Digital Control in Switched Mode Power Converters and FPGA-based Prototyping
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Module - 01
Introduction to Digital Control in SMPCs
Lecture - 01
Digital Control in Switched Mode Power Converters - Course Introduction

Welcome to the NPTEL online certification course. The title of this course is Digital Control in Switch Mode Power Converter and FPGA-Based Prototyping. I am Dr. Santanu Kapat, an Associate Professor in the Department of Electrical Engineering, IIT Kharagpur.

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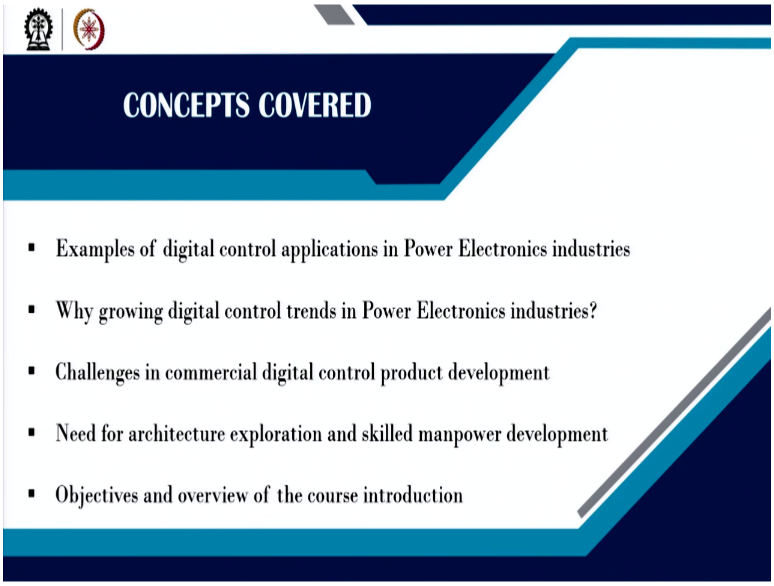

So, in this course, particularly in this lecture, we want to show some examples of digital control applications in Power Electronics industries. Then I want to emphasize why there is a growing trend in digital control in Power Electronics industry, then what are the challenges in commercial digital control products. And, then what are what is the need for architecture exploration and skill manpower development? And finally, what are the objectives and overview of this course?

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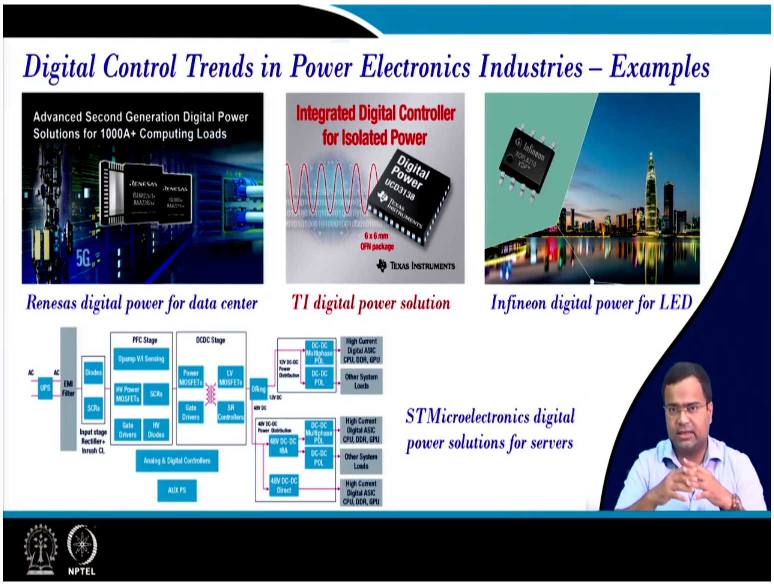

So, the digital control trends in power electronics industry. So, some of the examples I am showing. One is like you know for low voltage high current applications, particularly for cloud servers. And you know everything now like you know in the age of the internet we talk about cloud computing.

So, if you talk about cloud servers then this cloud server power supply requirement. The voltage can be 1.8~V or below, but the current can go like it can be 100s of amperes even if it can be beyond 1000~A. For such applications, digital control plays a significant role. And in this one example, I am showing the Renesas digital power product. I mean these are the for data center applications.

The other example I am showing is the STMicroelectronics solution for the server, where it is the complete server starting from the AC input and then AC to DC, then DC to DC. And nowadays there is a growing time for 48~V to direct conversion. So, that means, there are 48~V. It is the Google server standard. And then either you can we need to go for single stage 48 volt to POL or multi-phase or it can be you know two-stage architecture, and there has been a lot of research going on in this area.

But if you look at the majority of the product they are coming in digital power solutions. Another example is the Texas Instrument. In this particular example, I am showing where this UCD 3138. This IC can be used for isolated DC-DC various types of isolated DC-DC converters; that means, or even it can support various you know multiple converters. So, this one IC can be programmed and it can be configured to accommodate various topologies.

Another example I am showing there is Infineon digital power for LED driving applications. So, if you go for let us say street LED driving or LED TV, then you start from AC, and then DC, because LED is a DC load. So, if you take this Infineon digital power solution and it there can be a power factor character followed by LLC and other types of architecture for LED driving.

So, these are a few examples of a large you know amount of digital power solutions in power electronics industry and slowly most of industries are going for digital control.

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Now, where is where there is a growing trend for digital control? One of the reasons is that by using digital control we can make the design flexible; that means, as I said in the previous example the one IC can be used for various topologies; which means, we can program this IC through software and we can change the parameter we can configure it so that it can be used for other architecture or even it can be used for various power levels.

Then this design in this course we will be talking about hardware descriptive language Verilog HDL based you know design and the programming where this design is portable, it can be mapped to various process technology or even you know digital control can be you know different type of microcontrollers are available. So, this design should be flexible and they are reconfigurable; that means the controller can be reconfigured for achieving very light load efficiency at the same time high performance under nominal load conditions.

Then, digital control and communication because now we talk about PM bus, where this is a protocol where multiple converters can interact by the clock as that and the data so that we can make the power supply reliable and fault-tolerant. The whole network can be smart because they can communicate.

Then one of the examples I was showing was that if you take one digital control IC that IC can be configured its parameter can be configured. So, this IC even the commercial ASIC IC that IC can be programmed through external software; that means, we need to have; means, there is an increasing trend of hardware software and farmer integration. So, this is for the ASIC solution. And if you go for a modular microcontroller-based solution, then you have that hardware software as well as the farmer integration.

And that will use that can be used to optimize you know from a power converter you can optimize from the very switch level to the whole converter level; that means, for example, for gate drive we can make smart gate drive or intelligent gate drive to make it more efficient, we can even reduce the effect of EMI. And at the same time, overall converter efficiency can be improved.

You know overall from light load to high load over a wide range of input voltage or even there are multiple converters, for example, the onboard charger you have PFC and LLC. And there may be other architectures; it can be bidirectional such kinds of converters frequently the digital control solutions are used where you can interface the third party solution; that means, the power stage can be one you know one company then the digital controller can be other company. So, it can be plug-and-play.

We can achieve high efficiency; that means, as I said that we can improve the very light load efficiency; that means, we want to achieve the flat efficiency curve over a wide range of load current, and then we are also trying to reduce the component because everything else is integrated in the ASIC solution or can be in the microcontroller itself.

Then, we can actually implement various advanced control because in the later of this course, I will show you some commercial products where the digital platform can be used to implement non-linear as well as linear control combinations. So, in the large signal if it can be configured to non-linear control where it can achieve more or less the fastest transient like a time optimal response.

And then under steady state, there is a scope for you know parameter optimization, there are scope for frequency modulation as well as ripple minimization, and light load efficiency improvement. So, all these features can be incorporated using digital control. Then there are different levels of digital control products. One can be digital power management IC where the controller ADC switches all are integrated into a single IC for low power application and the only off-chip will be the inductor and capacitor.

So, such an application can actually you know reduce the size of the space because of your controller component I mean unless unlike in analog control where we generally have off-chip capacitor resistance. So, that can be integrated inside the digital controller. So, it can be made more high power density solution.

Similarly, digital control IC: For example, if you go for high current application where there are multiple phases and there are scale level phases. So, each phase has its hub bridge switch cell as well as the driver integrator. So, it is a smart phase; and each of these phases has its own current sensing arrangement and driver optimization arrangement.

And there is a centralized digital controller which interfaces among multiple phases and it controls the multi-phase overall control in such a way it can reduce the ripple it can improve the transient response and can do phase sharing operations, improve the light load efficiency, and so on.

Similarly, if you go for a digital control system solution like a plug and play; for example, if you take an onboard charger, where you can have PFC, LLC. So, the whole converter can be controlled through one digital controller. So, it can be plug-and-play and such a digital controller card can be used to improve the overall efficiency you know to take care of the soft start, protection circuit, what shopping. So, many features can be incorporated.

And finally, digital control can reduce technology development as well as product development time. So, it can reduce the time to market. So, as a result, it can give some edge to the industry to come up with the new product in a shorter time.

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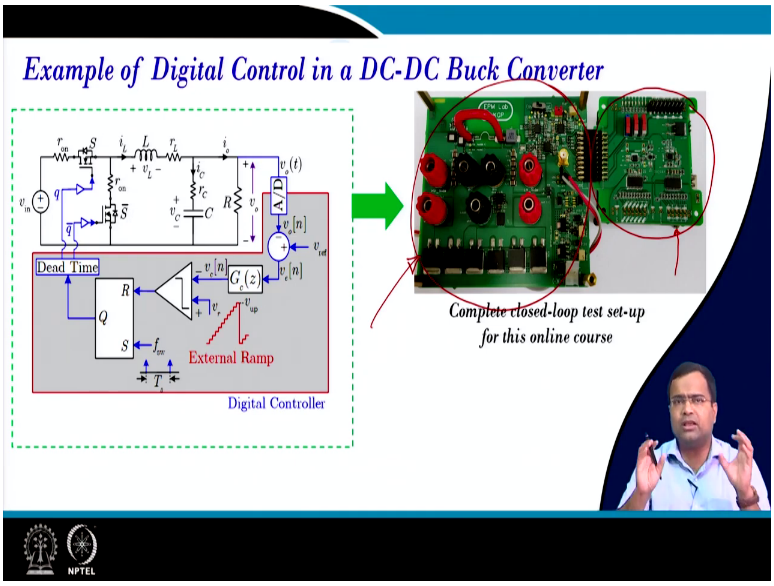

So, here I am showing an example of a buck converter. In this course, we will have buck and boost converter hardware extensive case studies. And, we are going to use this test setup, where you know in this particular setup this is our power stage architecture. And here on here is a board-to-board connector it is a signal conditioning board and just below this board there is another board it is just you know below this board, I will explain this board in the next lecture where we are using an FPGA card.

So, I am just showing one example that you can use here this power test is configured in such a way we can use both as a buck as well as a boost converter. So, I will be showing multiple experimental case studies using this setup where we will implement a digital controller using an FPGA.

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But what are the challenges in digital control? Because digital control will come with also some additional costs and there are challenges in how to deal with and how compete with this analog counterpart. So, one of the primary aspects is the cost because we are using an ADC, we are using a DAC; not all digital control techniques require DAC.

So, we need to understand thoroughly different architectures and we need to optimize the number of ADC and DAC so, that they can because can reduce the cost. Again for a given ADC, we need to be careful about the selection of bit size, and the selection of sampling rate because we try to reduce delay as well as we want to reduce the hardware architecture size and the power consumption so that you can reduce the silicon size.

Then, we need to also reduce the computational time. So, all this computational time, bit size, and sampling rate; come with an additional controller and that may incur costs. So, there will be challenging to optimize the cost and there are opportunities for cost optimization and then the level of digitization.

So, the digital control we can let us consider; if you take a pure analog control. For example, if we take a pure voltage mode control or a current mode control. We all know about the current mode control which is a two-loop control. And in the current mode control if you keep both the inductor current loop as well as the voltage loop in the analog domain as it is like a traditional analog current mode control.

Then we can start with the basic housekeeping; that means we want to program the reference voltage because we need to change the reference voltage in order to meet certain DVS applications, Dynamic Voltage Scaling applications where the reference voltage should be adapted based on the processor task requirement. So, such provision of programming a reference voltage can be done through a housekeeping arrangement. So, this is a very low level of digital you know utilization.

Then we can go to digitizing the loop; that means, in current mode control we can start digitizing the voltage loop which may be slower compared to the current loop, but we still keep the current loop in analog. So, this can be a part of the mixed-signal implementation. Another implementation every all the loop can be fully digital. So, in that case, we will say fully digital architecture. So, various types of digitization and various level of digitization are possible.

And for each digitization methodology, we need to adopt a certain modulation technique; that means, whether it is a fixed frequency modulation whether it is a variable frequency modulation. For each modulation, what will be the sampling rate and sampling frequency? Should it be uniform sampling? Should we synchronize the sampling rate with the clock? Should we use one sample per cycle or a multi-sample per cycle? Should we use event-based sampling or uniform sampling?

So, this aspect will be also they are challenging and it will be discussed thoroughly in this course. Then there are implementation platforms; that means if you take mixed-signal architecture. So, some part analog some part digital. So, there has to be some data conversion block to interface between analog and digital. So, based on the implementation platform there are many digital control architectures.

Another important very important factor is the power consumption because if you consider an A to D converter, and if you want to reduce the loop delay sometimes you need to increase the sampling rate, but the same is see if you operate at a higher sampling rate it will consume more power. So, your power consumption can increase. So, there is a trade-off.

Similarly, if we want to achieve higher voltage resolution we may want to go for a higher bit size, but that may be counterproductive in terms of the size of the architecture or even the power consumption and the propagation delay. So, we have to be very careful about the selection.

And we will also see this bit selection also imposes a constant in terms of duty ratio resolution. So, we have to meet certain requirement minimum requirements to actually ensure some of you know the stability aspect and the performance aspect. Then, under such a resource constant; that means, we have a finite sampling rate and there will be some sampling delay because of the conversion time and computation time.

So, keeping that delay in mind, are we going to face some stability in the issue that we will see in the subsequent lecture? And we will find there is a significant impact of the sampling delay on the stability. But, we need to understand how to model that and how to ensure stability and within that sampling delay what should be the criteria for the design of the controller. It should not be simply mapping analog to digital because we will end up with some sort of non-linear behavior which may not be acceptable.

So, we need to understand modeling analysis and design methodology and the stability and performance in order to keep the converter stable as well as we need to achieve certain acceptable performance. Finally, our design is in the mixed domain because some part in digital some part is analog.

And in the digital domain of this course, I will be showing Verilog hardware descriptive language-based development. So, we will start developing the digital architecture of the controller starting from the gate level because we may not go to the switch level, but at the gate level we will talk about Verilog coding and this code while we will be prototyping using FPGA, one can try to go synthesize using ASIC solution.

So, in this development by HDL base, we can also go for ASIC solution, or even in this course, we will show some demonstration using microcontrollers. So, one can also use microcontroller-based implementation, particularly for high-power applications.

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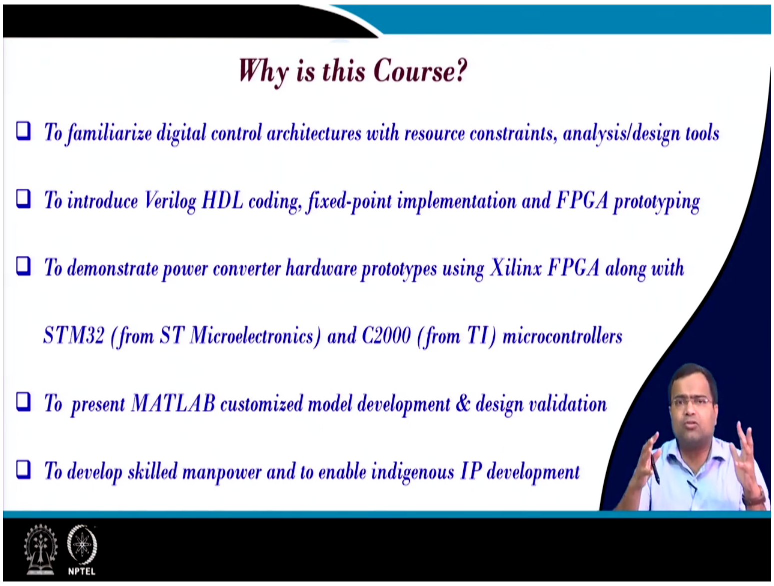

So, why is this course? In this course, we are going to familiarize various digital control architectures, keeping in mind that ultimately this will go to some sort of commercial product. So, we need to keep in mind, we may end up with a very complex control algorithm that can be a very high five mathematical formula, but this may not be accepted from the product point of view because it should be simple, it should be robust and it should be area and the power-efficient ok.

So, keeping all these minds we need to understand what are the resource constants and what are the feasible and acceptable solutions from a product point of view. Similarly, we have to understand some analysis and design tools. So, these things will be covered in this course. Then I will be talking about Verilog's harder descriptive language. I will give you almost two weeks' introduction to HDL and fixed point implementation and how to implement a PID controller, and digital PID controller and that part will be discussed.

Then subsequently I will be showing various prototyping steps, how to prototype this HDL code using FPGA and how to validate, how to demonstrate, how to use a power converter, and how to control it. And in this course, we will be extensively using a Xilinx FPGA-based hardware demonstration. And there will be a couple of microcontroller-based digital control implementation video lectures that will be demonstrated what we will be using like STM 32 as well as C2000 micro controller.

And the design expert from ST Microelectronics as well as the Texas instrument will be demonstrating the implementation using a microcontroller and how to implement digital control with power converter case studies. In this course, we will be also demonstrating MATLAB customize, and how to develop a customized model using MATLAB simulation Simulink.

Then, we will develop different Simulink architectures for different controllers. And, then we want to validate. Although this validation may not be part of the exam, this validation will show some optional lectures that would show how to validate your MATLAB model with your mathematical model.

And finally, this course is aimed to develop skilled manpower to understand the digital control architecture and also to develop indigenous IP; which means, intellectual property.

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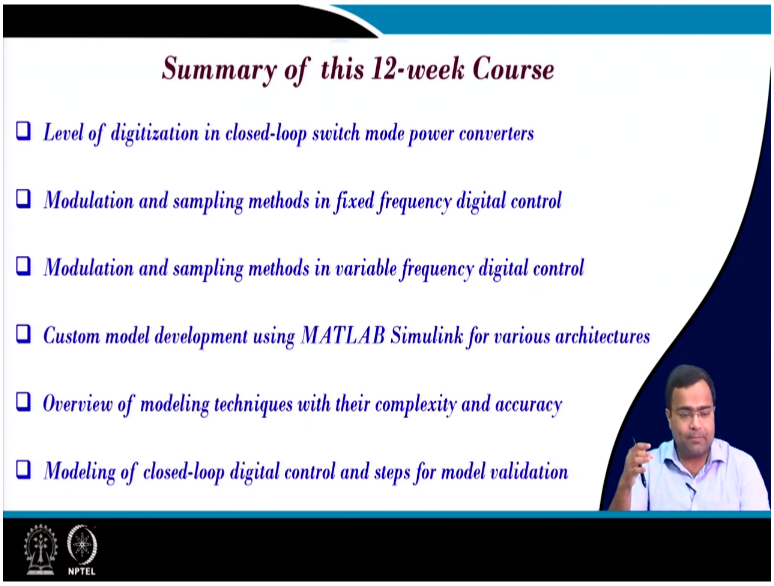

So, this course is a 12-week course. And, we will first discuss some level of digitization in closed-loop switch mode power converters. We will also discuss various fixed frequency and modulation variable frequency modulation techniques and different sampling mechanisms which we will try to optimize the resources as well as to ensure stability.

So, we will talk about modulation and sampling methods in fixed frequency digital control as well as modulation and control technique for sampling techniques for variable frequency digital control. For example, we will talk about constant on-time control, constant off-time control then hysteresis control.

Then, we will also demonstrate custom MATLAB model development using MATLAB Simulink, and for different control architectures. Then, I will also give you an overview of various modeling techniques and what are their complexity and accuracy. And finally, what modeling technique should be used to get you to know how what is the design flow and then ultimately how to validate it? And I will also show modeling of closed-loop digital control and step response and different step on how to validate the model.

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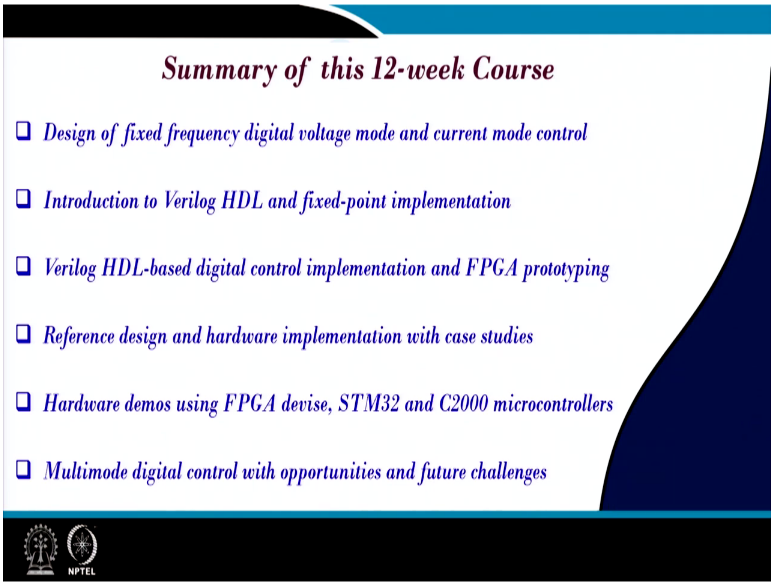

And then, I will also show how to design fixed frequency voltage mode and current mode control. You know what is the technique, what are the summary, then I will also introduce in detail the Verilog HDL and fixed-point implementation. Then I will talk about Verilog-based digital control implementation and FPGA-based prototyping.

Then we will also provide a buck and boost converter reference design with all the details. And we will also demonstrate hardware implementation with different implementation case studies. And finally, multiple hardware demonstrations will be carried out using FPGA devices, and also some selective digital control case studies will be shown using STM 32 and C2003s microcontrollers.

And finally, I will show using FPGA how to implement multimode digital control so that you can increase the light load efficiency as well as high load performance and some aspect of future challenges. So, that is it for today.

Thank you very much.