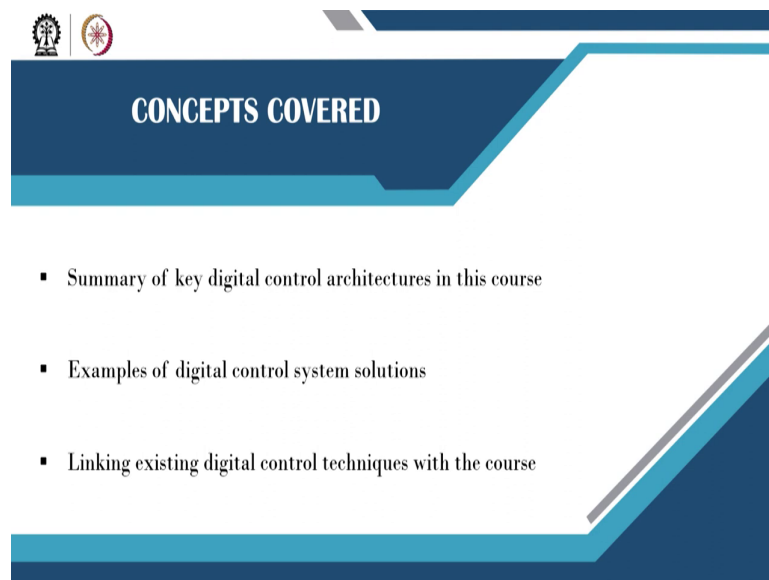


Digital Control in Switched Mode Power Converters and FPGA-based Prototyping
Dr. Santanu Kapat
Department of Electrical Engineering
Indian Institute of Technology, Kharagpur

Module - 12
Hardware Case Studies of Advanced Digital Control Techniques and Course Summary
Lecture - 118
Industry-Driven Architecture for Digital Control System Solutions in SMPCs

Welcome. In this lecture, we are going to discuss some industry is driven (Refer Time: 00:31) digital control architecture and their system solution for high-power locations and we want to link our course concept with this kind of architecture.

(Refer Slide Time: 00:34)



The slide features a dark blue background with a light blue geometric shape on the left side. At the top left, there are two small circular logos. The title 'CONCEPTS COVERED' is centered in white. Below the title, there are three bullet points, each preceded by a small square icon. The slide is decorated with light blue and dark blue geometric shapes on the right and bottom edges.

CONCEPTS COVERED


- Summary of key digital control architectures in this course
- Examples of digital control system solutions
- Linking existing digital control techniques with the course

So, we will take will summary of digital control architecture in this course then an example of a digital control system solution and how can you link existing digital control techniques with this course ok.

(Refer Slide Time: 00:49)

Digital Voltage Mode Control for System Solution

Lectures-71 to 75




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(Refer Slide Time: 00:59)

Voltage based COT Digital Control for System Solutions

Lecture-96



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So, for the digital control system solution, we have discussed digital voltage mode control in lecture number 71 and 75. We have synthesized the Verilog HDL code, we have discussed digital-based voltage-based constant on-time digital control and we have discussed with Verilog HDL synthesis we did in lecture number 96.

(Refer Slide Time: 01:36)

Spread Spectrum Technique in DPWM Control

The slide shows a power converter circuit on the left and its digital control block diagram on the right. The circuit includes an input voltage v_{in} , a MOSFET Q_H with gate driver Q_L , an inductor L with resistance r_L , a capacitor C with resistance r_C , and a load resistor R with output voltage v_o . The control block diagram shows an A/D converter receiving v_{fb} and outputting adc_data . This data is processed by a 10-bit DPWM block, which also receives f_{adc} , Q_{tran} , and BF_op . The DPWM block outputs PWM_high , PWM_low , and Q_{load} , and is clocked by f_{clk} . The text "Lectures-111 & 112" is displayed below the block diagram.

Lectures-111 & 112

And we developed this core architecture using Verilog HDL, then we also discussed the spread spectrum technique in digital pulse skip modulation control we developed the Verilog HDL synthesize code and we have done we did FPGA implementation in lectures 111 and 112.

(Refer Slide Time: 01:56)

Multimode Digital PWM/PSM Control

The slide shows the same power converter circuit as the previous slide. The digital control block diagram is updated to include a "Multimode" block. This block receives adc_data from the A/D converter, f_{adc} , Q_{tran} , and f_{clk} . It also receives an $op_multimode$ control signal. The Multimode block outputs PWM_high , PWM_low , and Q_{load} . The text "Lectures-113 & 114" is displayed below the block diagram.

Lectures-113 & 114


Then we have also discussed multimode digital control PWM and PSM which is a voltage base, you can do also the current base. And we have synthesized this multimode digital control using Verilog HDL and prototype using FPGA in lectures 113 and 114.

(Refer Slide Time: 02:14)

Mixed-Signal Peak Current based Multimode PWM/PFM Control

The slide shows a circuit diagram of a boost converter on the left and a block diagram of its digital control system on the right. The circuit includes an input voltage v_u , a MOSFET S_1 , a diode S_2 , an inductor L , and a capacitor C . The control block diagram features an A/D converter (10-bit), a Multi-mode Digital CMC, and a D/A converter. The CMC receives feedback signals i_{comp} and v_c and outputs PWM signals. The system is also influenced by f_{clk} , Q_{mode} , Q_{setd} , and $Q_{multimode}$. The output is compared with a reference v_r to produce v_p .

Lectures-115 & 116



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And we have shown also experimental results. We have also discussed mixed signal peak current-based multi-mode PWM and PFM control and we have developed this architecture and synthesized using Verilog HDL we have presented FPGA prototyping with experimental results in lectures 115 and 116.


(Refer Slide Time: 02:30)

3 Channel Interleaved Boost PFC

- 3~kW 3 channel interleaved PFC
- Output Voltage: 400V
- Switching frequency:~111 kHz
- Hardware/software/firmware

STMicroelectronics STM32 microcontroller based digitally controlled interleaved PFC

Source: [STEVAL-IPFC01V1](#)



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So, with this understanding of the key architecture that we have discussed and we have also developed their Verilog HDL synthesize file and have a prototype with this concept it is reasonable to link with some of the commercial products. So, one example is the 3 level 3

channel interleaved boost PFC which is from ST microelectronics this is a 3 kilowatt I am not going to discuss this because one can get detail with this part number.

(Refer Slide Time: 02:59)

3 Channel Interleaved Boost PFC

- Mixed-signal average CMC
- Current loop Analog PI controller
- Voltage loop Digital PI Controller
- Input voltage, load feed-forward
- Burst Mode
- Phase Shedding

STMicroelectronics STM32 microcontroller based digitally controlled interleaved PFC

Source: [STEVAL-IPFC01V1](#)

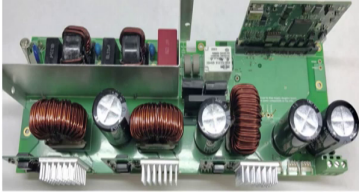
Hardware implementation of mixed-signal peak CMC in Lectures-75 to 78

Now, in this part it is mentioned that mixed signal average current mode control with current loop analog, voltage loop digital. In our course, we have discussed the mixed signal peak current mode control in lectures 75 to 78. I think this lecture can be a basic very helpful to understand what might be there because in most commercial products the detail of the control logic may not be available explicitly in the public domain.

But, with the knowledge of this course particularly the mixed signal current mode control architecture, one can think about what could be the solution here or come up with a new solution.

(Refer Slide Time: 03:36)


GaN based Bidirectional Totem Pole PFC using C2000 Microcontroller



- Interleaved bridgeless totem pole PFC
- 3.3~kW bidirectional PFC
- Hardware/software/firmware
- Fully digital current control
- High efficiency Low THD

TI C2000 microcontroller based digitally controlled PFC

Source: T1DM-02008

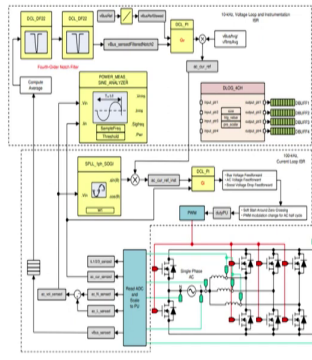


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Another aspect is a GaN-based totem pole you know PFC interleaved PFC which is like a using C2000 microcontroller. This architecture was considered with a small hardware demonstration in this course in week 9.

(Refer Slide Time: 03:58)

GaN based Bidirectional Totem Pole PFC using C2000 Microcontroller




- Fully digital multi-loop control solution
- Voltage Feedforward, Soft Start
- Notch Filter
- Software PLL

Hardware implementation of mixed-signal peak CMC in Lec.-75 to Lec.-78

MATLAB simulation of fully digital CMC in Lec.-27

Source: T1DM-02008



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And in this course, it is a 3.3-kilowatt converter and it is fully digital current control the other feature of this controller it uses a fully digital multi-loop control solution and it also has a feed-forward soft start. Now if we recall our digital current mode control architecture we

have discussed in lectures 75 to 78 mixed signal, how to implement digital current mode control using a mixed domain approach.

We have synthesized this architecture with Verilog HDL and we have also prototyped with FPGA. For fully digital we have carried out MATLAB simulation and developed the model in lecture number 27. So, this concept may be useful to link what is there inside or come up with an alternative solution.

(Refer Slide Time: 04:40)


3 Phase 30 kW SiC based Vienna PFC



- 30~kW Vienna Rectifier
- Switching Frequency:~140kHz
- Low THD
- High efficiency
- Dual core dsPIC33CH Microcontroller

*3 Phase 30 kW SiC based Vienna PFC Board
Microchip*

Source: [MSCSICPFC/REF5](#)



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If you go for 30 kilowatts 3 phase SiC based I know Vienna rectifier. This is coming from microchip technology.

(Refer Slide Time: 04:49)


3 Phase 30 kW SiC based Vienna PFC

- Fully digital control solution
- 3 level modulator
- Verified open source software
- PI-RES algorithm minimize harmonics

Control Function Block Diagram

Source: [MSCSICPFC/REF5](#)

Various digital control architectures discussed in Lectures-12 to 20



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As you all the digital control solution may not be readily available, but it says about digital control solution which means the digital control is very much used for this particular high power converter we have discussed in detail from lectures 12 to 20, the different digital control architecture some of this architecture may be useful to link with this what is there inside or maybe thinking alternative solution, because the digital architecture may not be publicly available.


(Refer Slide Time: 05:18)

Bridgeless Dual Boost PFC using XMC 1300 Microcontroller

- High Power Density
- Hardware/software/firmware
- CCM/ CRM/ DCM operation
- 3~kW PFC

Fully digital control implementation using the XMC 1300 microcontroller dual boost PFC Infineon

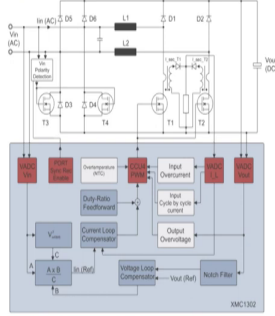
Source: [EVAL_3KW_DB_PFC_C7_2](#)



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(Refer Slide Time: 05:32)

Bridgeless Dual Boost PFC using XMC 1300 Microcontroller




- Fully Digital Control
- Duty ratio feedforward
- Digital Notch Filter
- PWM sampling correction

Week-8
Week-10 to
Week-12
Verilog HDL synthesis

Fully digital control implementation using the XMC 1300 microcontroller dual boost PFC Infineon
Source: EVAL 3KW DB PFC C7.2

Various digital control architectures discussed in Lectures-12 to 20



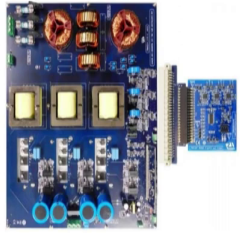
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Then we are talking about a bridgeless dual boost PFC and this is for Infineon technology, where you know it talks about high power density 3 kilowatt PFC, and it takes it to consider fully digital control and which has a duty ratio feed-forward notch filter and sampling, but all details of this control architecture may not be publicly available.

But, we have learned from lecture number 12 to 20 about all digital control architecture. In fact, from week I would say week 8 then week 10 to week 12 we discussed a lot of Verilog HDL synthesis of multiple digital control architectures including voltage mode current mode architecture, fixed frequency variable frequency architecture then multi-mode digital control architecture. Then we discussed spectral spreading. So, this architecture will be helpful either to understand this concept what might be or to find an alternative solution.

(Refer Slide Time: 06:28)


Mixed Signal Control of three-phase Vienna Rectifier



- 15~kW PFC
- Switching Frequency:~ 70kHz
- High efficiency
- Low THD

Mixed Signal Control using STNRG388A digital controller STMicroelectronics

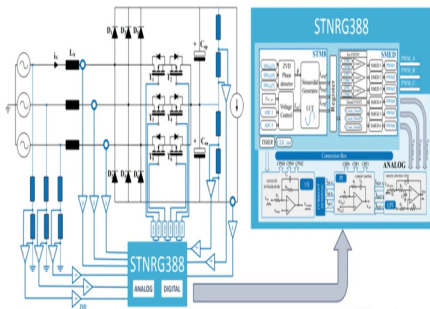
Source: [STDES-VIENNARECT](#)



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(Refer Slide Time: 06:37)

Mixed Signal Control of three-phase Vienna Rectifier




- Mixed Signal Control
- High BW- analog circuitry
- Event Driven State Machines

Week - 10 to Week - 12
Verilog HDL

Mixed Signal Control using STNRG388A digital controller STMicroelectronics

Source: [STDES-VIENNARECT](#)

Hardware implementation of mixed-signal peak CMC in Lectures-75 to 78



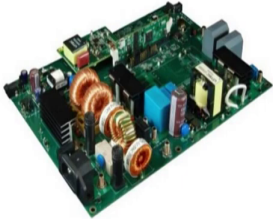
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So, this is another one from ST microelectronics the 3-phase Vienna rectifier where it is a mixed signal control, and the inside of all these control logics are not available, but it said that the event-driven state machine is using a mixed signal control.

So, if you go to the mixed signal current mode control in 75 to 78 as well as if you go to week 10 to I think week you know week 12 we have discussed a lot of Verilog HDL coding and synthesis of the digital control architecture for various digital voltage current mode control. So, this will be useful.

(Refer Slide Time: 07:17)

Digitally Controlled Solar Microinverter



- Active clamp flyback converter
- Grid tied DC/AC inverter
- Hardware/Software/Firmware
- Switching frequency:~ 100kHz
- Low THD

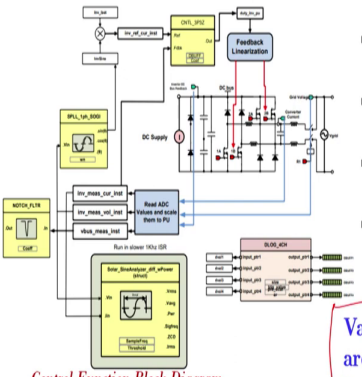
Digitally Controlled Solar Micro Inverter Design using C2000 Piccolo Microcontroller TI

Source: [TIDM-SOLARUINV](#)

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(Refer Slide Time: 07:24)

Digitally Controlled Solar Microinverter



- Fully digital control solution
- MPPT, PLL
- Digital Notch Filter
- Feedback Linearization

Control Function Block Diagram

Source: [TIDM-SOLARUINV](#)

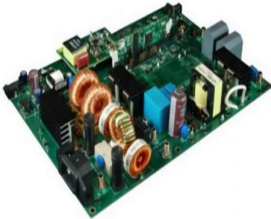
Various digital control architectures discussed in Lectures-12 to 20

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Now, digitally controlled solar microinverter, so this is from a Texas instrument that it uses for micro inverter and all these MPPT algorithms it is a fully digital control solution and you will get the idea of the basic digital control architecture voltage mode current mode architecture in lecture 11 to 20 and we have also discussed details in week 10 week 11 week 12 various architecture. Some of this architecture may be helpful to come up with an alternative solution for digital control solar micro-inverters.

(Refer Slide Time: 07:49)


Digitally Controlled Microinverter for plug in PV panels



- 250 W grid connected microinverter
- High frequency isolated DC-DC Converter
- Full Bridge DC-AC Inverter

Digitally Controlled microinverter for plug in PV panels using STM 32 microcontroller
STMicroelectronics

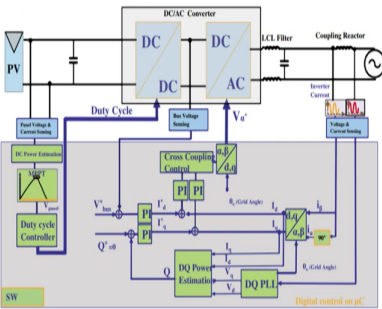
Source: [STEVAL-ISV003V1](#)



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(Refer Slide Time: 07:57)

Digitally Controlled Microinverter for plug in PV panels




- Fully digital control solution
- MPPT, PLL
- Burst Mode at Startup
- Voltage and Frequency detection, anti-islanding

Control Block Diagram *Week-8 Weeks-10 to 12*

Various digital control architectures discussed in Lectures-12 to 20

Source: [AN4070](#)




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So, then solar microinverter in plug-in PV is for micro ST microelectronics where it also uses you know fully digital control solution and burst mode control for light load efficiency improvement and we have discussed various digital control architecture in lectures 11 12 to 20 and we have also discussed in week 10 week 8 and week 10 to 12.

So, this will be useful for how understanding the implementation of digital control which may be helpful to come up with a digital control solution for the micro inverters.

(Refer Slide Time: 08:25)


Grid Connected Solar Microinverter



- 215W Solar Microinverter
- High frequency isolated DC-DC Converter
- dsPIC33 Digital Signal Controllers (DSCs)

Grid Connected Solar Microinverter controlled using dsPIC DSC Microcontroller Microchip

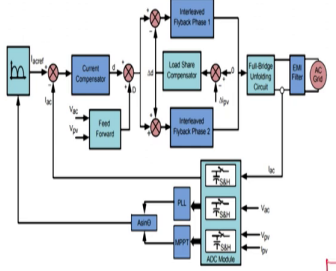
Source: AN1444



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(Refer Slide Time: 08:30)

Grid Connected Solar Microinverter




- Fully digital control solution
- Burst Mode for light load
- State Machines, MPPT, PLL
- System islanding, Fault Handling

Control Block Diagram

Source: AN1444

Various digital control architectures discussed in Lectures-12 to 20

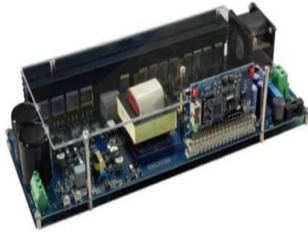


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Then solar grid micro inverter from microchip technology also uses digital control and we have discussed this digital control in weeks 12 to 20 and we have this whole lecture on digital control. So, I think if one can understand this lecture very well. I think they can come up with a new or maybe alternative digital control solution.

(Refer Slide Time: 08:46)


3 kW Full Bridge LLC resonant digital power supply evaluation kit



- Input Voltage: 375V to 425V
- Output Voltage: 48V
- Output Power: 3kW
- Resonant frequency: 175kHz
- 95.3% Peak efficiency

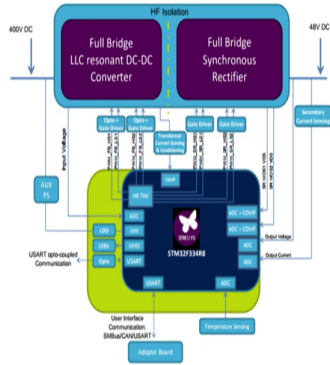
STMicroelectronics STM32 microcontroller based digitally controlled LLC

Source: [STEVAL-DPSLLCK1](#)




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(Refer Slide Time: 08:55)



- Digitally controlled - STM32F334 MCU
- Adaptive Synchronous rectification
- ZVS over entire operating range
- Light Load burst mode } Week -11 and Week-12
- 95.3% Peak efficiency

Various digital control architectures discussed in Lectures-12 to 20



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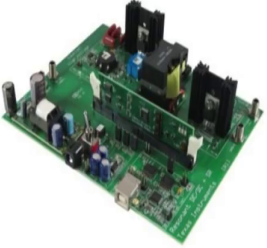
Then this is the 3 kilowatt LLC converter from ST microelectronics, then it uses you know fully digital control solution and adaptive synchronous rectification; that means, you can also do you know burst I mean the dead time optimization.

Then light load control improvement and we discussed lectures 12 to 20 the different architectures and this light load control we have taken week would say 11 and 12. So, which considers extensively light load control technique digital control, how to synthesize? How to implement synthesizing Verilog HDL? How to implement using FPGA? So, this technique

will be useful. I am not exactly in burst mode, but we have talked about constant on time. Pulse skipping modulation then you know eruptive on time control technique and also multimode technique.

(Refer Slide Time: 09:44)


300W Resonant LLC Half-Bridge DC/DC Converter



- Input Voltage: 375V to 405V
- Output Voltage: 12V
- Output Power: 300W
- Resonant frequency: ~130kHz
- >90% efficiency

TI C2000 microcontroller based digitally controlled LLC

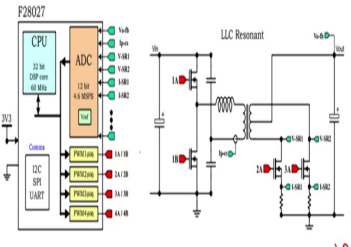
Source: [TIDM-RESLLC-DCDC](#)



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(Refer Slide Time: 09:48)

300W Resonant LLC Half-Bridge DC/DC Converter



- Fully digital multi-loop control solution
- Synchronous rectification support
- ZVS across entire load range
- >90% efficiency across wide load range


TMDSHVRESLLCKIT Circuit Diagram 10, 12

Week 10, 12

Various digital CMC architectures discussed in Lectures-14, 15, 17 to 20

Lec ~ 75, 76, 77, 78

Source: [TIDM-RESLLC-DCDC](#)




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Then this is another resonant converter from Texas instrument which also uses you know fully digital multi-loop control we have discussed digital current mode control in lectures 14, 15, 17, and 20 and then we have also discussed in lectures 75 to 78 you know 75, 76, 77, 78 all the digital current mode control architectures are discussed.

So, one can get details about this about current mode control because it may be linked with multi-mode or it can be other architecture which is proprietary may not be available, but if we go to our week you know 10 to 12 weeks you will get to know a lot of digital control architecture that may be useful.

(Refer Slide Time: 10:30)

340W Digitally Controlled LLC Resonant Half-Bridge Converter




- Fully digital control using 3138ACC32EVM-149 daughter-card
- Preloaded firmware
- Cycle by cycle current limiting
- Synchronous rectification

TI 3138ACC32EVM-149 daughter-card based digitally controlled LLC

Source: [TIDA-00512](#)

Various digital control architectures discussed in [Lectures-12 to 20](#)

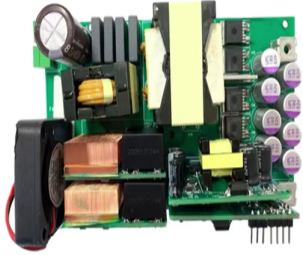


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Then digitally control resonant half-bridge converter this is from you know Texas instrument which also uses the fully digital control solution. And we have discussed various architectures of digital control from lectures 12 to 20. So, some of this architecture including extensive implementation from week 8 as well as weeks 10 to 12 will be helpful.

(Refer Slide Time: 10:53)


GaN System's 3kW DC/DC LLC resonant Converter



- Input Voltage: 350V to 420V
- Output Voltage: 54V
- Output Power: 3kW
- Resonant frequency: ~250kHz
- >98% efficiency

GaN System's digitally controlled LLC

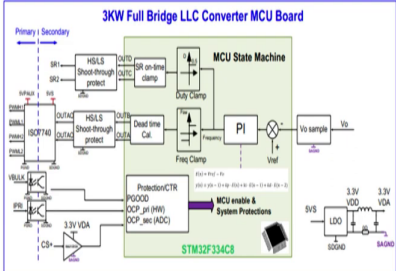
Source: [GS-EVB-LLC-3KW-GS](#)



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(Refer Slide Time: 10:58)

GaN System's 3kW DC/DC LLC resonant Converter




- Mixed signal control
- Opto-coupler isolation
- Input Voltage Brownout protection

GaN System's digitally controlled LLC

Source: [GS-EVB-LLC-3KW-GS](#)

Various digital control architectures discussed in Lectures-12 to 20

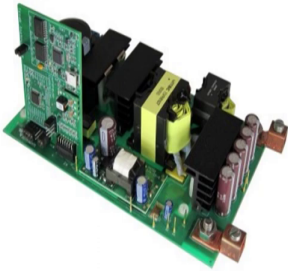


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Then GaN-based 3-kilowatt converter you know GaN system this also uses the digital control mixed-signal control and we have discussed lecture 12 to lecture 20 as well as weeks 8 week 10 week 11 week 12. All digital control techniques are implementations are discussed.

(Refer Slide Time: 11:14)


600W Phase-Shifted Full Bridge DC/DC Power Converter



- Input Voltage: 400V
- Output Voltage: 12V
- Output Power: 600W
- >95% efficiency

TI C2000 microcontroller based digitally controlled LLC

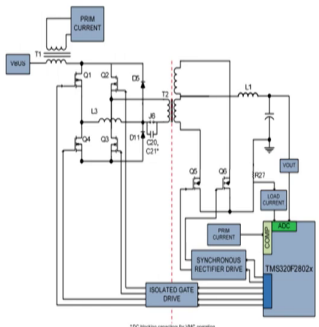
Source: [TIDM-PSFB-DCDC](#)



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(Refer Slide Time: 11:17)

600W Phase-Shifted Full Bridge DC/DC Power Converter




- Fully digital multi-loop control solution
- Synchronous rectification support
- Peak Current mode control
- Adaptive ZVS
- Slope Compensation

Week - 8, Week - 10 to Week - 12

Various digital CMC architectures discussed in [Lectures-15, 17 to 20](#)

PSFB System Block Diagram

Source: [TIDM-PSFB-DCDC](#)

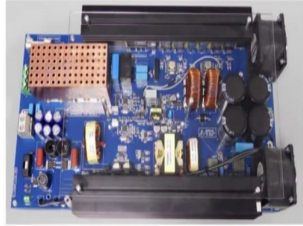


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Then this is a phase-shifted full bridge converter from Texas instrument which also uses fully digital control multi-loop and again we have discussed multi-loop digital control both fixed frequency variable frequency as well as keep peak current mode control. We implemented this thing in week 8 then from week 10 to week 12 different architecture.

(Refer Slide Time: 11:40)

2kW Fully Digital AC-DC Power Supply



- Input Voltage: 90V to 264V
- Output Voltage: 48V or 52V
- PFC Switching frequency: ~60kHz
- DC-DC switching frequency: 100kHz
- Output Power: 2kW

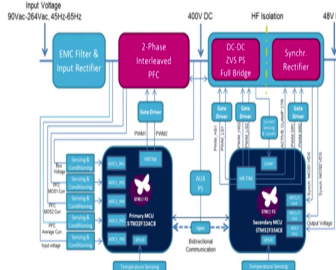
STMicroelectronics STM32 microcontroller based digitally controlled AC-DC Power supply

Source: [STEVAL-ISA172V2](#)

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(Refer Slide Time: 11:45)

2kW Fully Digital AC-DC Power Supply



- Fully digital multi-loop control solution
- PFC with Average Current mode control
- synchronous rectification
- Cycle by cycle PFC current control

Block diagram of the STEVAL-ISA172V2 system architecture

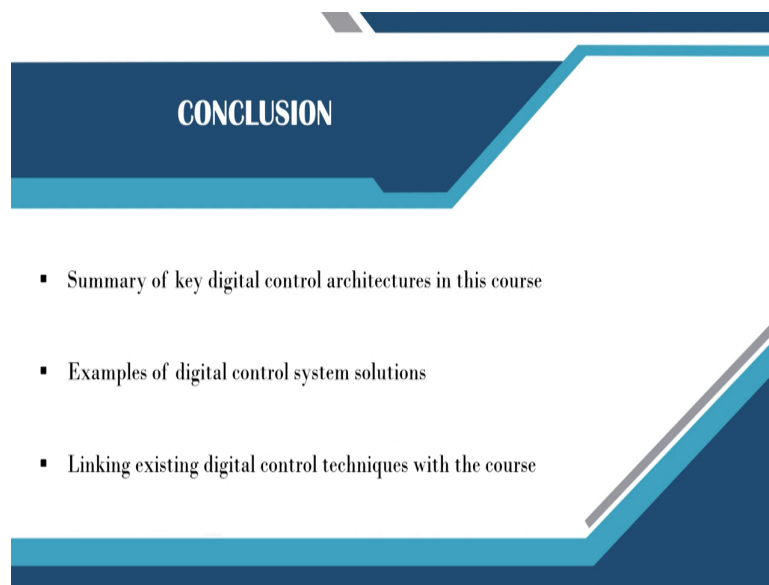
Source: [STEVAL-ISA172V2](#)

Various digital CMC architectures discussed in Lectures-15, 17 to 20

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So, this may be more helpful than another fully digital AC DC power supply from ST also use a digital control solution and various digital control architectures we have discussed, and in week 8 week 10 week 11 week 12 we have synthesized various control architectures that may be useful for PFC converter.

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CONCLUSION

- Summary of key digital control architectures in this course
- Examples of digital control system solutions
- Linking existing digital control techniques with the course

So, what we wanted to say is we have shown all the digital control system solutions to show there is an increasing trend of digital control for high power converters for power factor corrector converters, LLC converters, electric vehicle EV chargers then EV power trains then solar micro-inverter DC grid so then LED driver.

So, this increase in (Refer Time: 12:24) I would say our summary of digital control architecture in this course would be very helpful to understand that architecture as well as come up with a new architecture for future this commercial product. So, we have taken many examples of digital control system solutions and we try to link the knowledge that we gain in this course with this existing system that is it for today.

Thank you very much.