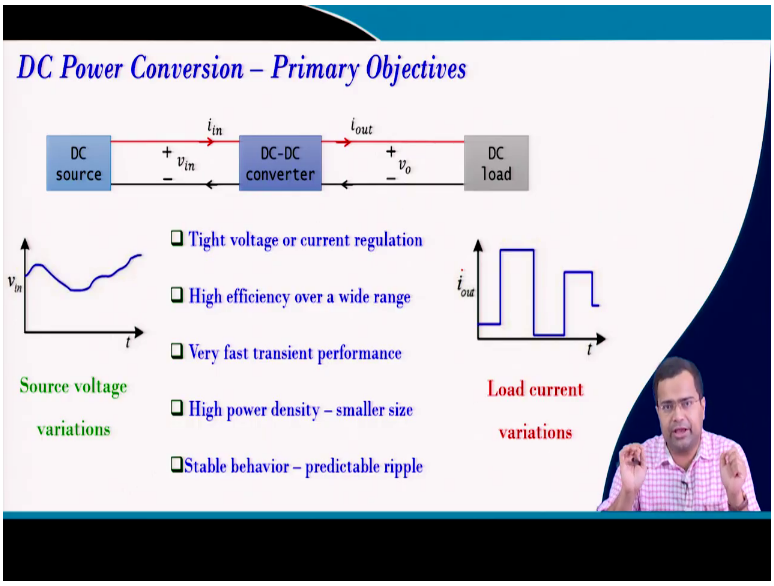

Source voltage can vary, load current can vary, and the current can vary in step transient. In some cases, the load voltage can also vary in dynamic voltage scaling application. So, our primary objective is to achieve tight voltage regulation in case of voltage regulator. Also, in some applications, we need to regulate current where we need to maintain precise current. For example, in constant current, battery charging, LED driving, we need to achieve high efficiency over a wide range of load current and input voltage and we need to achieve fast transient response.

And we need to reduce the size of the converter because everything starting from our mobile phone, you know the car, everywhere we want to reduce the power processing, size, and weight, so we need to achieve high power density. And we need to ensure stable periodic behavior in order to predict the ripple parameter.

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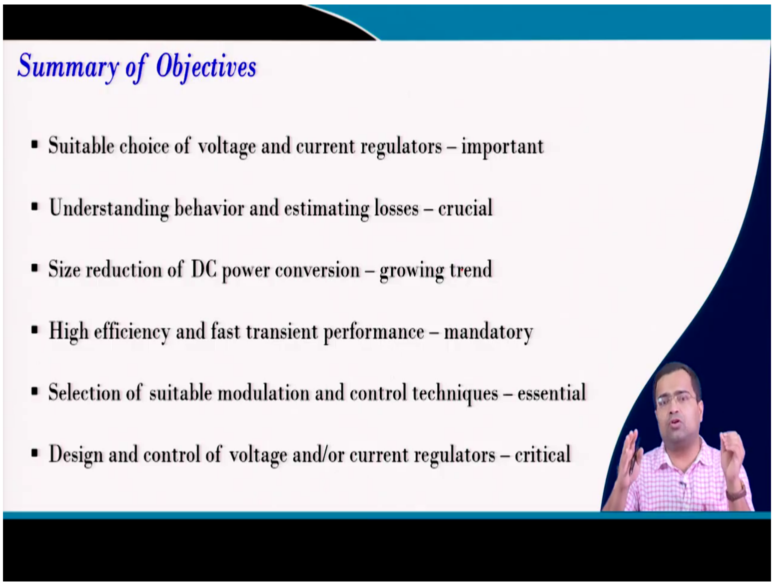

In summary, the objective is to identify suitable voltage or current regulator depending upon nature of applications. We need to understand the behavior, and we need estimate the losses. These are also very important. Then, our objective is to reduce size for the DC power conversion system. And as I said that is the growing trend where we want to use more wide band gap device.

And also I will show the control can play a significant role even for reduction in the transient time, transient overshoot, undershoot as well as to improve efficiency and also to reduce the sizes. Control can also play role, play a role. Then, we also need to achieve high performance and efficiency, and selection of suitable modulation and control technique is very important, and design and control of voltage and current regulator are critical.

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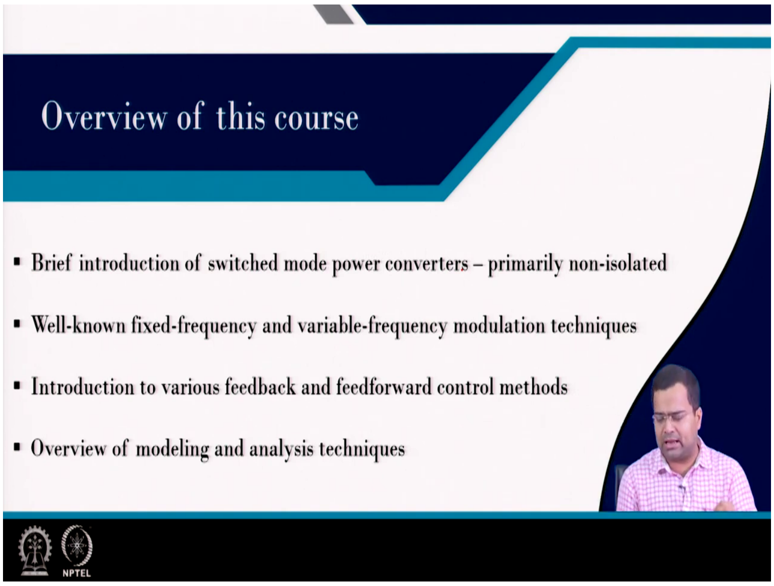

So, keeping that in mind this course is designed for 12 week. And this course we are going to touch upon various basic DC-DC power converter architecture. We will primarily consider non-isolated, but you know some of this technique can be used for isolated converter also.

Then, I will also discuss about different fixed frequency and variable frequency modulation technique. I also discuss various feedback and feed forward control method. Different, I want to give you an overview of modeling and analysis technique.

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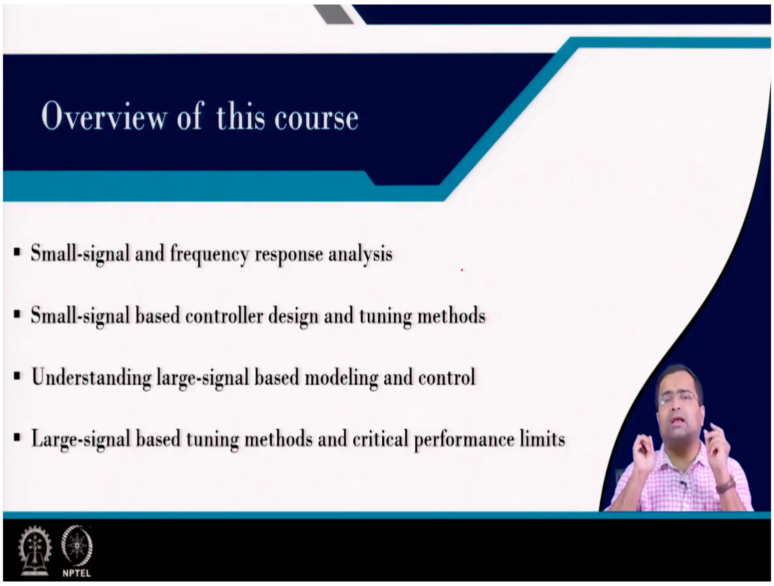

I also want to discuss about small-signal modeling, frequency response analysis, then, how to design small signal base controller and also what are the tuning method and their summary.

Then, I also want to identify what are the limits in order if you want to achieve high bandwidth using small-signal base control. And then what is the requirement for going for you know large signal base control and tuning method. And then, we want to show some of the large signal based control and tuning method and then how to identify critical performance limit.

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So, for this course, the primary references, you know this is a tutorial paper which is an open access journal, this will be a very valuable resource for this course. Then, you know there are very well known books like you know the book written by Professors Erickson and Maksimovic. This book will be useful for many design and topological aspects.

Also, the Elements of Power Electronics book written by Prof. Philip Krein will be very useful, in particular for the geometric control, the non-linear control method. And then, you can also refer the NPTEL Switch Mode Power Converter course which can be used like a preliminary resources particularly to understand the topological aspect, the laws aspect, the switching device, you know magnetic selection, power (Refer Time: 36:10) design. In depth you can get the resource.

Thank you very much for this you know lecture.