Digital Control in Switched Mode Power Converters and FPGA-based Prototyping

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Module - 12
Hardware Case Studies of Advanced Digital Control Techniques & Course Summary
Lecture - 120
Key Takeaways and Course Usefulness for Skilled Manpower Development

Welcome this is the last lecture of this course and I think we have spent enough time and we understood a lot of modeling theory architecture analysis design Verilog HDL programming then we have also learned STM 32 C2000 series microcontroller programming and then we have considered a lot of case study of the experimental case study. So, in this lecture, I want to summarize the key takeaway as well as the team introduction and usefulness of this course for skilled manpower development.

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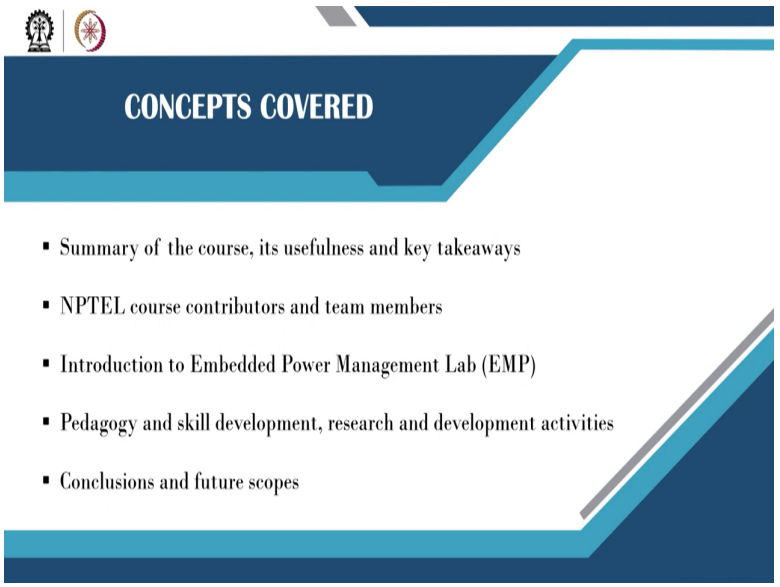

So, I will first summarize the course, its outcome and its usefulness, and the key take away then I will introduce our NPTEL course contributor and the team members then I will introduce our embedded power management lab and what we do. So, far we did so, for the pedagogy and skill development as well as what research and development activity is going on in our EPM lab that we will discuss summarize, and then finally, conclusion and some future scope.

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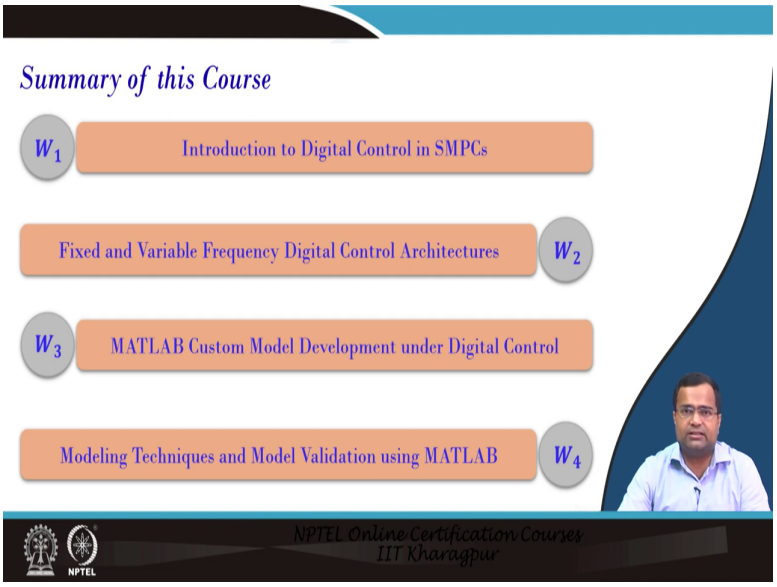

So, in this course we have in week 1 we have discussed the introduction to digital control in switched mode power converter. Then week 2 we considered fixed and variable frequency digital control architecture. Then week 3 we developed a MATLAB custom model under various digital control. Then week 4 we considered the modeling technique and the model validation using MATLAB.

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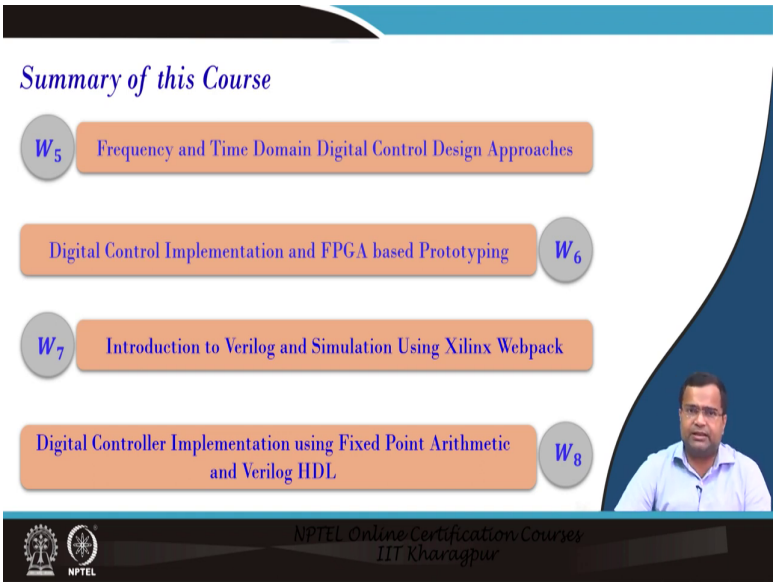

Then week 5, we considered the frequency domain at frequency and time domain digital control design approaches. In week 6, we considered digital control implementation and

FPGA-based prototyping. Then week 7 we considered an introduction to Verilog and Verilog HDL as well as simulation using Xilinx Webpack.

Then week 8, we discussed digital control implementation using fixed point arithmetic and Verilog HDL.

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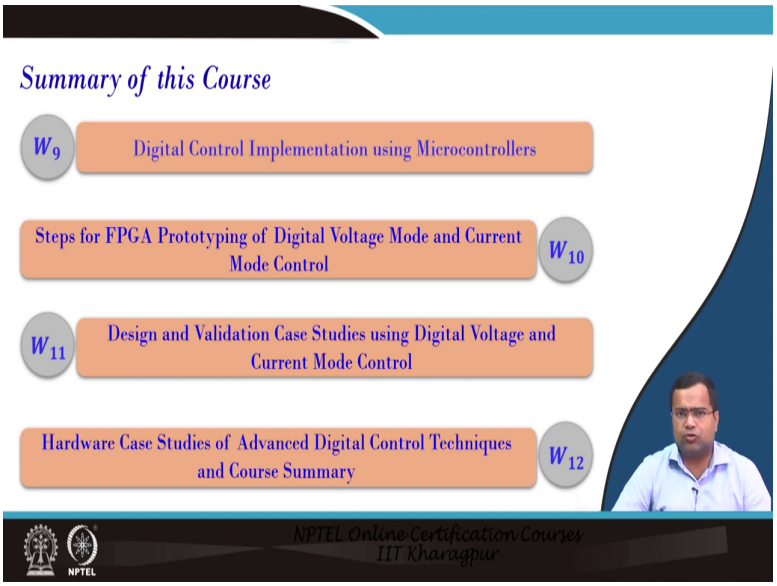

Week 9, we discussed digital control implementation using microcontrollers using STM 32 and C2000 series microcontrollers. Then week 10, we talked about the steps for FPGA prototyping for digital voltage mode and current mode control. Then week 11, we considered the design and validation case study using digital voltage mode and current mode control.

Then we discussed in week 12, the hardware case study of advanced digital control techniques, for example, the multi-mode control technique frequency spread spectrum technique, and then finally, the course summary.

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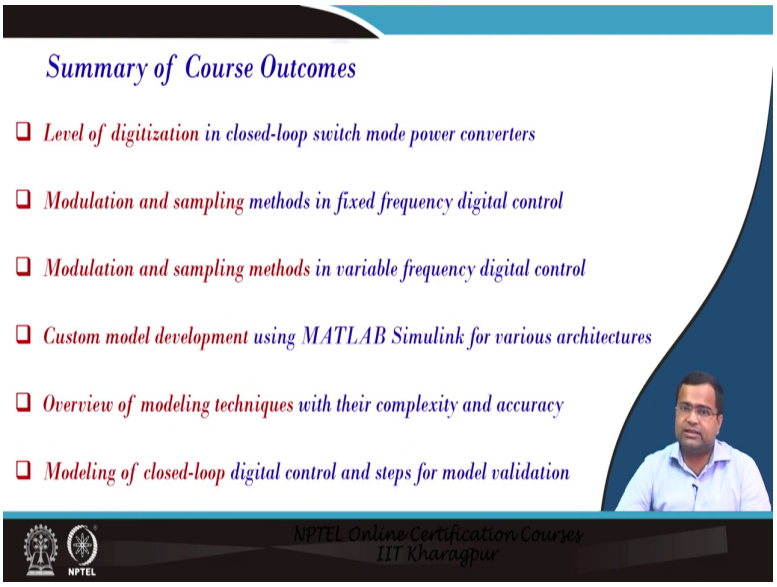

So, in this course, if we want to summarize the outcome we have learned various levels of digitization in closed loop switch mode power converter we have also learned a lot of modulation and sampling techniques in fixed frequency digital control.

We have learned modulation and sampling methods in variable frequency digital control then we have learned custom model development using MATLAB Simulink which is a customized MATLAB script as well as Simulink interactive MATLAB simulation for various architectures. Then we discussed an overview of modeling techniques with their complexity and accuracy aspects.

Then modeling of closed-loop digital control and the step for model validation. We have also discussed the design method for fixed frequency digital voltage mode and current mode control technique.

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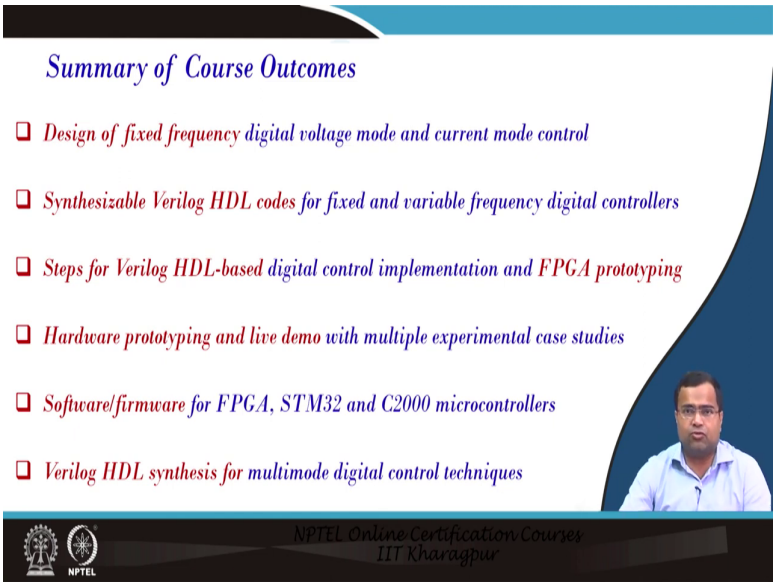

We have also developed a lot of synthesizable Verilog HDL codes for fixed and variable frequency digital controllers. Then we discussed what is the step for Verilog HDL-based digital control implementation and FPGA prototyping. Then we also developed and discussed you know presented a lot of hardware prototyping and live demos with multiple experimental case studies. And we have also discussed the software and firmware aspects of FPGA STM 32 and C2000 series microcontrollers.

Then we discussed Verilog HDL synthesis for multimode digital control techniques.

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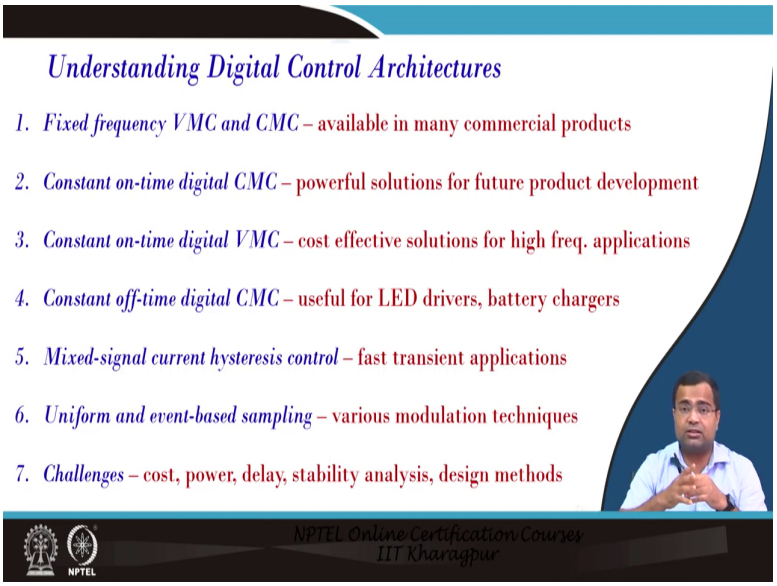

So, in summary, we understood various digital control architectures first we fixed frequency voltage mode and current mode control these are already available in many commercial products. Then we have also discussed constantly on-time digital current mode control these are very powerful solutions for future product development these are already being used for you know multi-phase and other low-duty ratio high-frequency applications.

Then digital constant on-time voltage mode control is a cost-effective solution for high-frequency applications, current mode control is also very useful for you to know the multi-phase and also other applications where we need precise current regulation.

The constant off-time digital current mode control is also a very powerful solution for led-driving battery charging applications. Then we discussed mixed signal hysteresis control which can achieve a very fast transient response and we have also learned uniform and event-based sampling techniques for various modulation techniques. These are kind of developing an upcoming research topic and one can keep watching what is coming.

But these are very important aspects of various modulation techniques. Finally, we understood the challenges of cost power delay and then stability analysis, and what is the methodology for design to design this digital control method.

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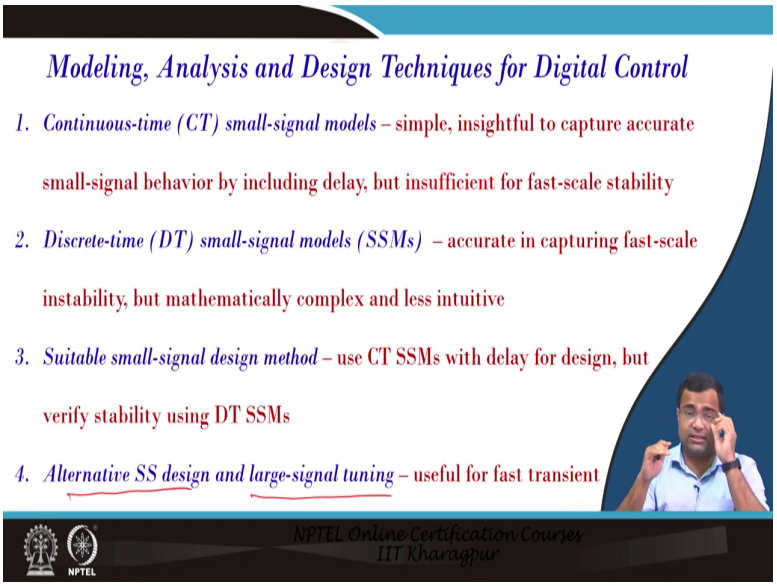

In the context of modeling analysis and design technique, we have learned that the continuous time small signal model is simple and insightful because it gives us pole-zero concepts is gives us the concept of input impedance output impedance audio susceptibility.

And they are reasonable to capture small signal behavior by including delay effect, but they are not sufficient to capture fast scale instability particularly because this model simply ignores the ripple information and which can be very useful to predict various instability in digital control. Then we learn discrete time small signal modeling which is very accurate it can capture all sorts of instability, but these methods are mathematically complex because you have a lot of matrix exponential and all and these are less intuitive in terms of pole-zero.

So, the effective way to design a small signal-based control one can start with a small signal-based continuous times small signal model by incorporating the delay the lump delay. And this we have discussed in week 5, but we need to finally, verify our phase margin as well as the stability by using our discrete-time small signal model. So, we need to use this combination of these two.

The starting point will be continuous times small signal models which are intuitive and which map into various kinds of impedance shaping and other technique. Then we also discussed the alternative small signal design method which earlier we considered stable pole-zero cancellation, but we found this technique is very non-robust because we cannot exactly cancel pole and zero also these techniques are not very effective for shaping output impedance.

Because we are mainly targeting the loop shaping approach, but in closed-loop output impedance we also have an open loop output impedance in the overall transfer function. As a result, this method is not you know kind of robust when the load current varies. Then we discussed an alternative small signal design method I think in week 5, and we found this method of PID controller digital PID controller is very useful can it can achieve the load-insensitive design.

As we discussed in week 10, I think in week 11 we have considered this you know I think in lecture number 103 to 105 we used this method to simulate as well as we have experimentally you know applied this technique for the digital control implementation.

Then we have also discussed large signal tuning because of how can we apply you know the large signal approach to achieve near-time optimal recovery under practical constraints. How can you scale those gains? And what will be the effect? That we have discussed this in detail I think in a lecture in week 5 I think it is I think lecture numbers 47, 48, and 49 we discussed 49 particularly dedicated to the large signal tuning under practical constraints, and these are very useful for a fast transient response.

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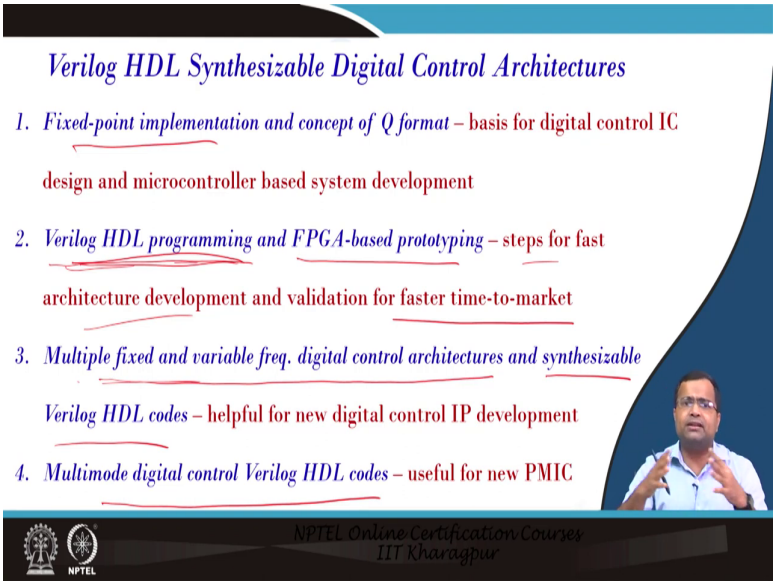

Then we discussed a lot of f Verilog synthesizable digital control architecture and we discussed the fixed point implementation and the concept of Q format. This concept is the basis for digital control for coefficient scaling you know and to get you to know to develop any topper type of digital control PID controller PI control in this architecture.

And this will be very useful for digital control IC as well as microcontroller-based development. Then because most of the low-power commercial products use fixed implementation, if you go for floating point processors they are quite expensive and power I mean power hungry.

So, depending upon the application requirement if you are talking about just a battery charger you know onboard charger or you can power management IC most of them go by a fixed point. Then we discussed a lot of Verilog HDL programming and we all understood what is the step for FPGA prototyping. This is one of the very crucial steps because this question often comes why should we go for FPGA rather than a microcontroller?

The answer is we are not primarily we are not going to use FPGA in our product, but we FPGA is using for prototyping, but whatever we have developed in Verilog HDL program synthesizable code can be easily imported to come up with an ASIC power management IC solution. So, that was the whole purpose of this course; that means, it will enable the designer to develop synthesizable HDL code which can be imported to any digital know design flow tools like a synopsis or cadence tool.

And one can come up with IC development, particularly for digital control of the ship. Then if before going to the IC design first step we want to verify whether your control logic timing diagram everything is working fine we can very quickly prototype. And this can save you know the time to market so, you can have a very faster time to market can develop technology more rapidly.

So, that was the purpose, but FPGA may not be used in the final product can be either microcontroller for high power or for low power high-frequency applications for IC implementation people directly go for ASIC, but this HDL which we have discussed in detail that can be very useful. Then if we go for multiple fixed and we have discussed multiple fixed and variable frequency digital control architecture we have developed multi-mode control we have developed variable frequency digital control fixed frequency digital control and all this control they can spectral spread spectrum technique and we have developed synthesizable Verilog code this can be very useful for new digital control IP as well as IC development.

And finally, the multi-mode digital control using Verilog code can be a very powerful solution for future IC development PMIC which can offer fast transient or high efficiency for a wide operating range.

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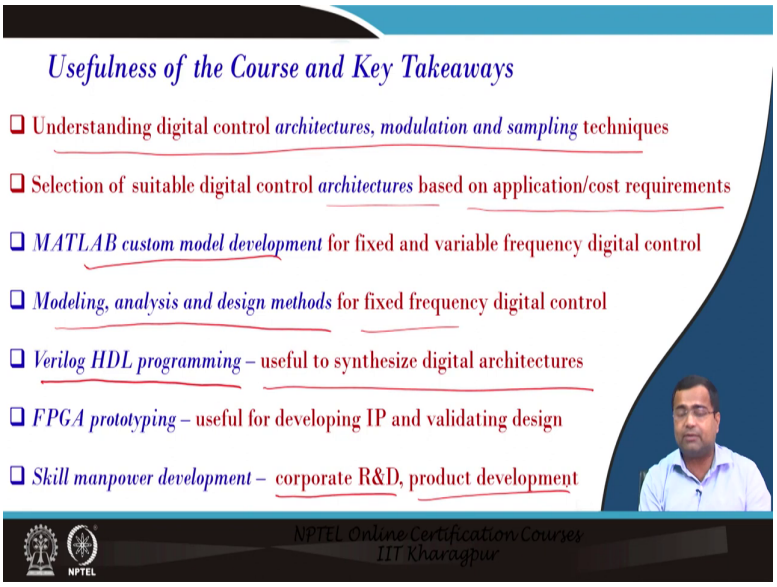

Now, the usefulness and the key (Refer Time: 11:55) key takeaway of this course. So, this course will help you to understand the digital control architecture modulation and sampling technique. So, this will be a key enabler because most of the industry is the semiconductor industry as well as the power supply industry even with the high power supply they are slowly shifting towards digital control.

So, this course can enable us to understand what is the basic digital control architecture some sort of advanced architecture some aspects of multi-mode this will help to identify and understand what the competitors are doing. You know to understand what can be done to get better? And what is the practical limitation? Then this understanding will help to come up with new architecture based on application requirements.

Suppose, if your power requirement is high for example, you are talking about an onboard charger or off-board charger the charger's power rating is more than a few kilowatts and you can afford to have a microcontroller that can consume a few watts of power. But imagine that if your power level is a few 100 watts or maybe a few tens of watts then you may not be able to use a dedicated microcontroller.

So, you may have to use a power management IC where the controller can be a separate IC we have discussed you know in the server application where the digital controller IC is used to centralize control of all the phases. Similarly, if there are multiple POL for automotive applications you can have a core digital processor which takes the algorithm and can have

central I think the algorithm can communicate with multiple converters so, all these features are very helpful.

We have learned a lot of MATLAB custom model development which will give us confidence before going to any hardware implementation Verilog coding is very important to come up with a new idea. Once the new idea comes suppose we have an idea about fixed frequency control with either uniform sampling or even base sampling or we want to sample at some instant point based on customer or our choice.

So, our custom model development flow which we discussed in week 3 is will enable you to build confidence and develop whatever concept you come it should be implementable in MATLAB by using custom difference equations that we have discussed. So, it will give you confidence the modeling analysis and design tool will be very useful to understand the stability aspect. What is the cause of instability? How can you make it stable? For fixed frequency as well as variable frequency digital control.

Though we have not covered the stability aspect of variable frequency these are more advanced topics. So, one can go through our publication and we have multiple research works based on the stability analytical tool for variable frequency digital control also. We have developed a lot of discussing a lot of Verilog HDL programming and I think we have many lectures on Verilog including week 7 is a complete introduction to Verilog HDL.

And based on that Q formatting we have developed a lot of control architecture this should be synthesizable to come up with a digital controller it will give you the confidence of the designer to understand better understand Verilog, but one can go for Verilog HDL also. But HDL programming understanding circuit understanding and what we saw solve in all cases we have not started Verilog from the very basic from the very beginning.

We first drew the equivalent digital circuit we tried to go deep into the circuit identified. What is the actual digital circuit inside? Once you know the digital circuit whether it is a sequential circuit or combinational circuit then you can write Verilog code without you knowing very rarely to have any errors.

So; that means, the best way to write Verilog code is first to draw the circuit understand the concept draws the circuit then try to write the Verilog using structural or data flow modeling

and as much as possible to avoid behavioral modeling or instead of writing full algorithm level we should implement the circuit level thing in Verilog.

Then we learn about the step for FPGA and prototyping I think this will be very powerful those who are not familiar with FPGA can quickly learn it they can use FPGA for prototyping, but the actual controller can be a microcontroller-based product or it can be ASIC development. So, this course will give a glimpse of you know what are the steps for FPGA prototyping.

Though we have used a very cost-effective Xilinx FPGA one can go for Altera FPGA another variant of FPGA or the very powerful FPGA, but the basic concept of tool development and the flow of prototyping those will be useful. And finally, this course will be helpful for skilled manpower development particularly to come up with the indigenous technology to thought process something sometimes we have an idea, but we may not have the right tool to validate it.

We can start with a simple MATLAB then one can go to simply and they can come to the Verilog HDL-based FPGA prototyping. So, this can skill manpower development will try to create an ecosystem for corporate research and development as well as the product development initiative that will be very helpful.

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Now, coming after so, many courses I mean this course would not have been possible without the help of the active cooperation of the team.

So, I want to introduce the NPTEL core team you know this is myself who was the course coordinator and you know and this is our teaching assistant, and this you know Dipayan Chatterjee, Anirban Nanda then Gopi Reddy, and Teja Golla these are my Ph.D. student; they are the TAs and they help like you know they have worked tremendously to come up assisting me to develop the content you know these are very helpful.

Then I want to appreciate our contribution from an industry partner. Particularly I want to you know thank mister Ranajay Mallik and Akshat Jain they have put a lot of effort in fact, to develop some content for STM 32 microcontroller-based digital control implementation for the LLC converter case study. And they have developed that hardware prototype and tested the design aspect I think that will be very useful for those who are working for EVs you can go through that LLC converter design aspect as good implementation.

I also want to thank our you know industry partners from Texas instrument that Aravindhan and Aditya who help you know develop you know the firmware and software introduction of the C2000 series microcontroller they also touch upon one case study of you know power converter which is like a bidirectional totem-pole PFC.

And I would like to thank Nitin Nigam from Keysight technology who came down to our campus to you know develop a few videos on how to use mixed signal oscilloscope what is its functionality. So, I want to thank all the industry contributors and our teaching assistants.

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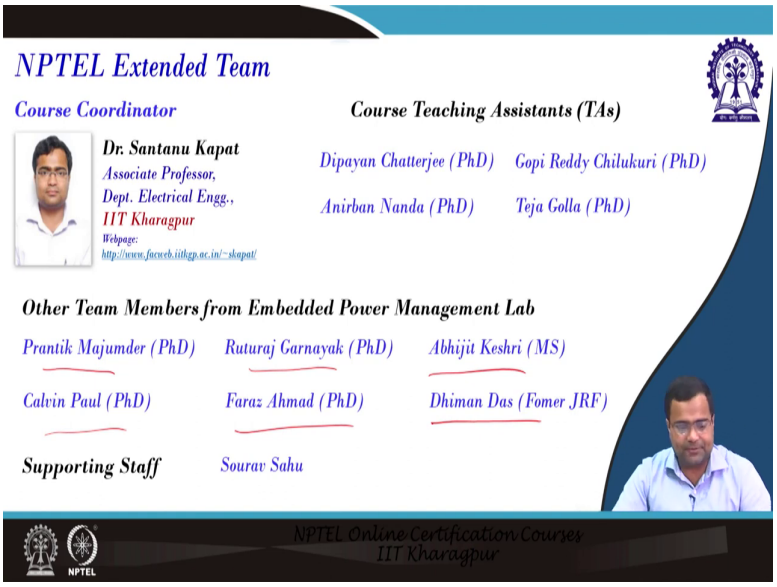

Now, as an extended team member beyond our TA, first of all, we have a teaching assistant who has helped we have other students who have immensely helped like Prantik Majumder, and Ruturaj they have helped a lot to develop this hardware prototype tested you know they are my senior Ph.D. student Abhijit Keshri who was an MS student very helpful in assisting me to develop that Verilog part of this course.

Then Calvin Paul and Faraz Ahmad are my Ph.D. student you know they are you know help whatever we need help they came forward then Dhiman Das who spent a short time with us and help also to come up with the power stage PCB aspect design and fabrication. Then Sourav Sahu helped you know to process all this video and you know on time and making this you know very video very high-quality content.

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Then I just want to briefly introduce IIT Kharagpur as you know IIT Kharagpur was the first IIT in the all-IIT chain and it was established in 1951. And I feel very proud and happy to be part of this institute and my M. Tech, Ph.D. also of this from this institute. And this is the department of electrical engineering where I was a student and also I am also a faculty member this department started in the same year of IIT Kharagpur inception.

And so, in this department, we have active faculty colleagues who are working on you know very active in research as well as industry collaboration.

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This is our embedded power management lab this lab we have it was developed and inaugurated in 2014 and we have almost come across 8 years span. And this past you know we have industry collaborations like STMicroelectronics, Qualcomm NXP, GE global research, and Texas instrument HCL technology.

We have collaborated either in the past or present we are collaborating with some of them in the various you know form in terms of research collaboration consultancy training programs.

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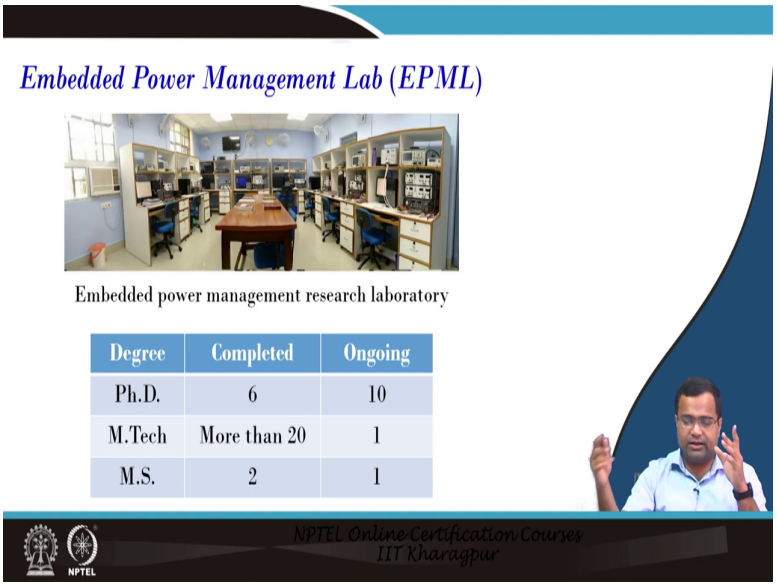

And in the embedded power management lab actually, we have like 6 Ph.D. students who have completed this embedded power management lab. 10 Ph.D. students are ongoing they will be so, slowly they will be finishing their some of them will be finishing their Ph.D. soon.

And we have more than 20 MTech students who graduated from this lab and 1 student is now going on 2 M.S. students have graduated one M.S. student is continuing

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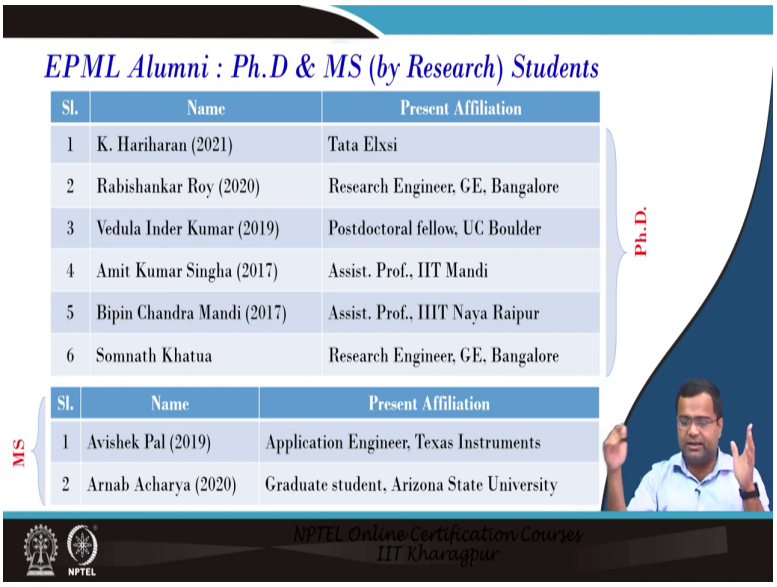

Since some of the alumni that graduated from this lab like Hariharan, Ravishankar, Inder, Amit, and Bipin have finished their Ph.D. and they are you know doing good, and Somnath he is about to finish their Ph.D. soon, Ph. D.t he is now in the industry.

So, Avishek Pal and Arnab Acharya are the 2 MS students and they already know Avishek is with Texas Instruments and Arnab is doing Ph.D. at Arizona State.

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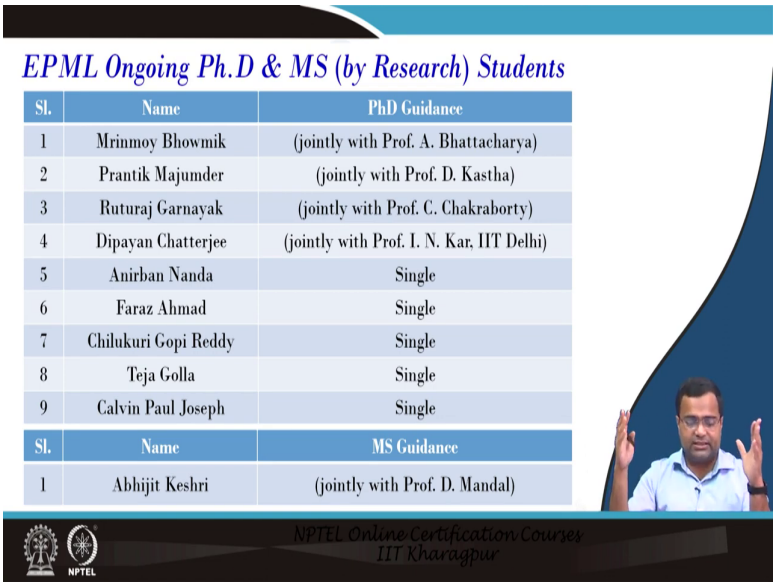

So, right now we have 10 Ph.D. students including Somnath who has joined the lab and will be slowly finishing they are quite active and very energetic I would say we have a fantastic team here, and Abhijit Keshri is also an MS student.

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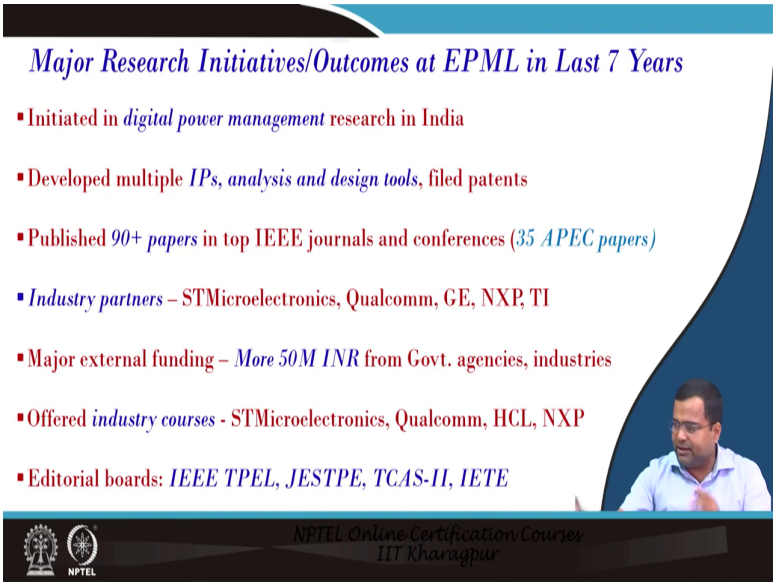

So, the major research initiative in our EPM lab I think more than the last 7 years we have initiated digital power management research. And develop multiple intellectual properties we have developed various tools for analysis and design and filed multiple patents we have published more than 90 papers in IEEE journals and conferences and out of their 35 APEC paper. The industry partners we have are STMicroelectronics, Qualcomm, and GE global research NXP Texas instrument.

The major external funding we have more than 5 crores of Indian rupees fund from government agencies and industries we have offered multiple courses for industries like STMicroelectronics, Qualcomm, HCL, and NXP and we have been serving actively in various IEEE journals on the editorial board.

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In the pedagogy and the industrial training program, we have offered courses on modeling control of switch mode power converter training for STMicroelectronics Qualcomm and HCL as well as NXP.

Then develop NPTEL online certificate course for control and tuning methods in switched mode power converter. This course is the basis of that current course because this course is developed last year and is also running this year this course we develop the fundamental concept of constant on-time ripple-based control and various modeling techniques.

And we have referred to various lectures of this course in this particular course and the available YouTube. And we are developing in fact, we have completed this digital control this course which will be also running for this time now.

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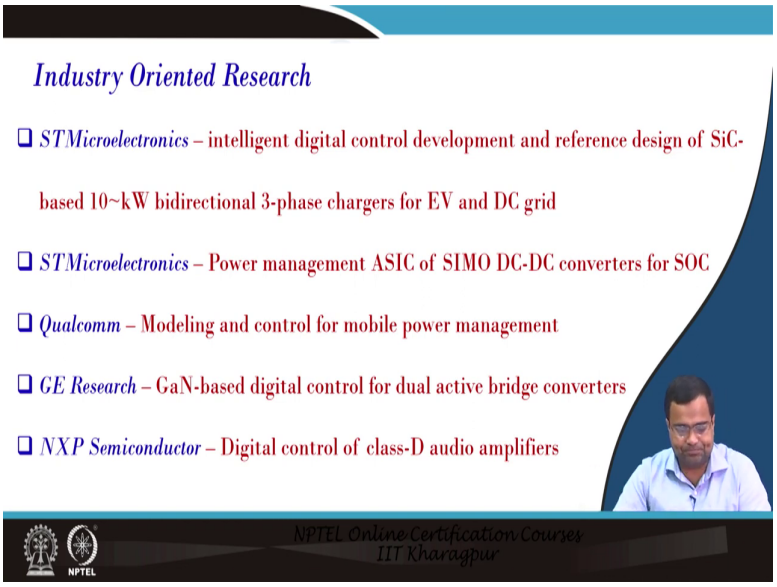

So, we are also carrying out industry-oriented research; that means, with STMicroelectronics we are working on intelligent digital control development as well as reference design sic based high power bidirectional converter for EV chargers and DC grid.

We are working on STMicroelectronics also in the ASIC power management IC for single input multiple output converter then we are also working with Qualcomm in the modeling and control for mobile power management application. We have worked with GE global research for GaN-based digital control for dual active bridge converter and NXP we have worked on class D audio amplifier.

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The ongoing research we are working on data center and cloud computing for highhigh-performancergy efficient digital control the QaN QaN-baseder supply for charger ADAS, multmulti-phasebrid converter portable and mobile applapplications fast recovery high-efficiency power supply automotive we are working on GaN and SiC based EV charger auxiliary power supply and ADAS.

Then we are also working on solar microinverters and for GaN and SiC-based solution hybrid converters and digital control. Then we have many unique tools in terms of analysis and design which has different level of complexity and accuracy and this can capture all type of control their stability analysis both large signal and small signal tool.

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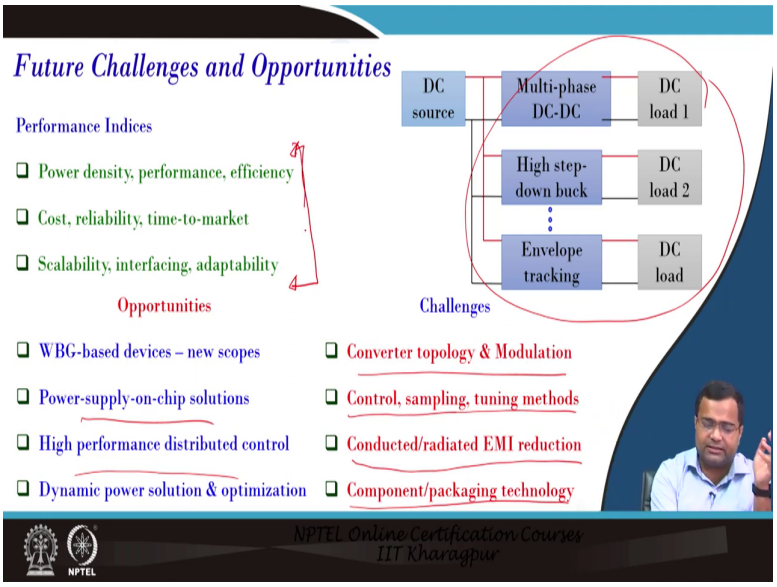

The future research challenges you know if you talk about the DC I you know data center application mobile phone even the automotive has multiple DC-DC converter multi-phase single stage envelope tracking for ADAS in automotive as well as for data center application also there can be 5G communication.

So, here the multiple converter communication performance indices will be power density then efficiency performance cost reliability time to market scalability interface and adaptability. So, this will have enormous implications for future digital control development and the opportunity will be wide band gap-based devices and power supply on chip because we want to achieve a high power density solution.

Then we want to achieve high-performance distributed control for such interconnected DC-DC converter networks and we need to also achieve very high performance and dynamic power solutions with optimization. But the challenges will be the converted topology selection modulation technique in the context of digital control. What is the right control technique? What are the sampling and the tuning method?

Then how to reduce conducted EMI aspect and the packaging technology will be helpful. So, some of these parts we touch upon in this course to show what are the challenges some idea about let us say frequency modulation for EMI reduction and tuning control sampling. But this is just the beginning more development will happen shortly and the industry will also

slowly shift to digital control for adaptability and all these performance indices become crucial.

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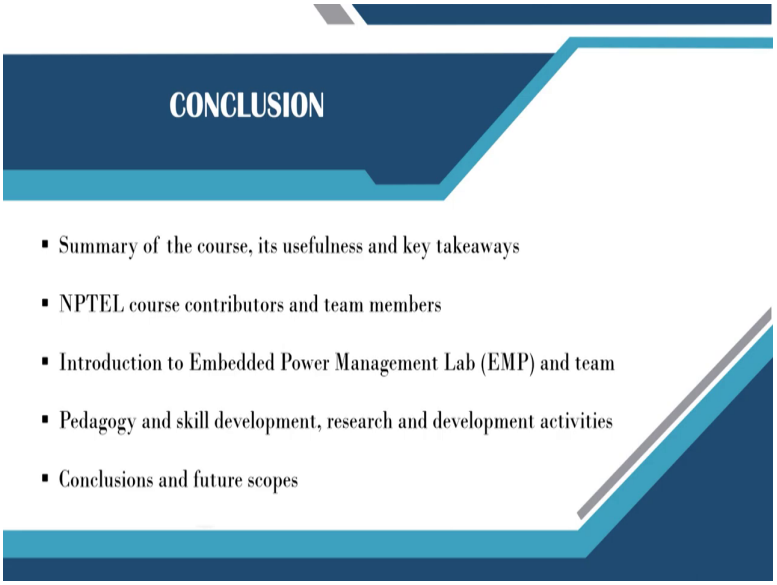

So, in summary, we have discussed the summary of this course its usefulness, and the key takeaway NPTEL course we have a team member we have introduced we have introduced our embedded power management lab introduced IIT Kharagpur our department of electrical engineering. Then we discussed what are the pedagogy and the skill development program we did and what are the research and development activities we are doing.

And finally, we have shown some future scope and the conclusion. And in summary, I want to say I hope this course took an enormous time because this course probably will be unique in terms of it has theory then it has MATLAB programming then it has Verilog HDL programming FPGA implementation then the step for HDL synthesis then hardware implementation experimental result.

Then we have also our invited speaker from the industry they have presented the STM 32 hardware firmware aspect from Texas instrument they have presented the hardware software aspect of the C2000 microcontroller. So, in some sense, this course gives a glimpse of most of the popular digital control platforms for both prototyping as well as commercial solutions, but this is still kind of a just-initiated digital control thing and in the future, we will find more, and more digital control development.

And I hope in this context this course will be useful for you know IP development product development and it will give up you know I think the boost in the confidence level and adapt with the digital control solution for indigenous technology development.

So, this course I hope will be useful for both industry practitioners then graduate Ph.D. students MTech students, and the students of you know other academic institute as well as you know I would say different professionals you know different professions the technical persons. That is it I think thank you very much and I hope you know this course will be useful for all of you.

Thank you.