An approach to practical digital power conversion

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Topics

- Why digital
- Moving from analog to digital
- LLC converter realization
  - Power plant, modulator, feedback management, protections
- Typical gain curve for wide output voltage range LLC converters
- 2.5 kW LEV battery charger details
- 6 kW DC DC converter

Why digital power (1)

- Digital power applications use digitally controlled solutions:
  - To increase power density
  - To accelerate control loops
  - To allow complex topology management, otherwise impossible with analog control
  - To significantly improve design flexibility
  - **Prototyping changes can be faster : instead of changing the hardware design, we change the code to try out a better or evolved control scheme**

Why digital power (2)

- Facilitates compliance with the most stringent energy efficiency requirements
  - By using clever algorithms, light load and switching pattens may be handled in a way to reduce losses
- Greater power density with higher switching frequency and faster control loops
  - With advanced wide band gap devices higher switching frequencies mean faster decisions to be made in nanoseconds
- System level reliability, and safety with failure prediction in power distribution
  - Model predictive control, AI and ML lends itself well to manage futuristic power conversion systems

Where do we find them?

- Mostly applied to switched-mode power supplies (SMPS)
- Digital power focuses mainly on solutions for:
  - Server and datacenters PSUs
  - Telecom power
  - EV charging stations
  - UPS, energy generation & storage systems
  - Recently adopted in sophisticated chargers and adapters for smartphones and laptops in high-end TV and lighting applications.
- Found earlier in high-performance, high-end systems but with new efficiency norms found in almost all power supply types

Moving from analog to digital design

- Pure analog
  - Use dedicated single or dual function controllers

- Hybrid: mixed analog + digital control
  - Dedicated analog controllers with one inner control loop (analog)
  - One digital controller (MCU) for outer loop

- Full-digital
  - Completely digital
  - Sensing, computing and decision making (acting)

LLC converter realization
Major philosophy

LLC converter is well known for its high efficiency, low EMI content and simple modulation scheme: PFM instead of PWM

Design however has these dimensions which must all be addressed together

- **Power plant design**
  - Topology, magnetics and the tank, switches and rectifiers
- **Modulator design**
  - VCO, phase shifter, dead-time generation and interlocking functions
- **Feedback management**
  - Voltage feedback? current feedback? error amplifier and its order stability: how fast, is it fast enough?
- **Protections**
  - Startup management, operating zones and anti capacitive region management, functional protections inherent to topology

This is 100% analog block!!

Rest can be partially or fully digital

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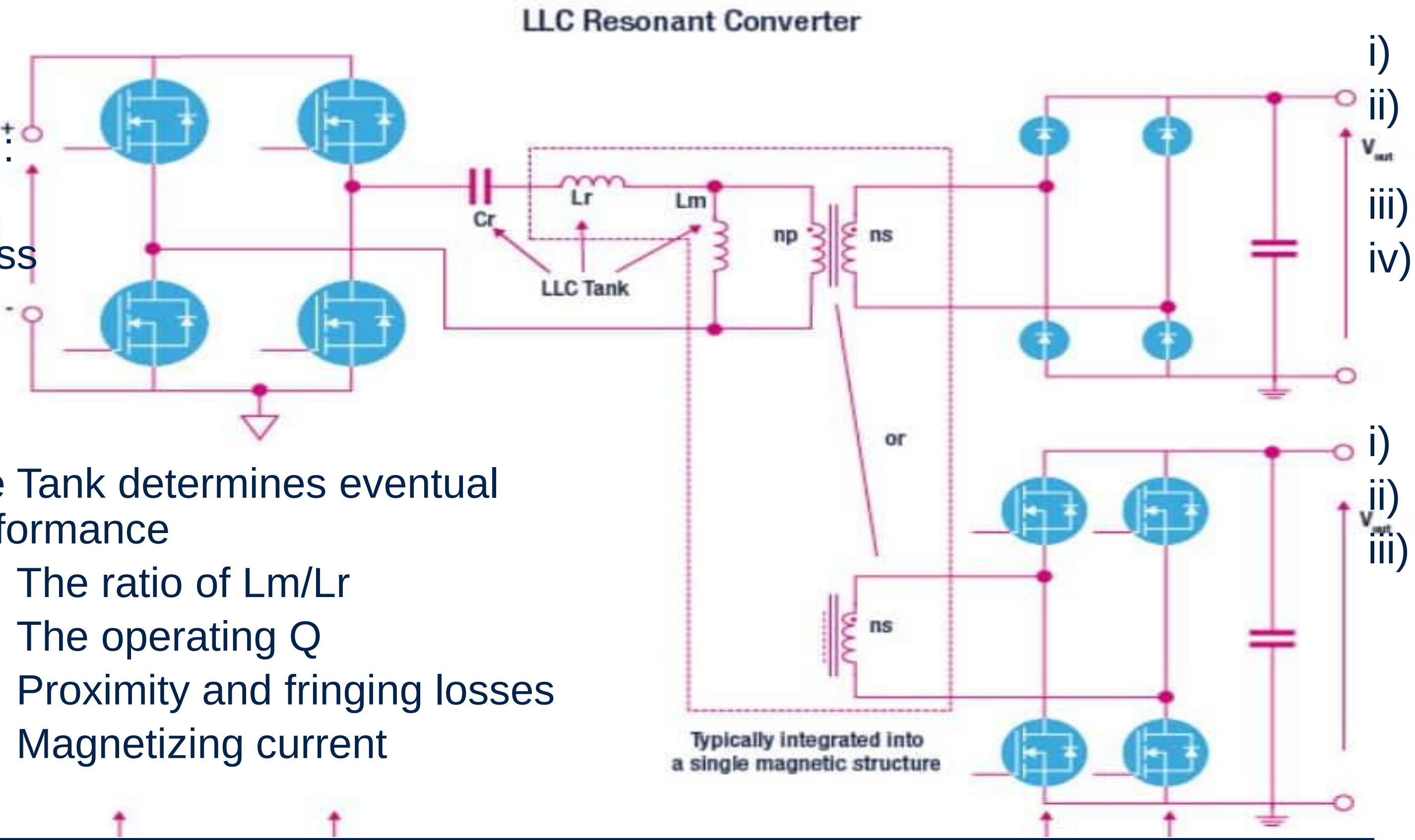
Power plant - full bridge LLC converter

MOSFET key FoM:

i) Low R_{dsON}
ii) Controlled Coss



i) Low voltage moderate current
ii) High voltage moderate to high current
iii) Key FoM: low Vf, Zero recovery
iv) Center tap less lossy

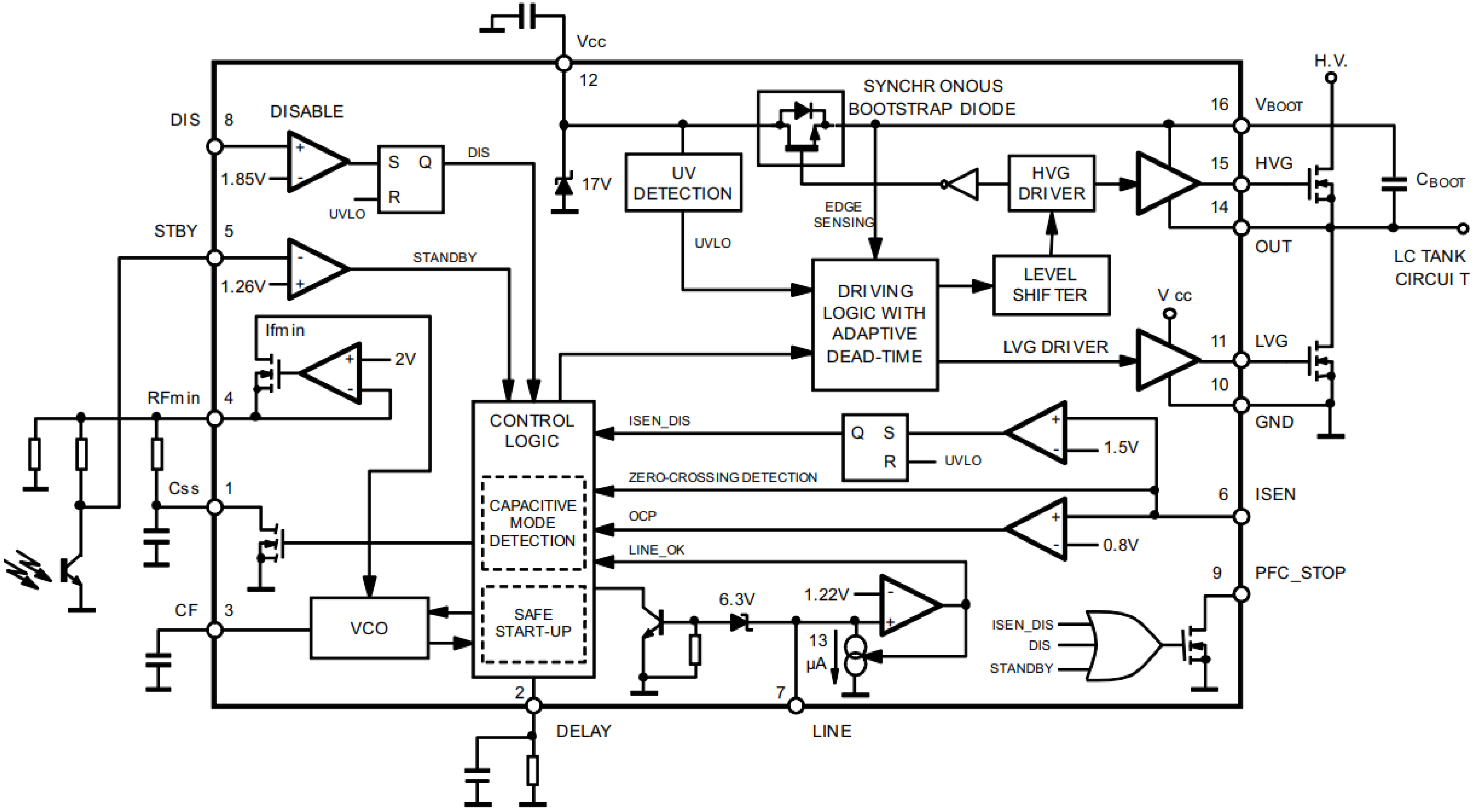
i) Low voltage high current
ii) High voltage rarely used
iii) Key FoM: Low R_{dsON}, Qg

The Tank determines eventual performance

i) The ratio of Lm/Lr
ii) The operating Q
iii) Proximity and fringing losses
iv) Magnetizing current

MODULATOR/CONTROLLER

Analog modulator - L6699 controller



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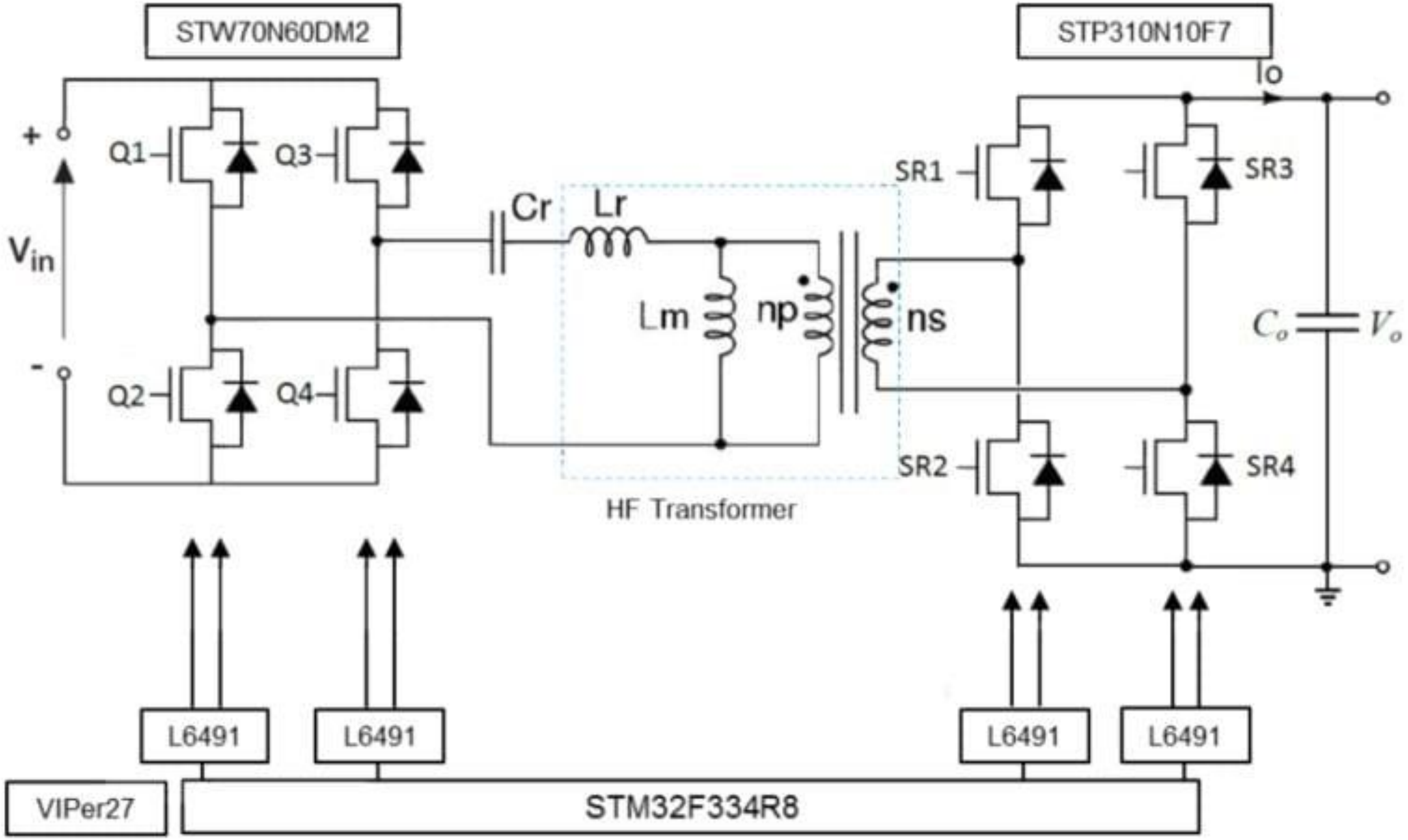
Digital modulator - implementation scheme



Protections

- Start-up sequence and preventing anti capacitive region operation
- Runtime over current/overload/short circuit
- Feedback loop open
- System level protections: over temperature/over voltage/load disconnections etc.
- Addressable in both discrete analog and interrupt/event driven digital formats

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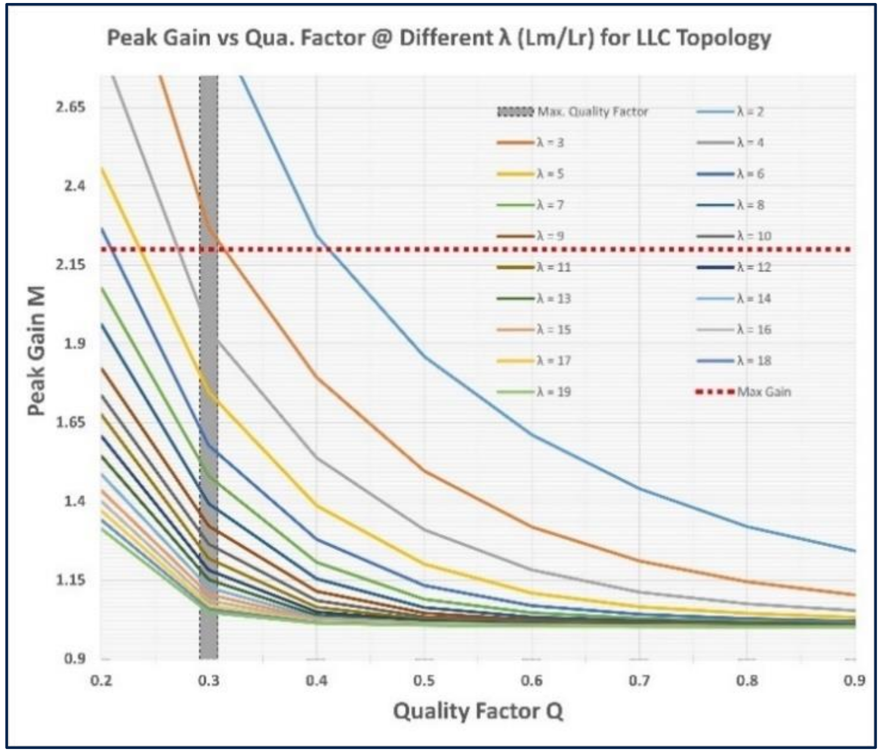
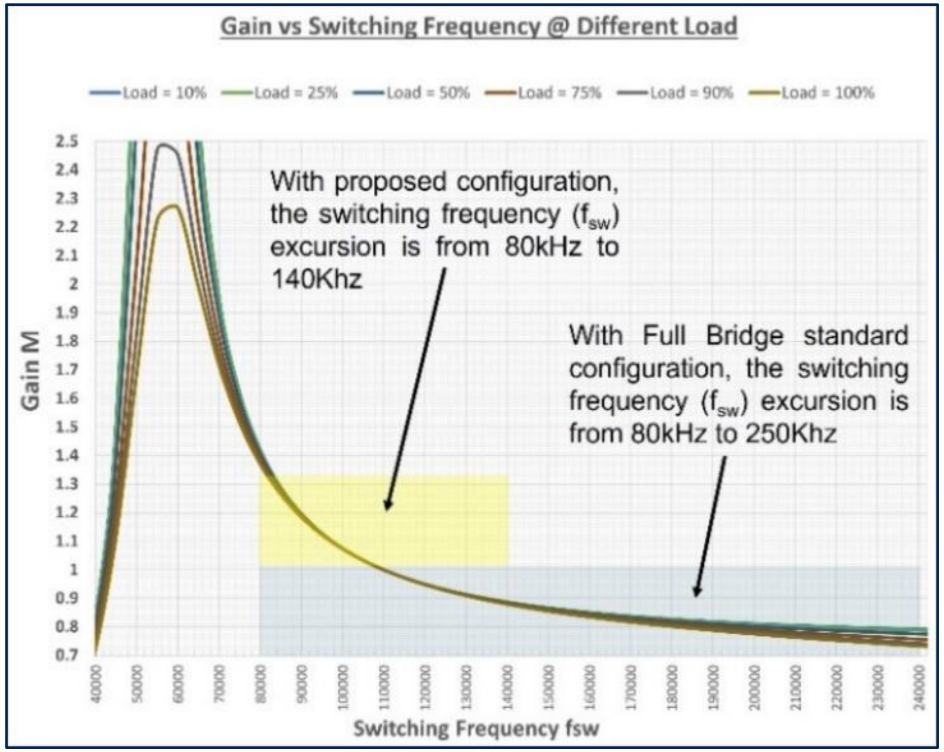
Tank gain curve and operating point for wide output voltage range





Very important to choose the correct Q, M, F_{min}-F_{max} and Np/Ns. Important also to consider production tolerances of magnetics in mass manufacturing. Certain digital techniques will circumvent that automatically

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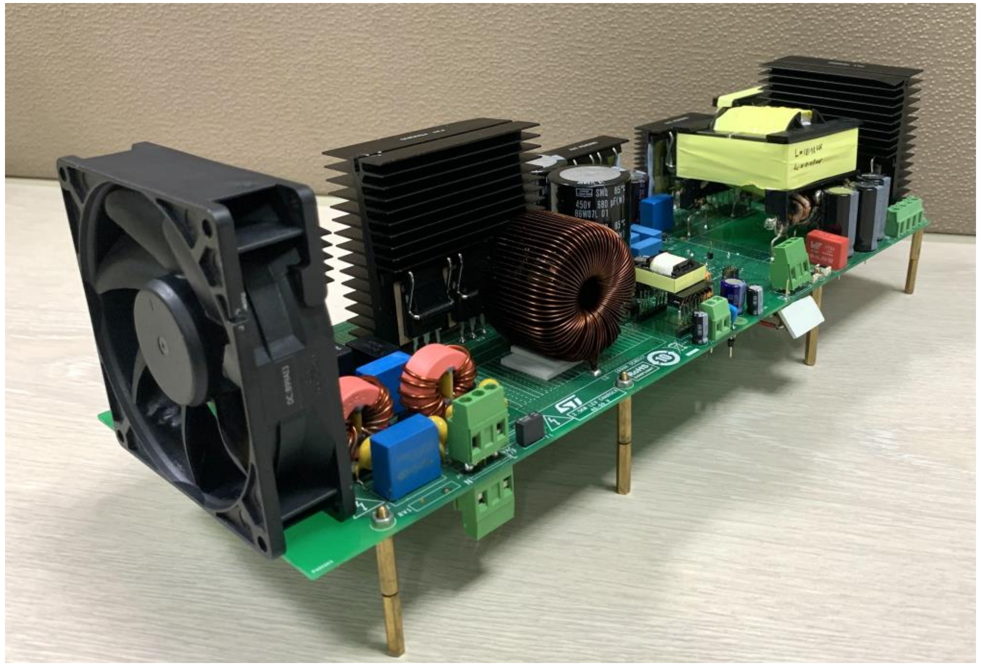
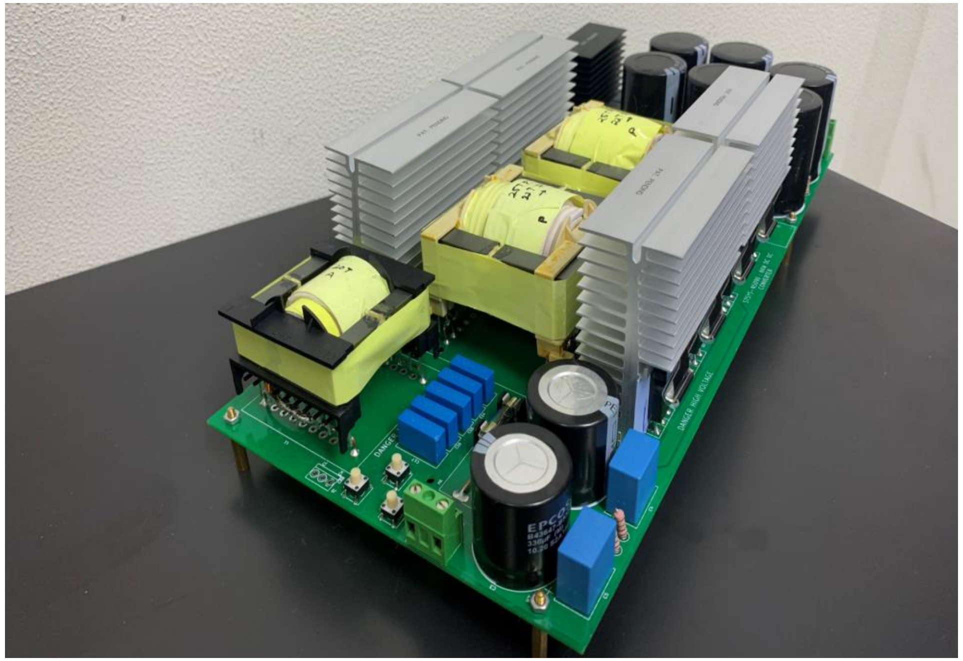
Real MCU based systems - kW level power converters



2500W light electric vehicle (LEV) charger



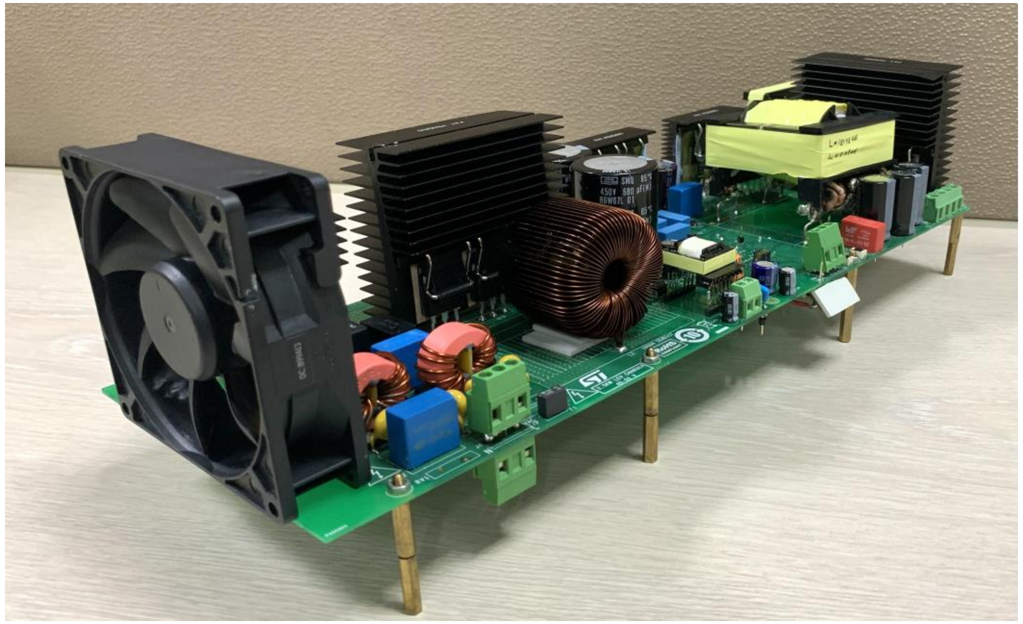
6000W wide output range LLC converter

Both MCU based, high performance converters, using LLC topology over a wide output range

2.5 kW light electric vehicle (LEV) charger

Key features

- Multi battery chemistry charger design
- CCM PFC + FB LLC 2.5kW converter
- 110V/230V in, 40-60DC wide output, 40A I_o max
- Mixed analog and MCU control
- Peak Efficiency 93.5% end to end
- PF>0.95 and THD <5% nominal power
- CAN/RS485 interface for remote configuration
- Comprehensive protection



Applications

- LEV charging
- Li Ion and general battery charger
- SMPS and robotic mobility

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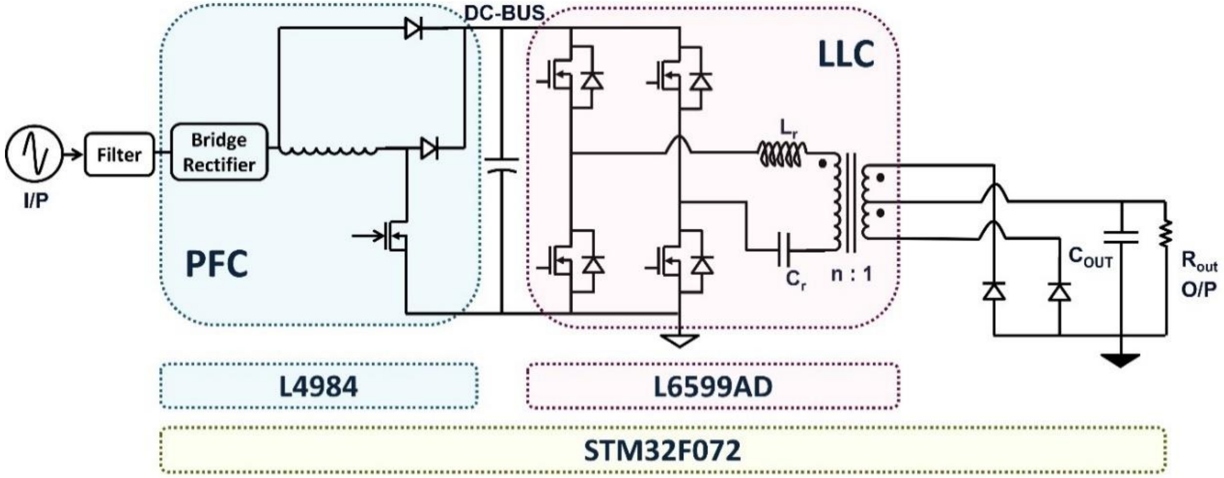
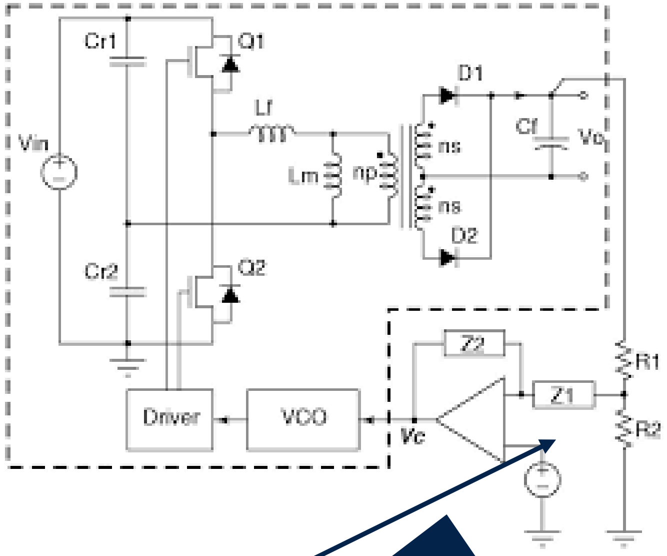
2.5 kW LEV battery charger

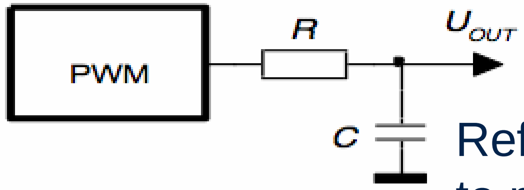
Hybrid (analog + digital) control scheme





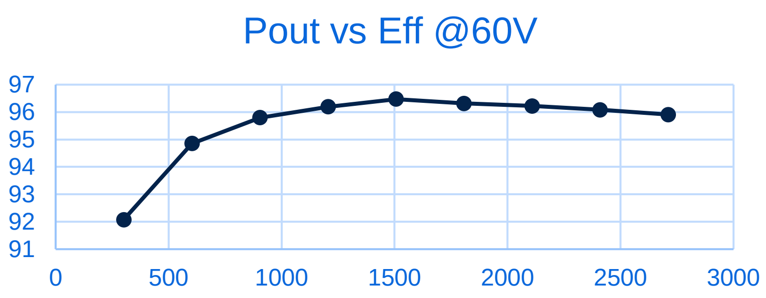
Vo
sample

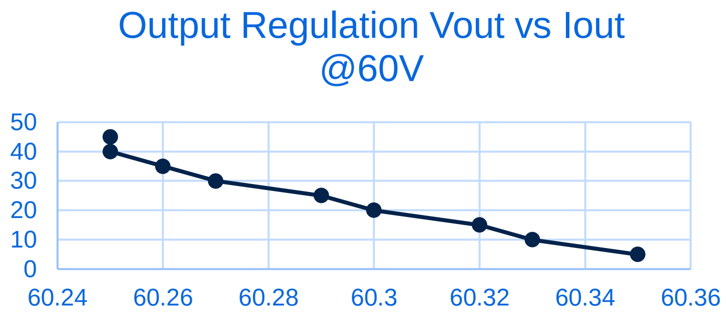
Vo
sample

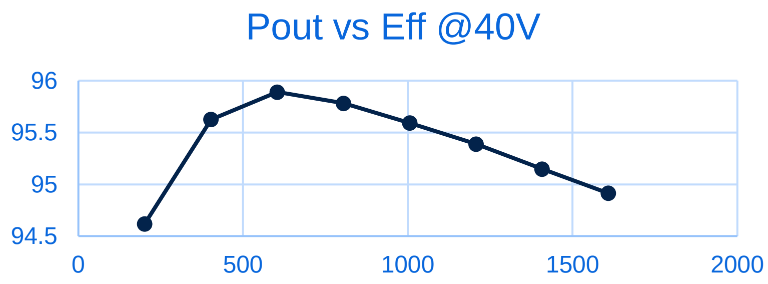


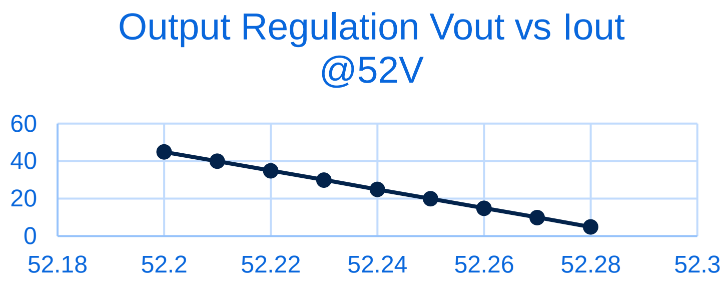
Reference modulation and over-ride to manipulate set point and hence O/P

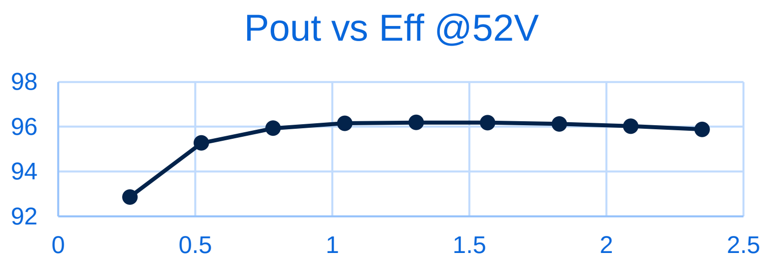
2.5 kW LEV battery charger performance details

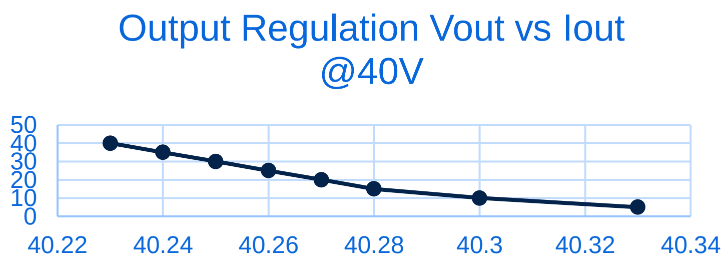












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Thermal performance @ 2.5kW load

TOLL PCB on heatsink

PCB trace heat: PCB is 130C class

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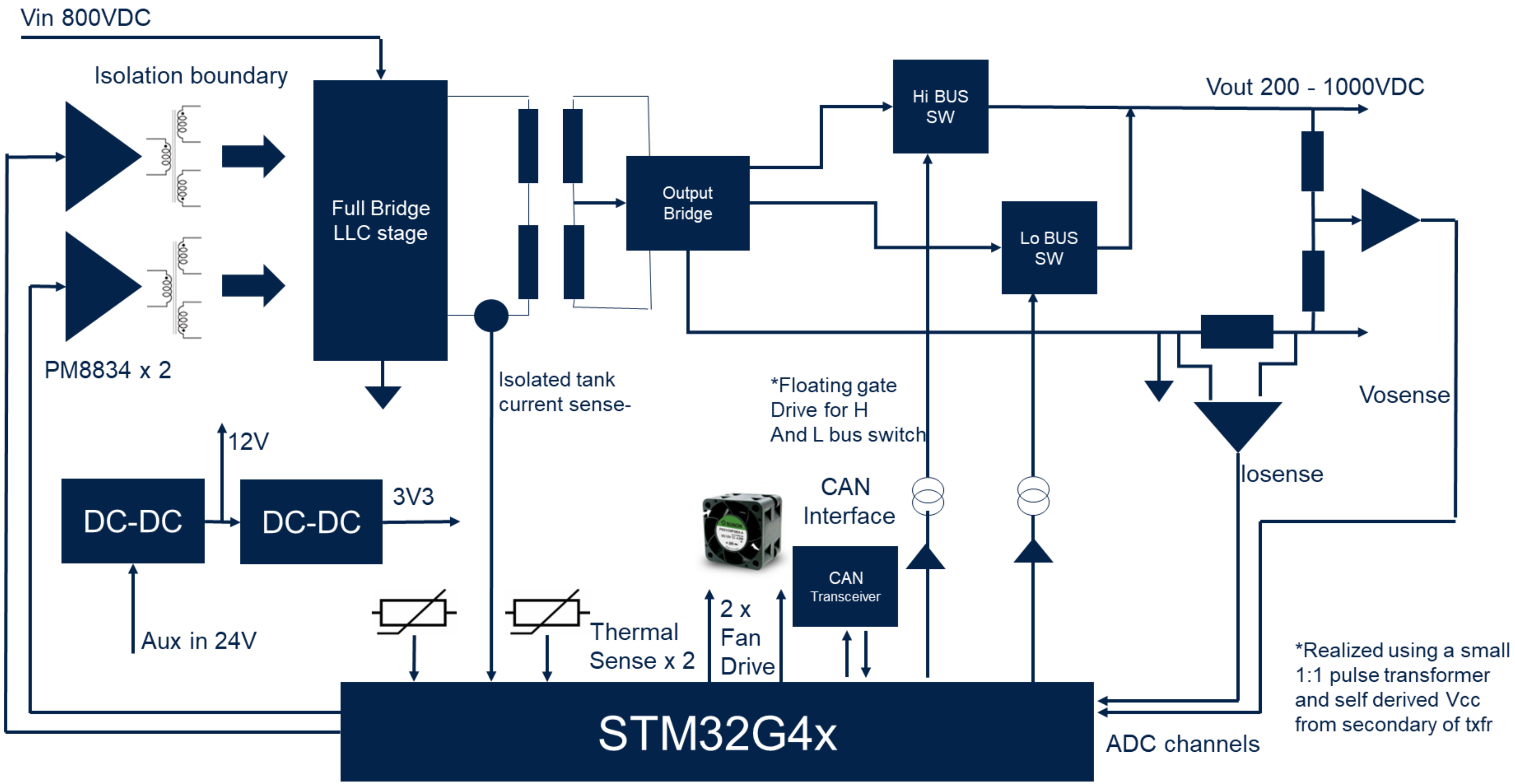
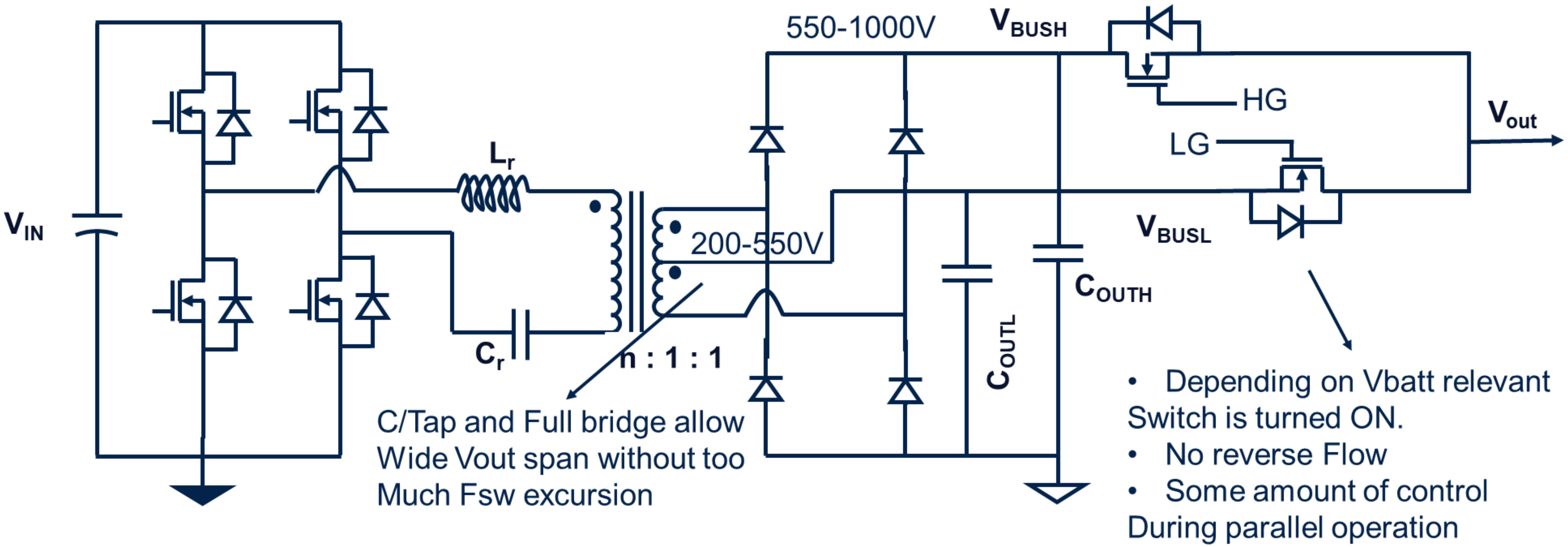
Block diagram
6 kW DC-DC digitally controlled LLC converter



Implementation
Full bridge LLC converter power plant

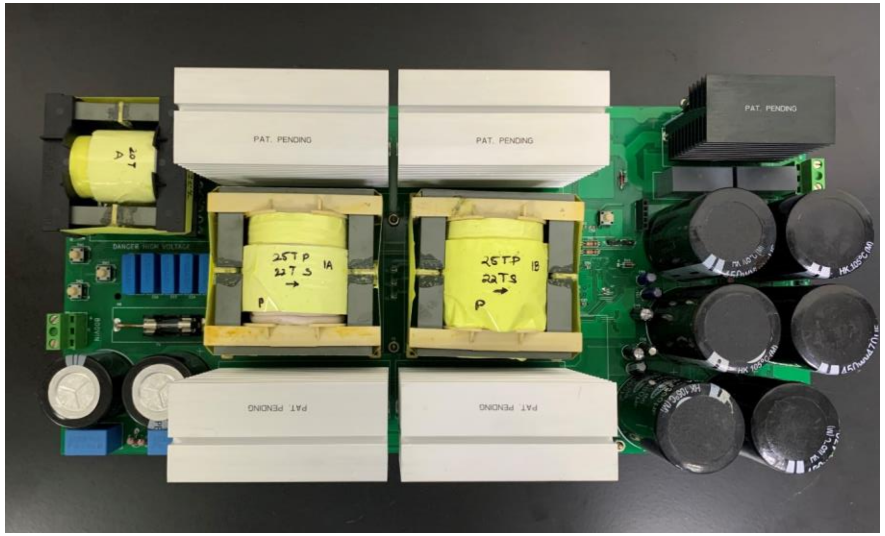


Full Bridge LLC power plant with output doubler configuration

6 kW DC-DC converter with wide range output voltage

Key Features :

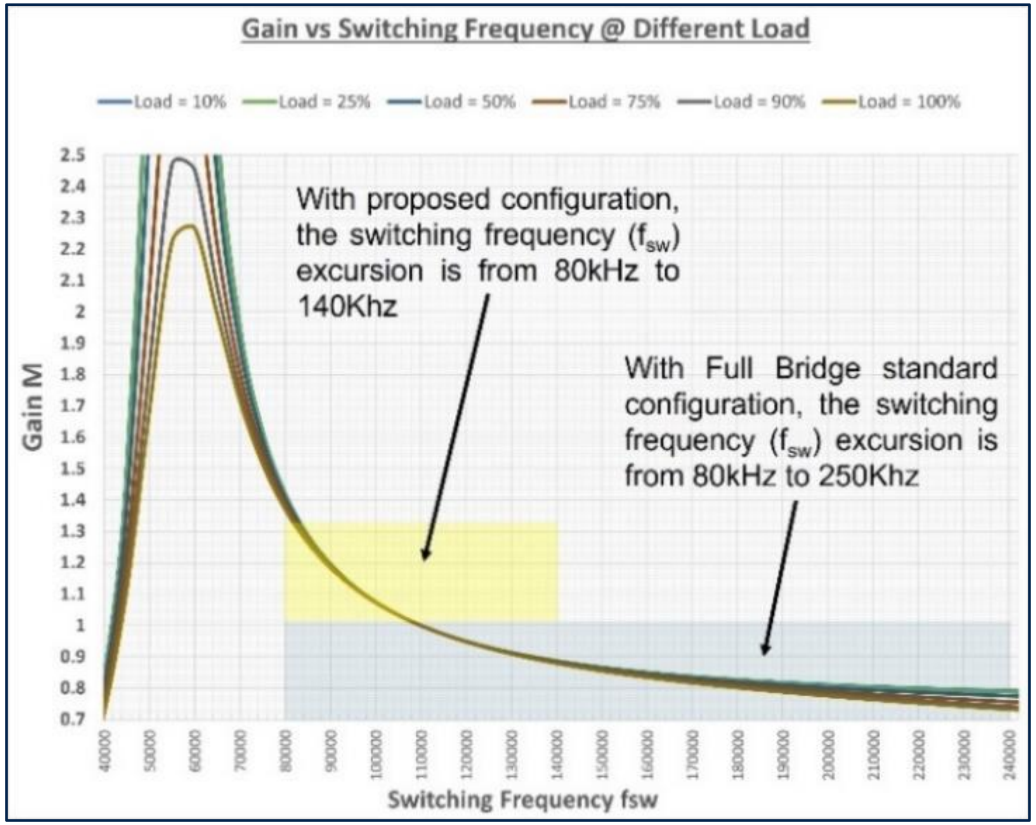
- Configuration: full Bridge LLC + full bridge rectification
- 6 kW power output with maximum efficiency > 97.9%
- Input Voltage: 700-800 DC
- Output voltage configuration: 200-1000V
    - Output high side MOSFET ON: 550 – 1000V
    - Output low side MOSFET ON: 200 – 550V
- Unique control technique to address low voltage requirements
- Comprehensive safety and protection mechanism



Applications:

- Battery charger
- EV applications

Resonant Tank - operating region

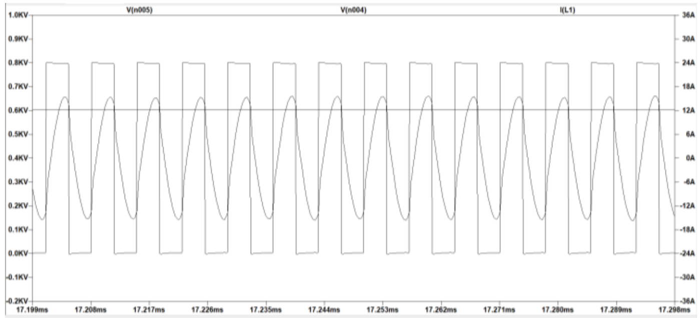


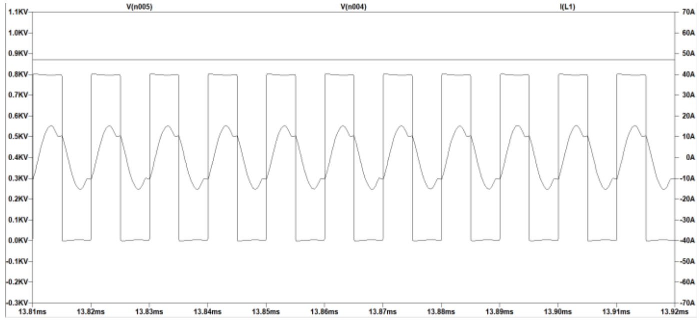
- Fres: 110 kHz
- Fmin: 80 kHz
- Fmax: 180 kHz(140 kHz)
- N = 1.08:1:1
- Q = 0.32 nominal
- Gain min = 1.33 Gain max = 2.4
- Vin 800V
- Po = 6000W
- Vo= 500-1000VDC (effective 200-1000V with margin) tolerance
- Lm/Lr = 3 → Low ratio lesser F span

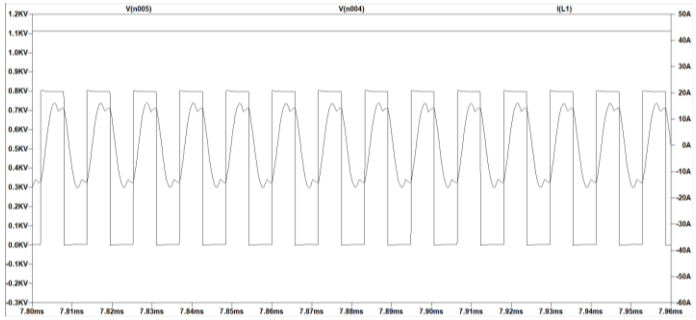
Very Important choose the correct Q, M, F_{min}-F_{max} and Np/Ns. important also to consider production tolerances of magnetics in mass manufacturing. Certain digital techniques will circumvent that automatically

6kW DC-DC converter simulation performance (1/4)

100% power





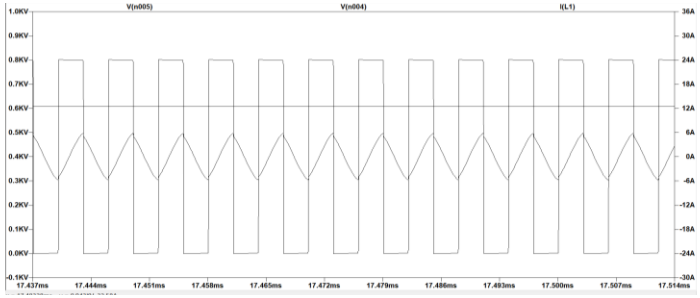


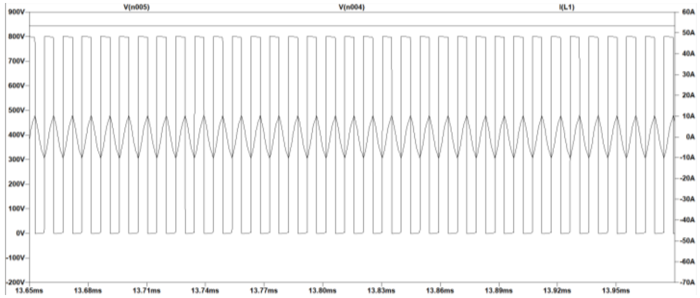
600V 10A 143kHz
Inductive zone

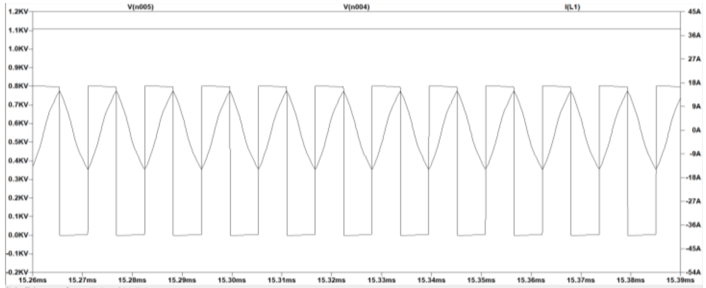
870V 7A 100kHz
Slightly left of resonance Fr

1100V 5.7A 86kHz
Left of resonance Fr

10% power







600V 1A 166kHz

870V 0.7A 104kHz

1100V 0.57A 88kHz

*Lower voltage range behaves identically as it is halved by the transformer

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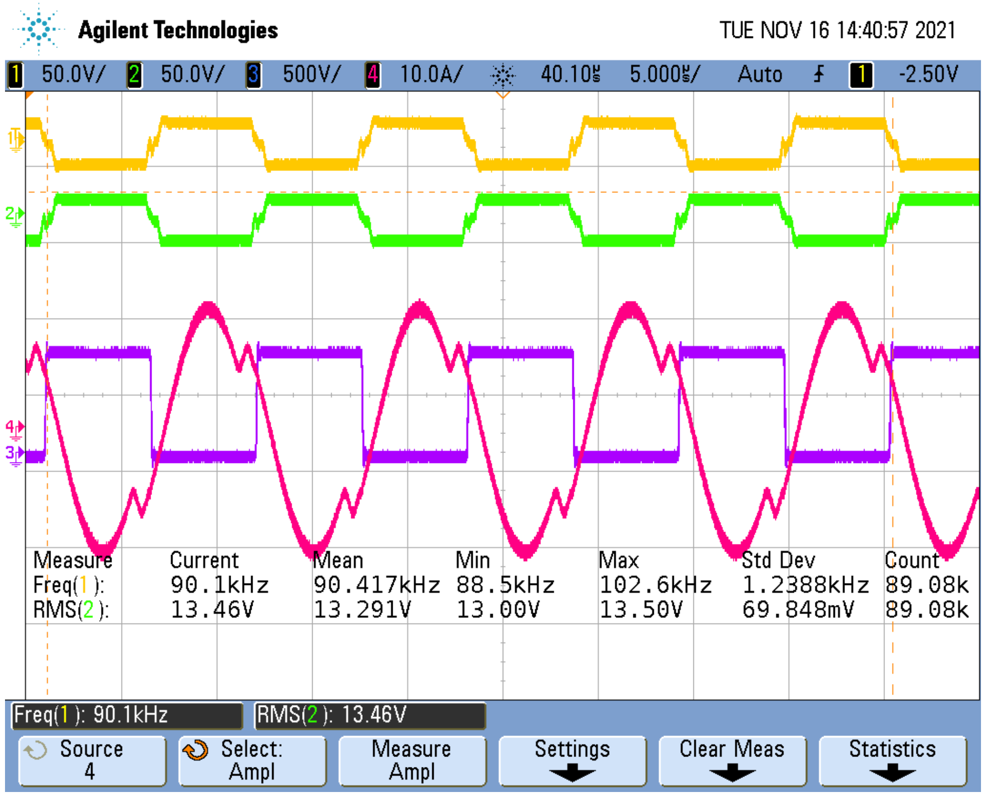
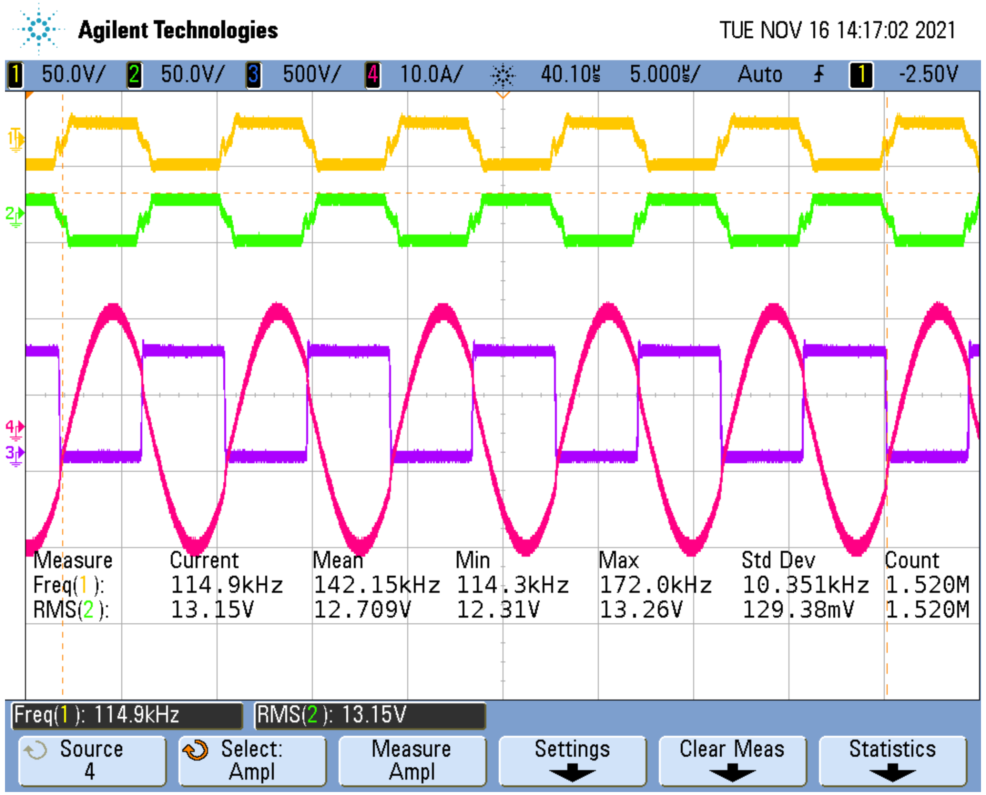
6kW DC-DC converter simulation performance (2/4)



800V output, 90kHz



700V output, 100kHz

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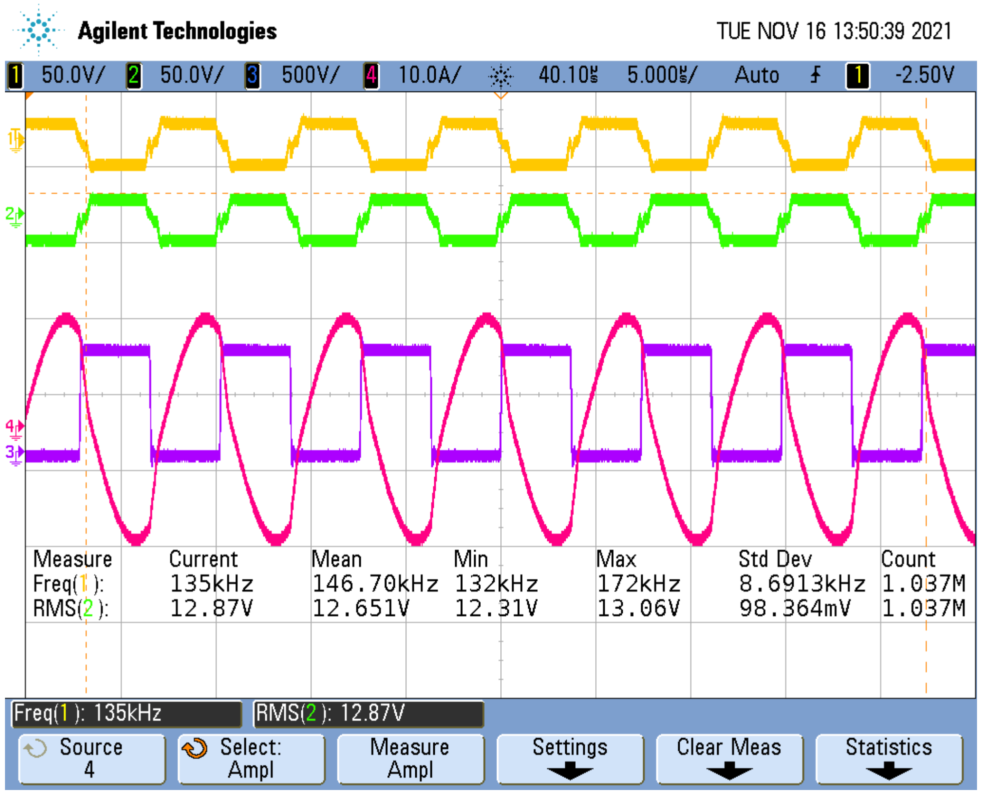
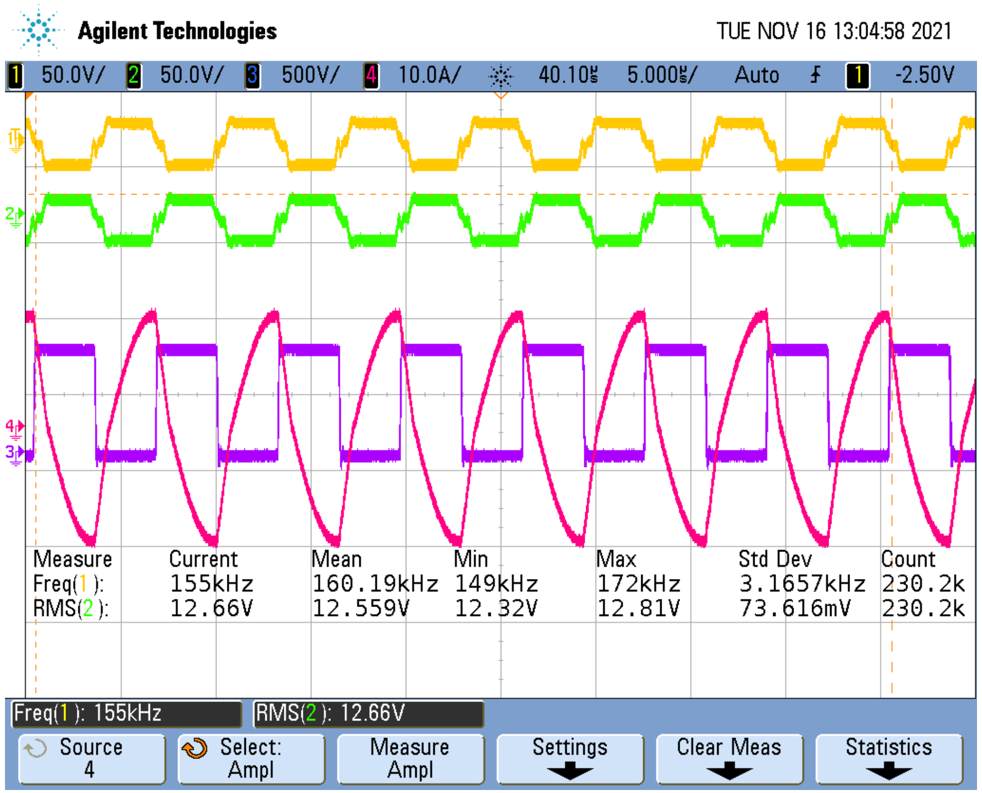
6kW DC-DC converter simulation performance (3/4)

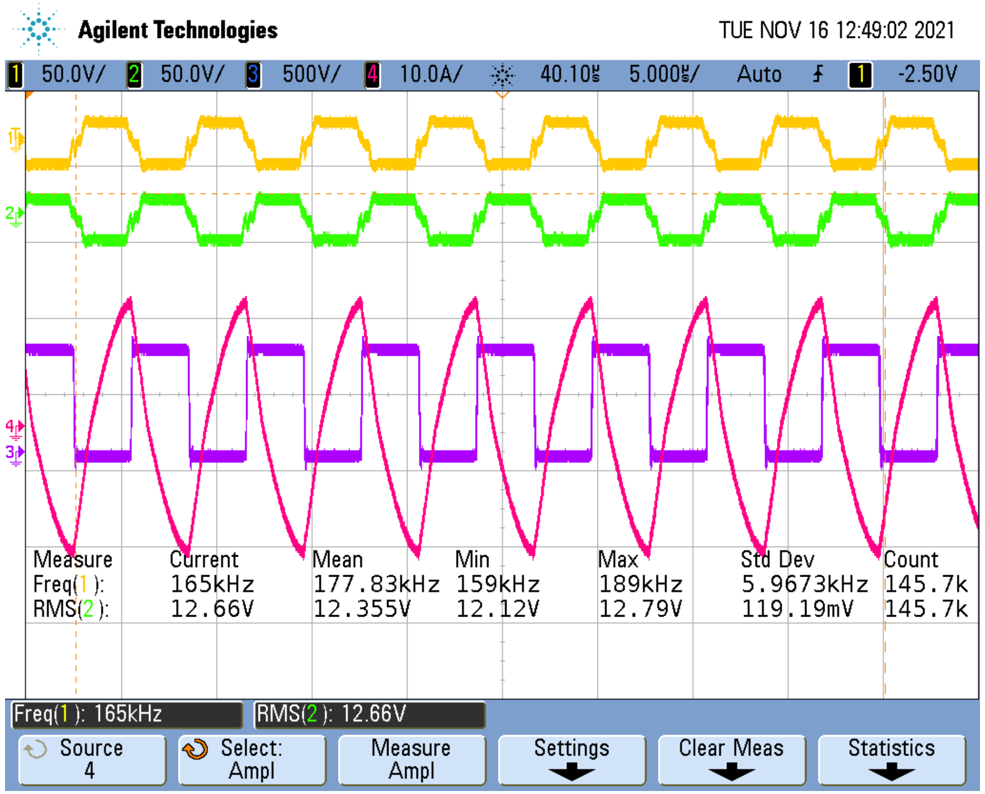


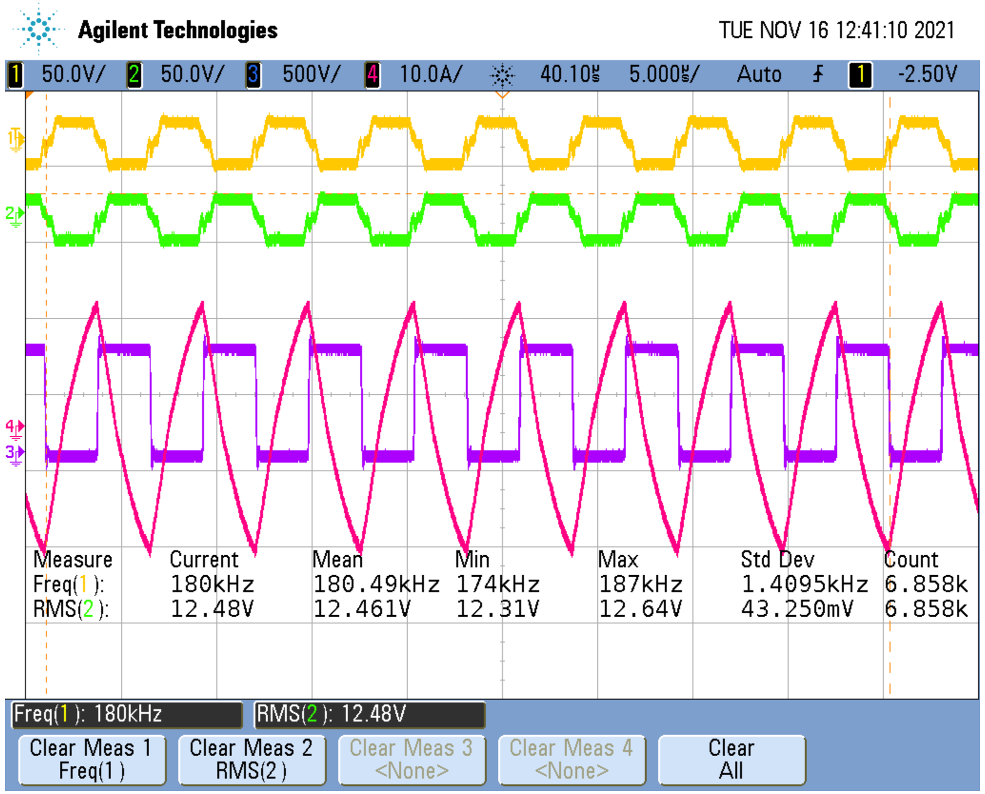
500V output, 135kHz



400V output, 145kHz → will shift to 90kHz with Bus switching scheme

6 kW DC-DC converter simulation performance (4/4)





300V output, 165kHz
➔ will shift to 120kHz with Bus switching scheme

200V output, 180kHz
➔ will shift to 130kHz with Bus switching scheme

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Performance at some typical operating points @Vin ~700V

MOSFET case temperature (worst case) <50C with forced air cooling, 30 minutes warmup

Vin(V)	Iin(A)	Pin(kW)	Fsw(kHz)	Vout(V)	Iout(A)	Pout(kW)	Efficiency(%)	Load
711.3	3.204	2.2788	180	210.9	9.572	2.0195	88.62120414	21 Ω
706.75	4.943	3.4934	165	307.95	10.413	3.207	91.80168317	28 Ω
704.93	5.515	4.1012	155	396.29	9.791	3.8815	94.64303131	38 Ω
701.57	7.529	5.2827	135	508.47	10.013	5.0929	96.40714029	48 Ω
698.76	9.37	6.5249	115	608.17	10.455	6.3606	97.48195375	54 Ω
702.44	7.049	4.952	100	692.9	6.962	4.825	97.43537964	92 Ω
686.07	8.998	6.1736	90	775.5	4.759	6.019	**97.49578852**	92 Ω
708.05	4.38	3.1016	115	625.38	4.8583	3.0351	**97.85594532**	122 Ω

Note efficiency variation under same power condition: mitigated by Vbus select scheme where it operates closer to resonance and higher efficiency. So, for example if we need 300V , operation point will be that of 600V with Vbus(LOW) selected.

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