Design and implementation of a LLC-ZCS Converter for Hybrid/Electric Vehicles

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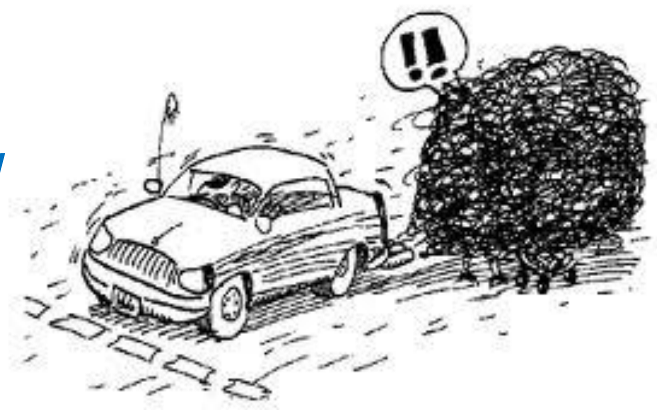
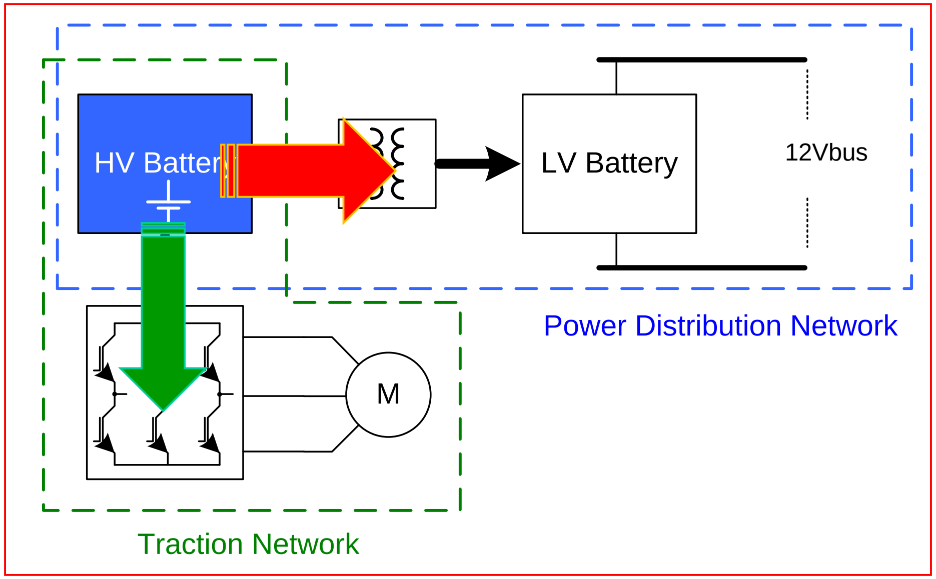
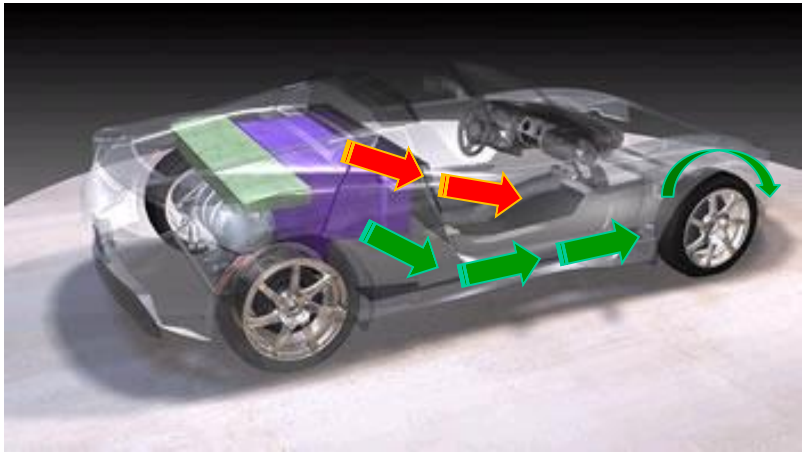
Need for clean

Hybrid and Full Electric vehicles allow pollution reduction ➔ this make them the new generation of transportation

Traction and power distribution networks are highly impacted by this evolution
HV battery in hybrid/electric vehicles allow traction as well as services to run out of the battery for a medium/long time.

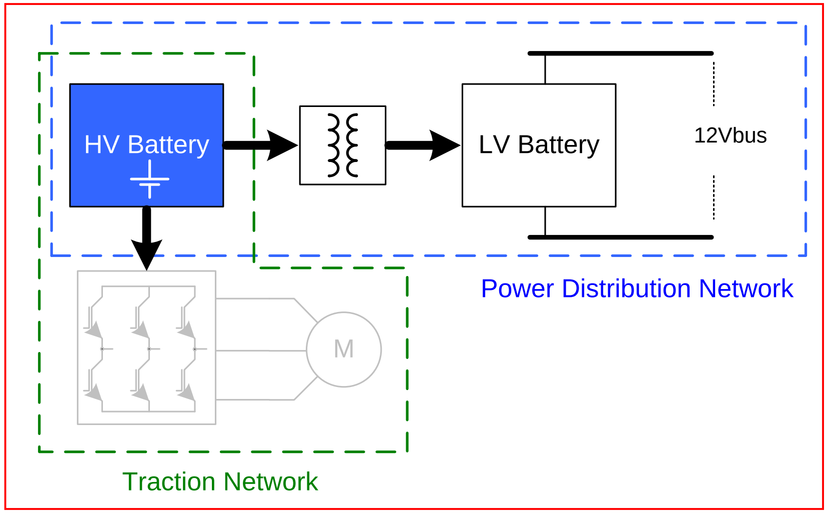






System Specification

Power distribution network: exploiting the energy of a HV battery for traction and services



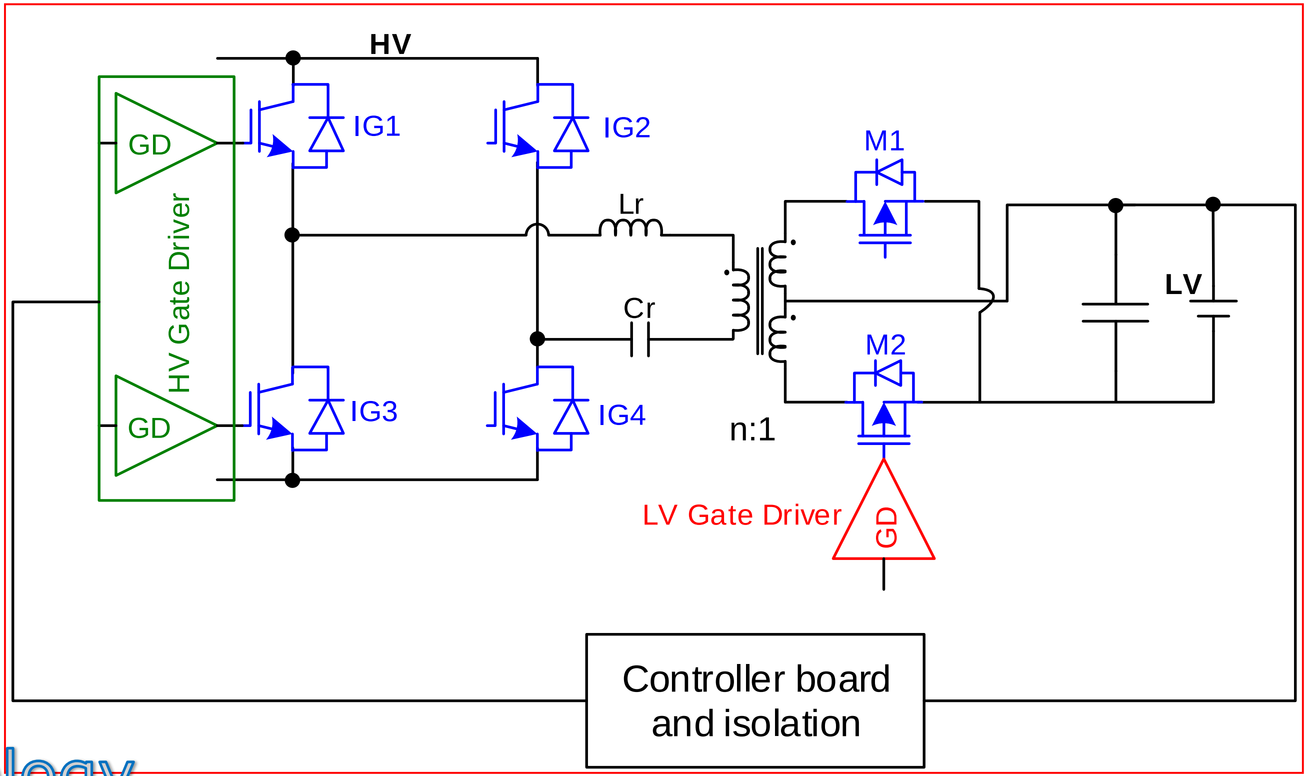
- While the traction inverter is directly supplied by the HV battery, all services in a car today still run out of a 12V battery, therefore a HV-DC/DC converter is needed to supply this battery line

System has been designed considering these ranges

Variable	Min.	Typ.	Max.
Input HVB [V]	250	350	450
Output LVB [V]		13	
Load power [W]	400		2400

System design: converter topology choice

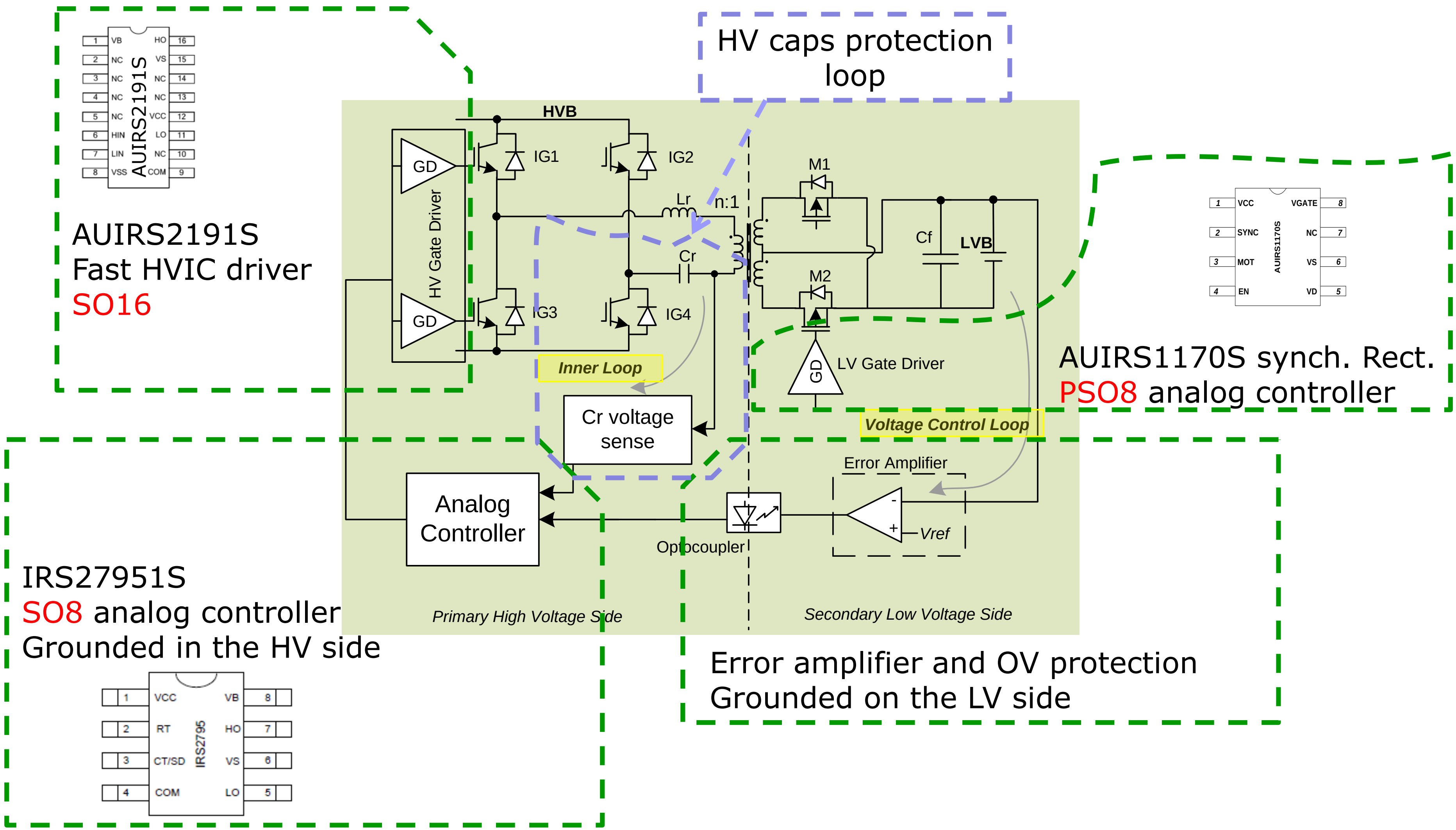
1. Galvanic isolated topology
2. Soft switching



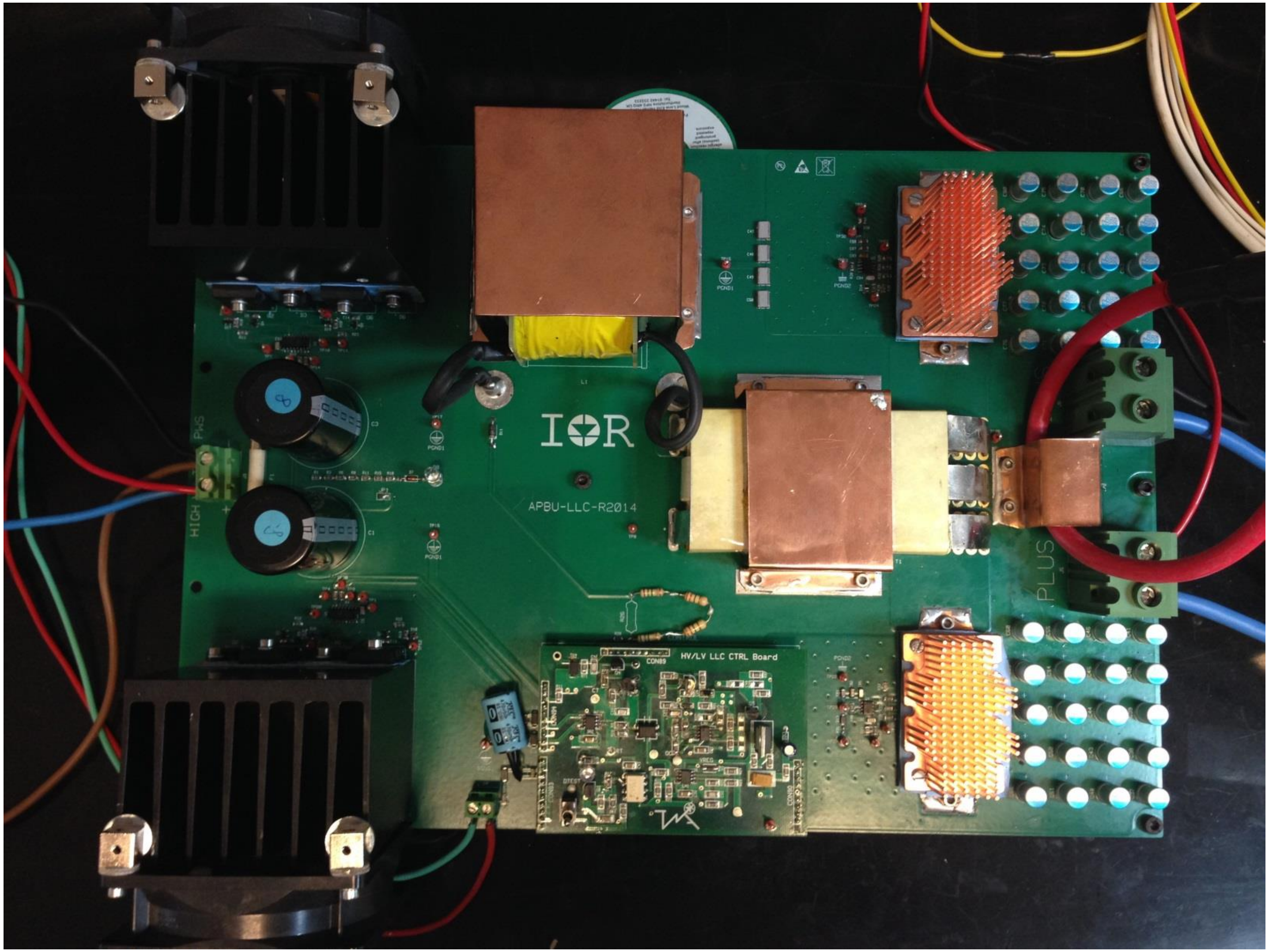
LLC ZCS Topology

- Behaves as current generator → intrinsically protected @ short circuit at the output.
- ZCS has the advantages of using IGBT with co-packed fast diode;
- Simplified output filtering uses only capacitors;
- No need to control the DC current through transformer, resonance Cap solves it.

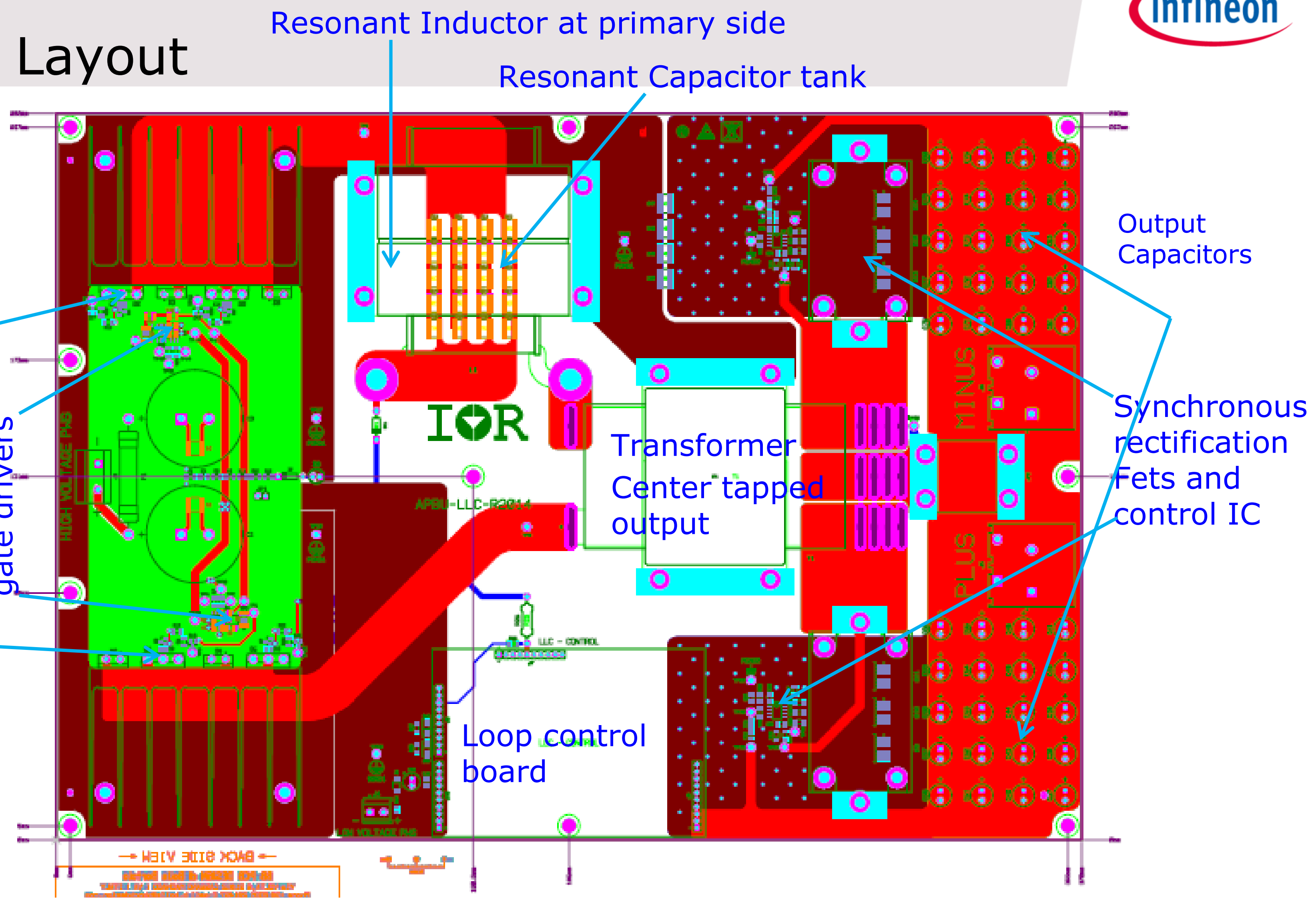
System design: control strategy



LLC DC/DC board, prototype picture



Board Layout



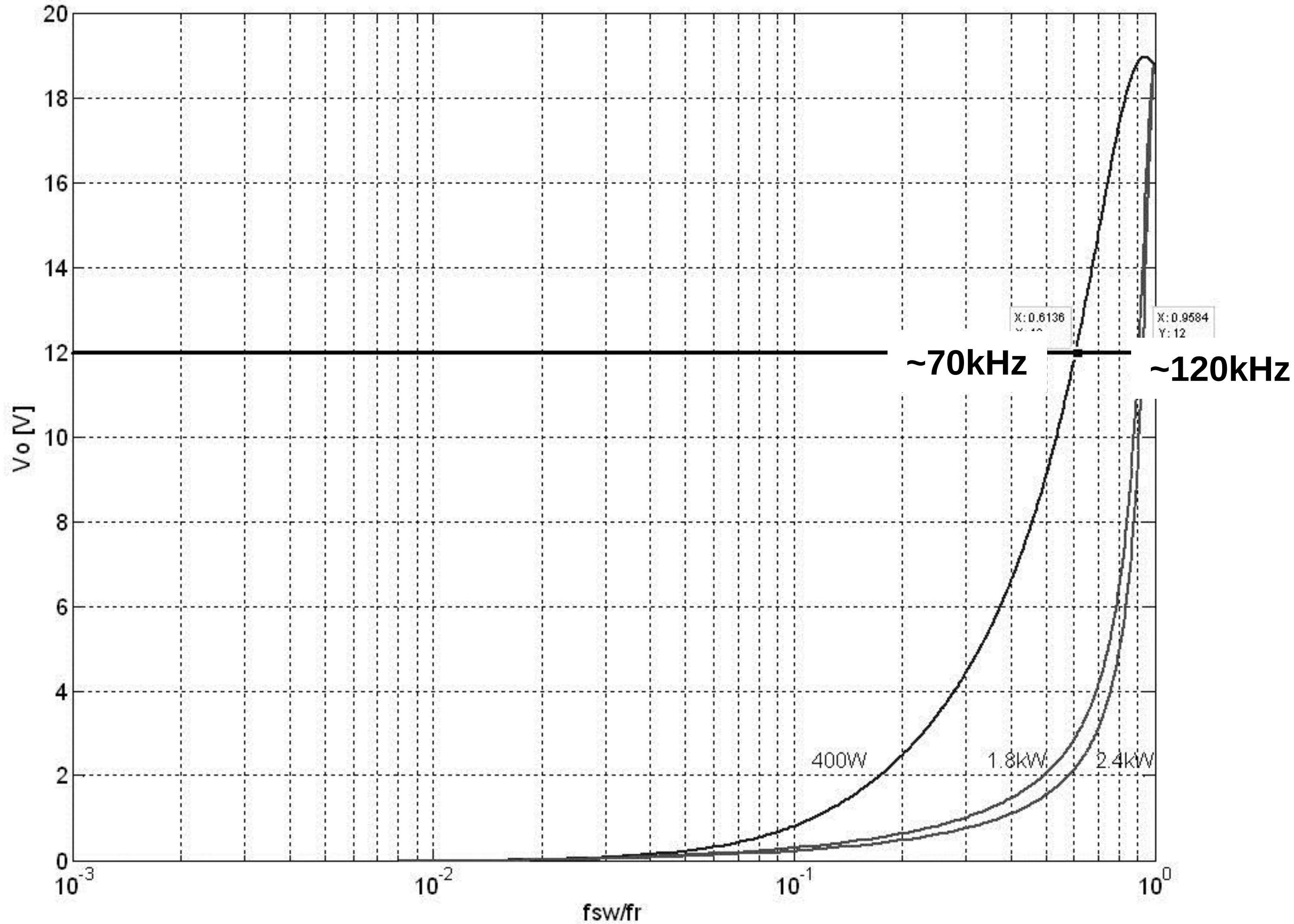
Layout is optmised for system testing and debugging.

System design: main BOM components

Output Flter	• It is made with only Organic Conductive Polymer capacitor, 4mF in total → no need for output inductor • System volume and cost are reduced • SR MOSFET voltage rating = 60V-80V ➔ higher power density and cheaper system
Magnetics and Resonant Tank	• Resonant inductor at primary side reduces size and weight; resonant capacitors also take care of balancing the magnetizing current
Mathlab routine has been implemented in order to design main parameters	• Resonant inductor and capacitor values have been optimized vs. load and input voltage variation
Transformer	•Magnetizing inductance Lm = abut 6 times resonant inductor value •Transformer ratio is 16:1+1; Isec. = 170Arms •Variable frequency from 60kHz to 125kHz
Resonant inductor	•Lr = 128uH •Irms~15A •System Resonant freq.: 125kHz
Resonant Capacitor	•Cr = 12,6nF •3kV •C0G (low ESR)
Synchronous rectification Fets	•Rds-on = 2,4mΩ max, 80V •3x each leg in parallel
Primary switching section	•650V – 40A IGBTs •Vce_sat= 1,80V @125C

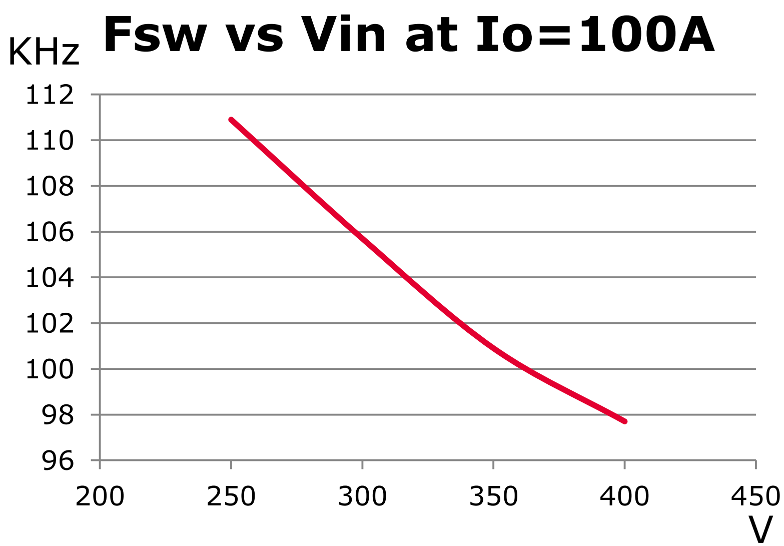
Simulation results

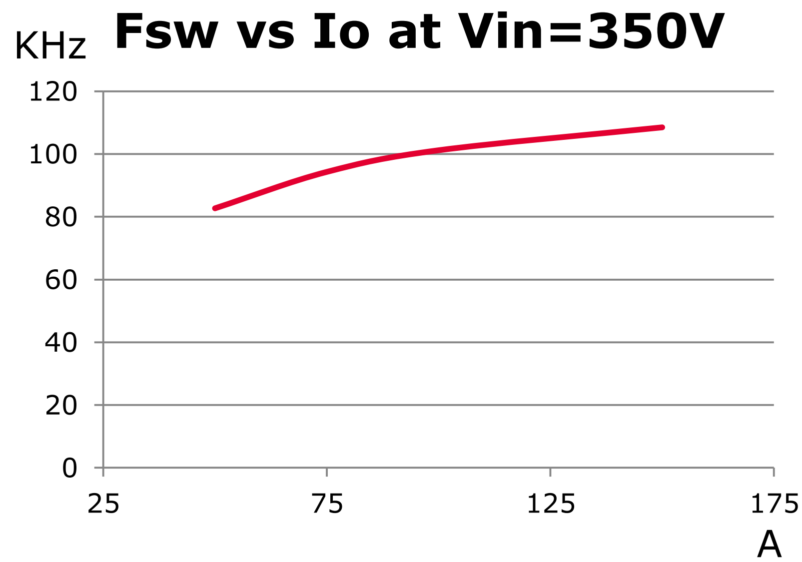
Transfer Function: switching from 70k to 120kHz at Vin=350V



Simulation at Vin = 350V, Vout = 12V and different power output

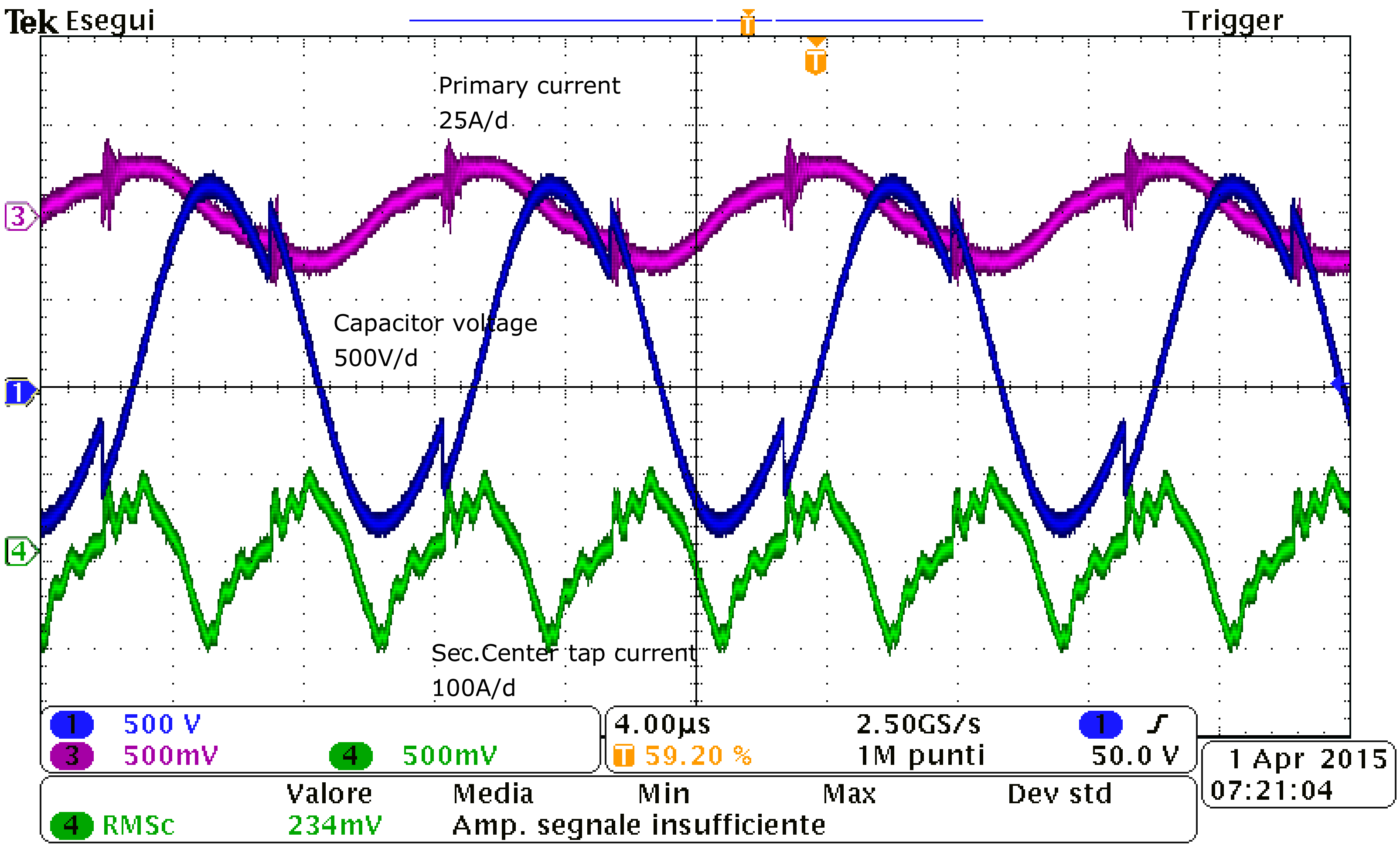
Measurements: Operating Frequency vs Input Voltage and load





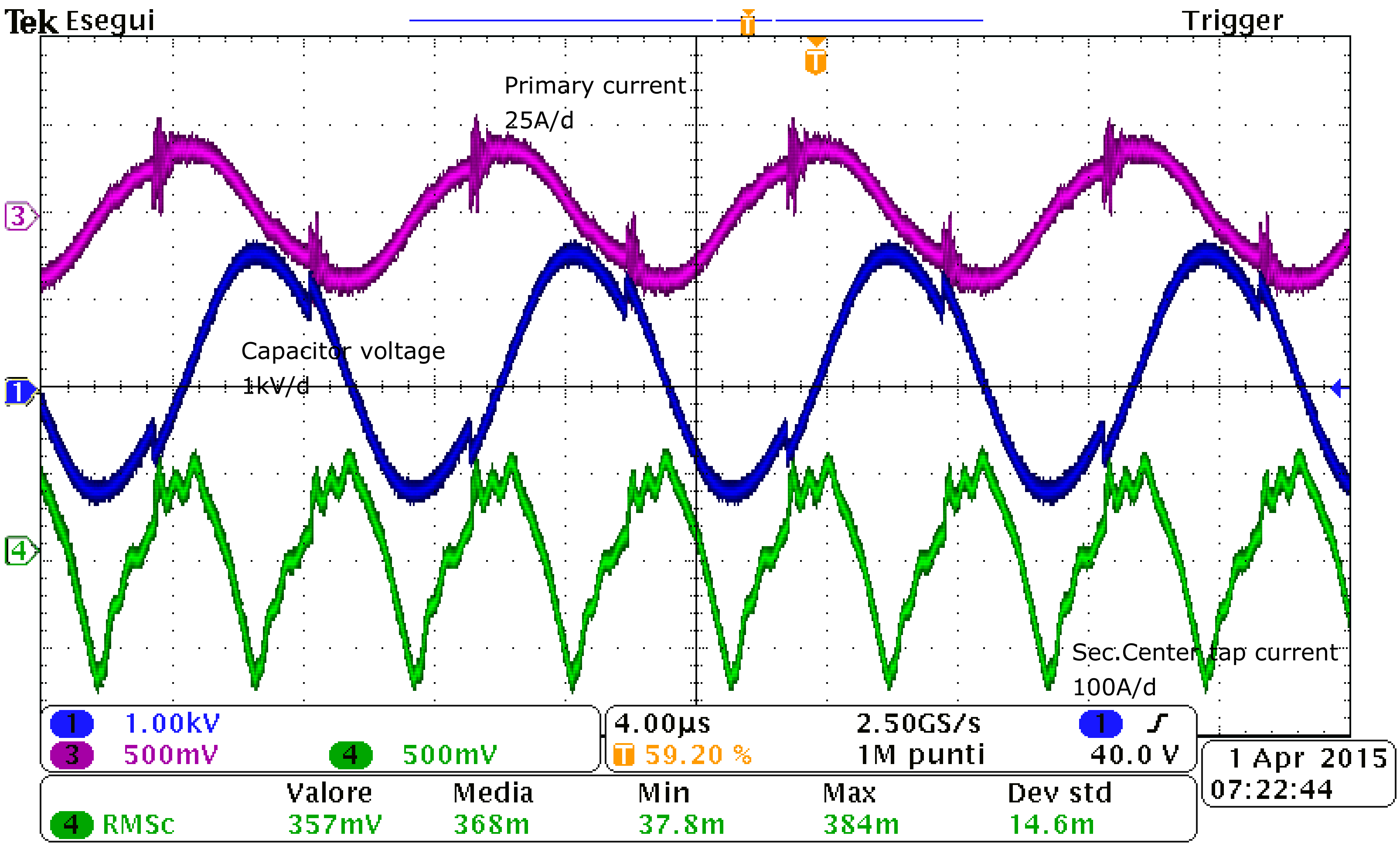
Low switching frequency variation vs. input voltage and load changes
Good matching with simulation

Operation at nominal input voltage: 400V – 100A



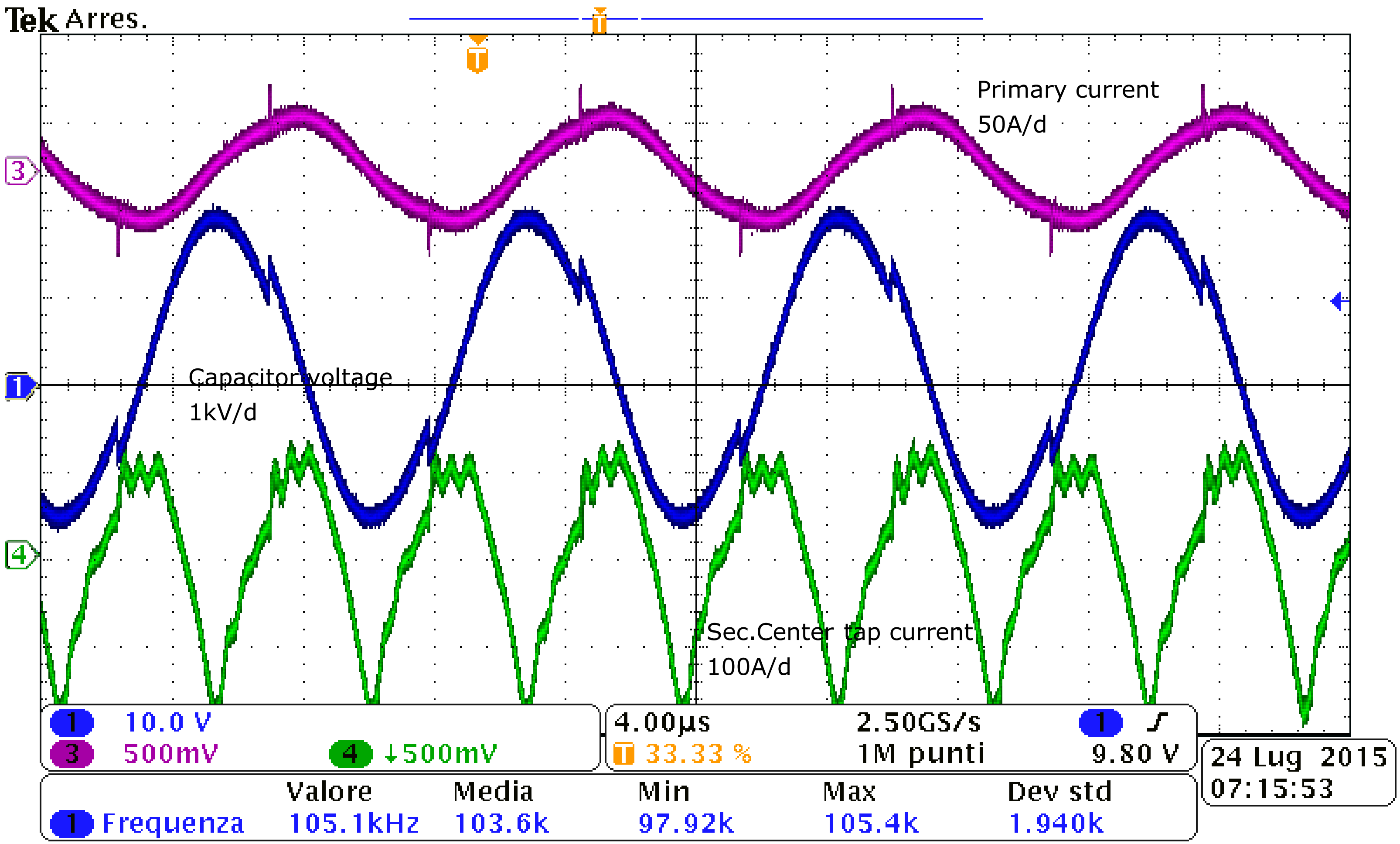
Clean sinusoidal voltage across resonance capacitors, some ringing noise visible on transformer‘s secondary current

Operation at nominal input voltage: 400V – 150A



Frequency, capacitors voltage and Primary/Secondary currents increase

Operational waveforms at 400V -180A



Very close to resonance (~110kHz), waveforms are almost sinusoidal.

Secondary side synchronous rectification

- In a LLC converter the secondary current and primary switching voltage are not in phase and their phase rotation depends on the load, this effect doesn't allow to use the primary PWM signal to control the secondary side switches.

- A dedicated IC reading the VDS voltage across the Synch Rectification Fets solves this problem

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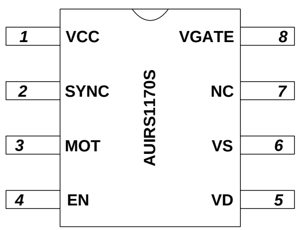
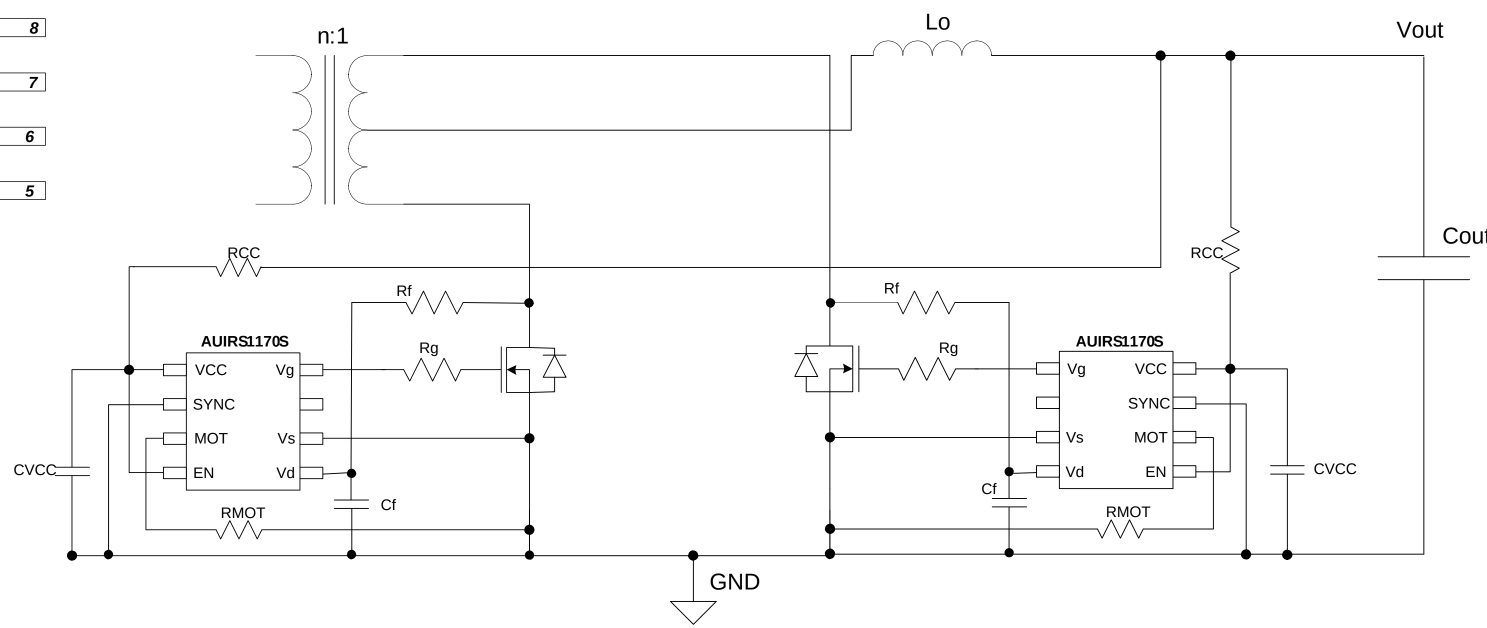
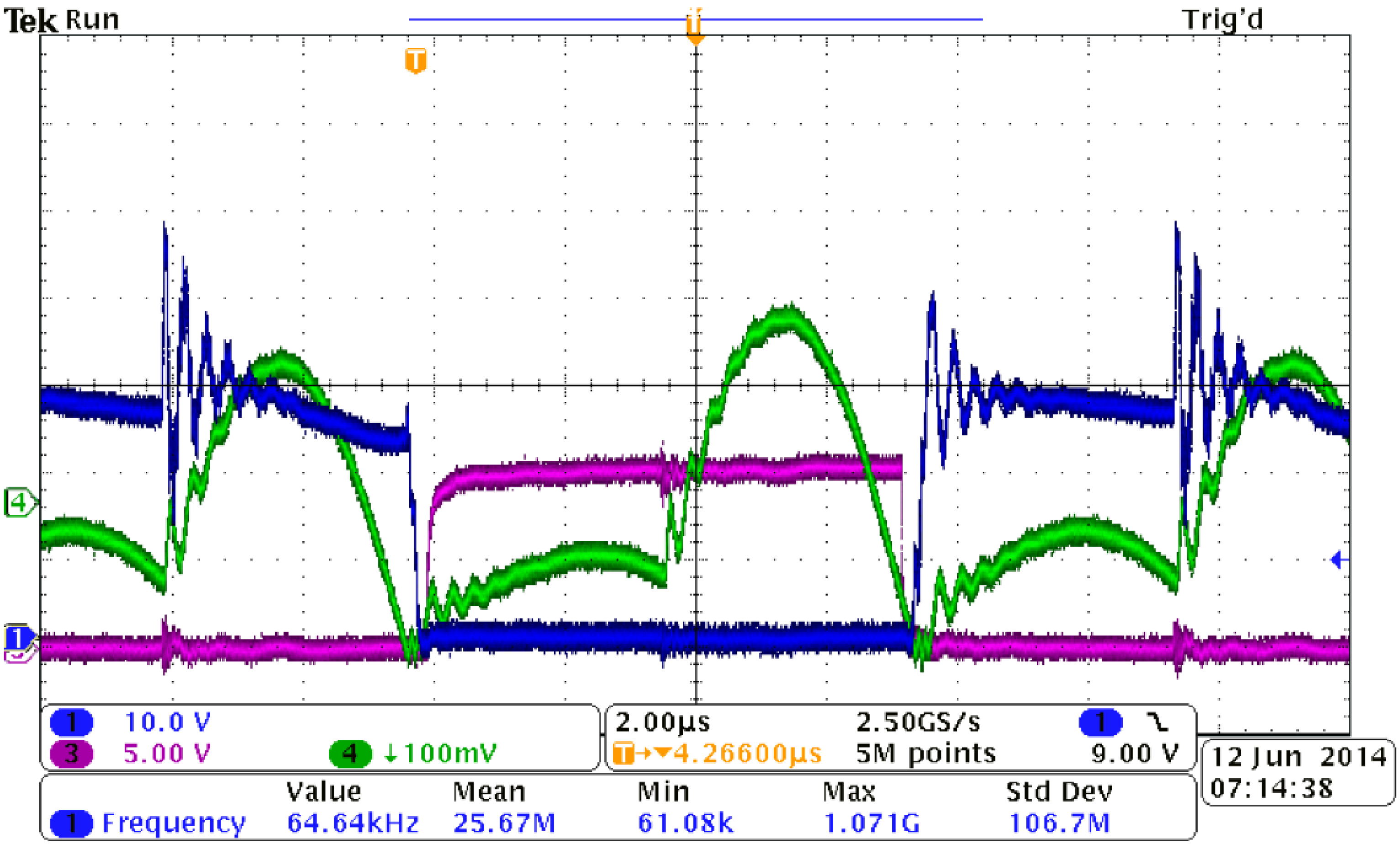


› Typical application schematic



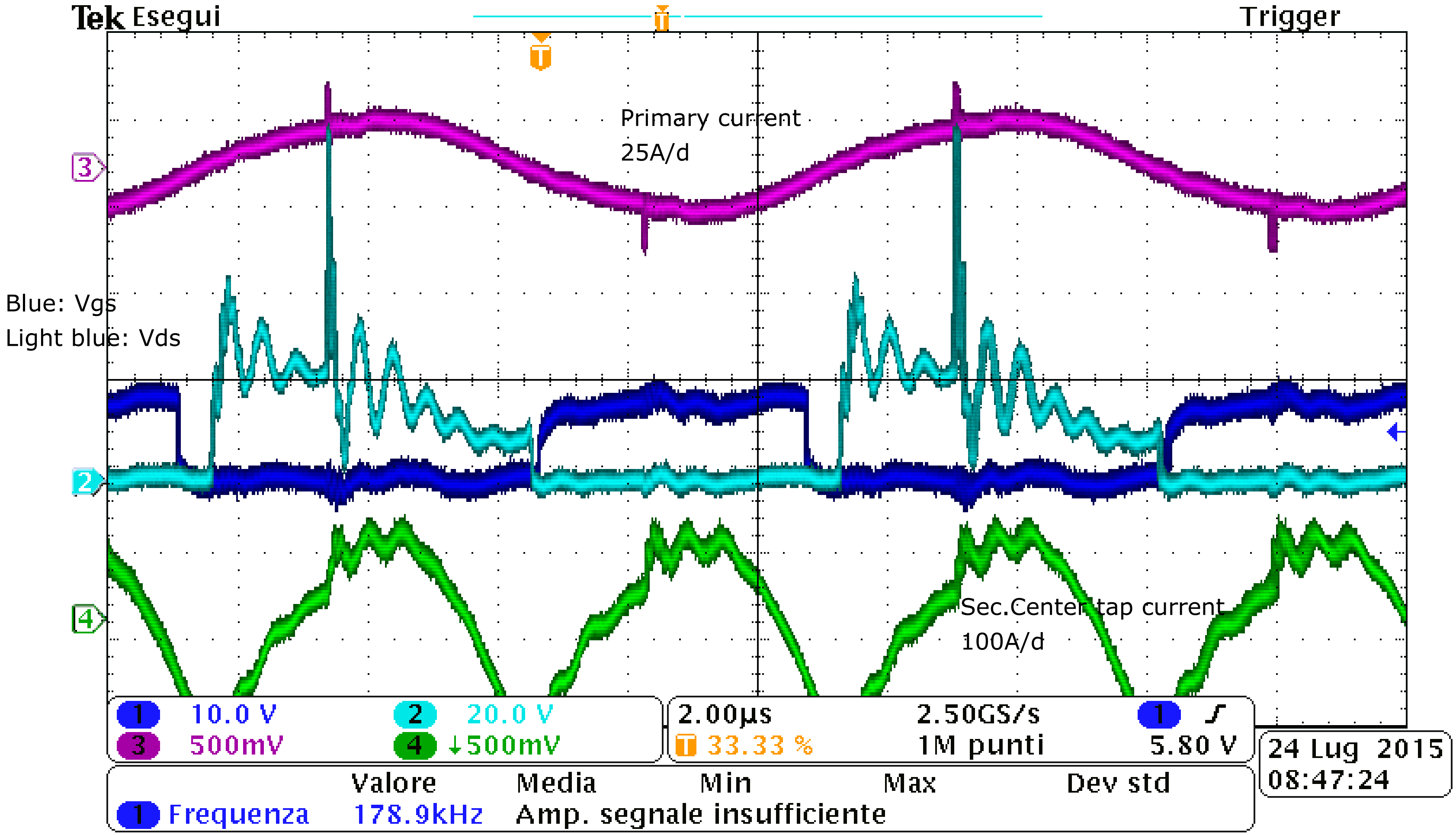
Secondary side waveforms at 400V and light load



Ch1= Vds [10V/d], Ch3= Vgate1 [5V/d], Ch4= Isec. [20A/d]

Waveform obtained at low current output of 30A only: the signal across the 0,8m Ω equivalent Rds-on of the Fets becomes quite small but the gate command signal is regular.

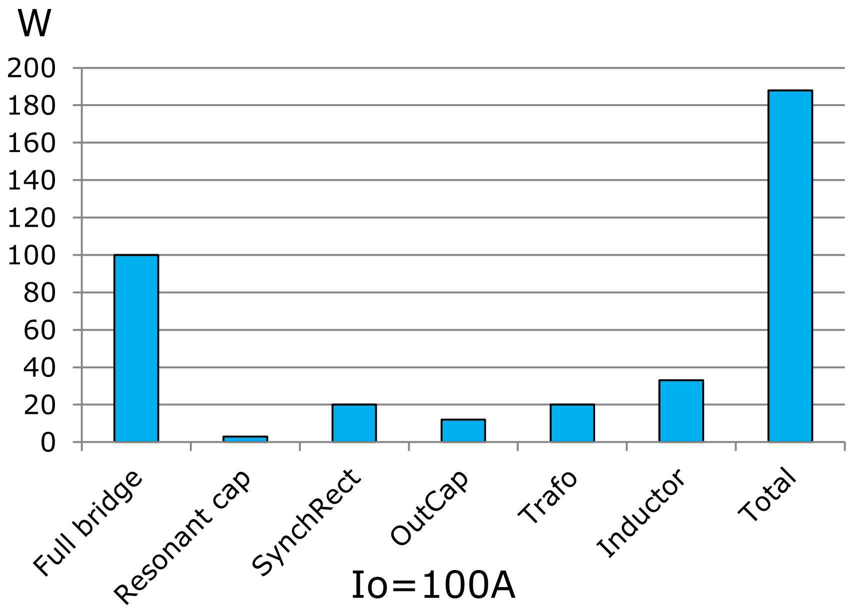
Secondary side waveforms at 400V and high load



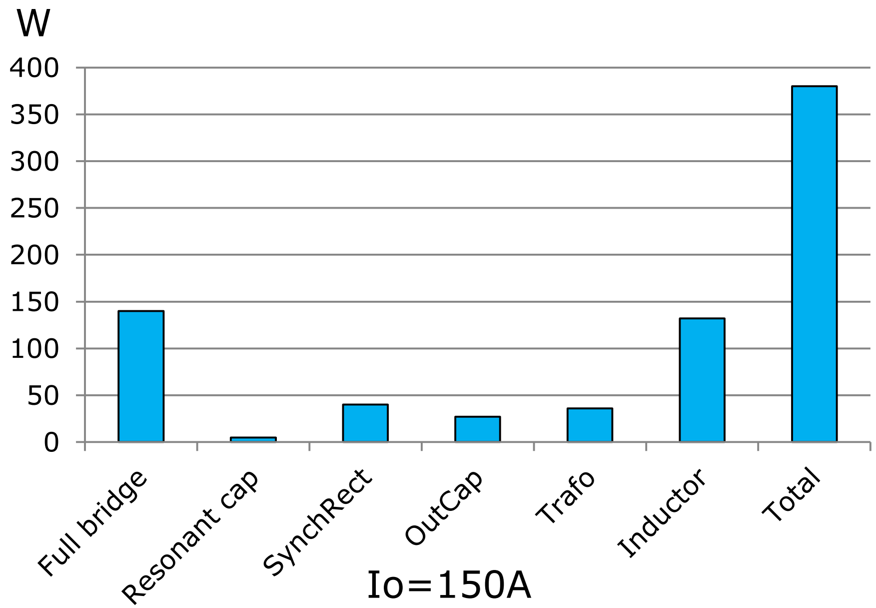
Waveform obtained at high current output of 160A: the signal across the 0,8m Ω SR Fets is much more evident as well as switching noise but the gate command signal is regular.

Power Losses Breakdown(350Vin)

Estimation done though thermal measurement and mathematical estrapolations



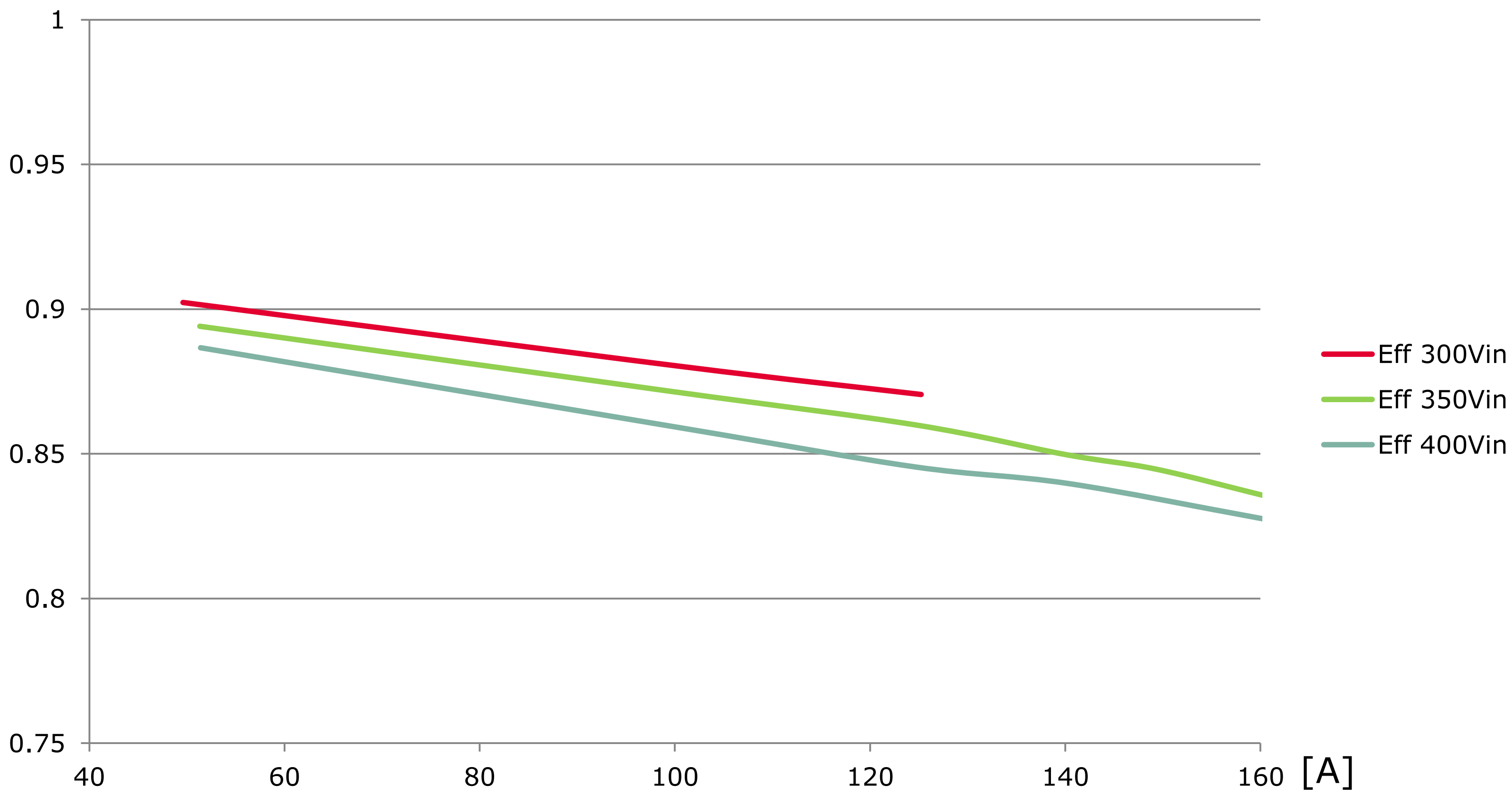
Io=100A



Io=150A

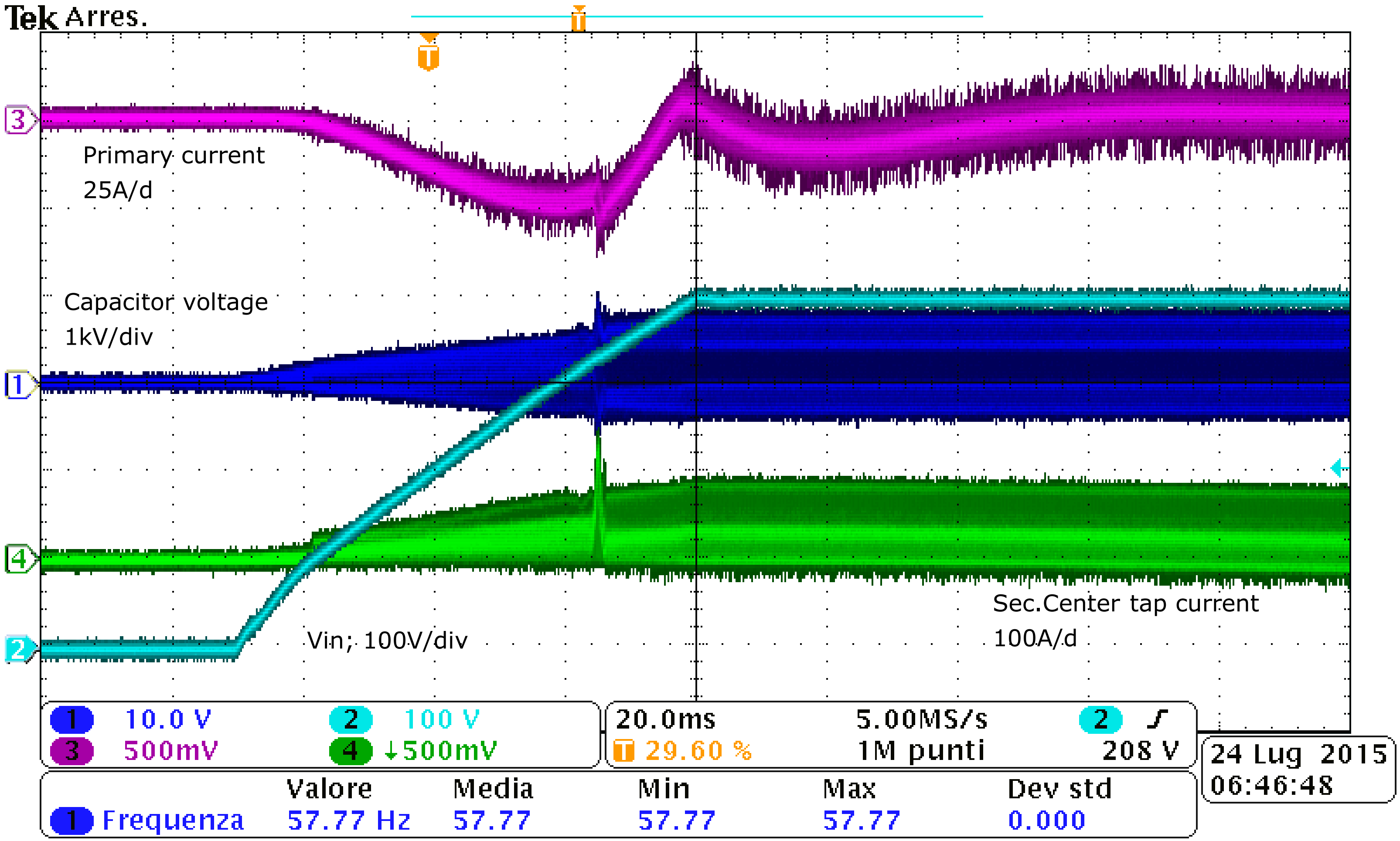
- Primary side losses look still predominat and increase proportionally with the output current;
- High $V_{ce_{sat}}$ of IGBTs still inpact this performances;
- Inductor losses seems to be increasing rapidly with output current, showing undersizing of the component, redesign is advisable;
- Resonant and output Capacitor losses have low inpact in the overall efficiency.

Efficiency results



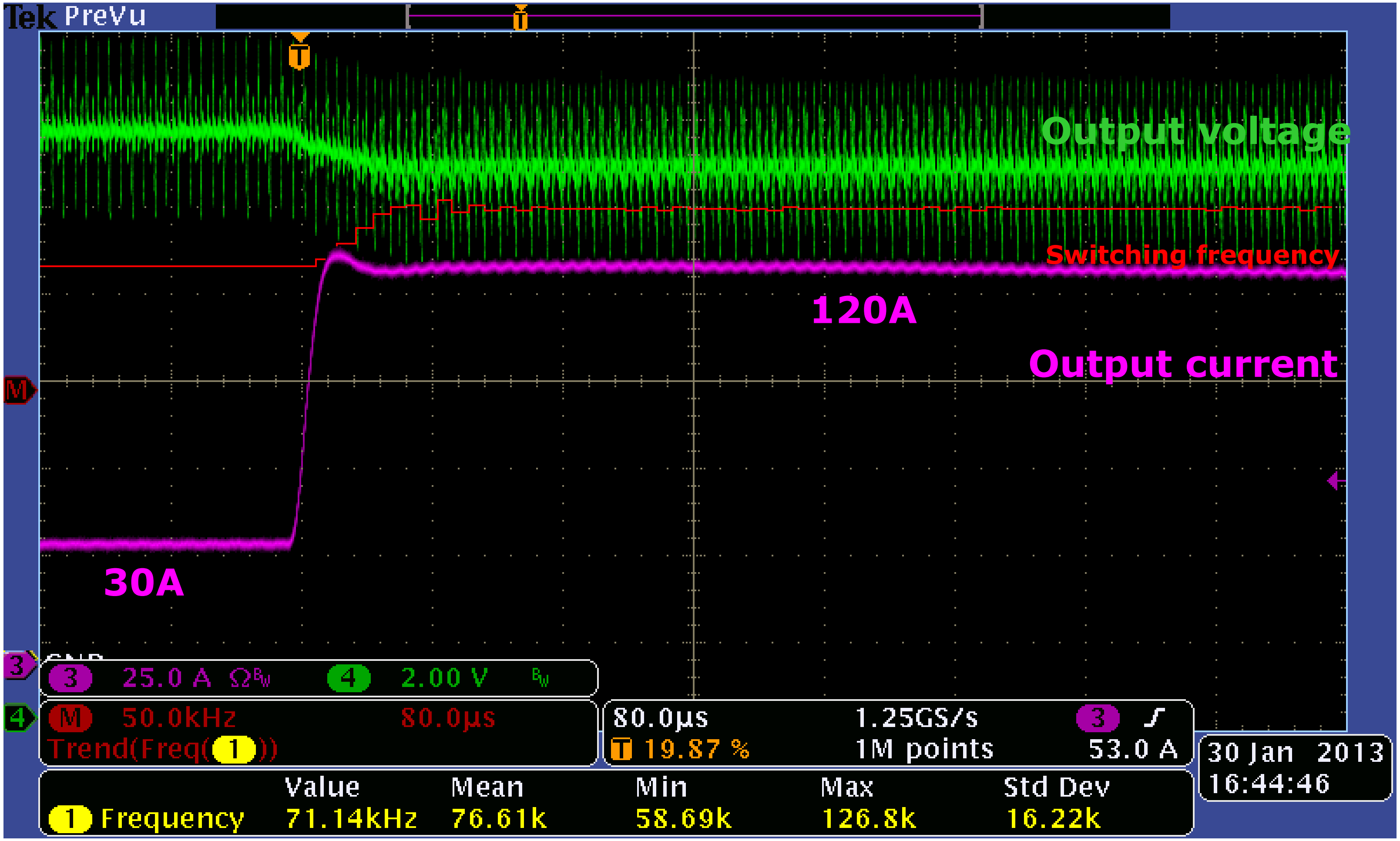
- Efficiency at light load is high, thanks to the low frequency operation of the input bridge;
- High $V_{ce,sat}$ of IGBTs and inductor losses inpact overall system performances;
- At I_{out}=150A, only 1mΩ pcb trace resistance in the secondary side means 23W dissipated and 1,3% efficiency loss.

Start up and Vin transients



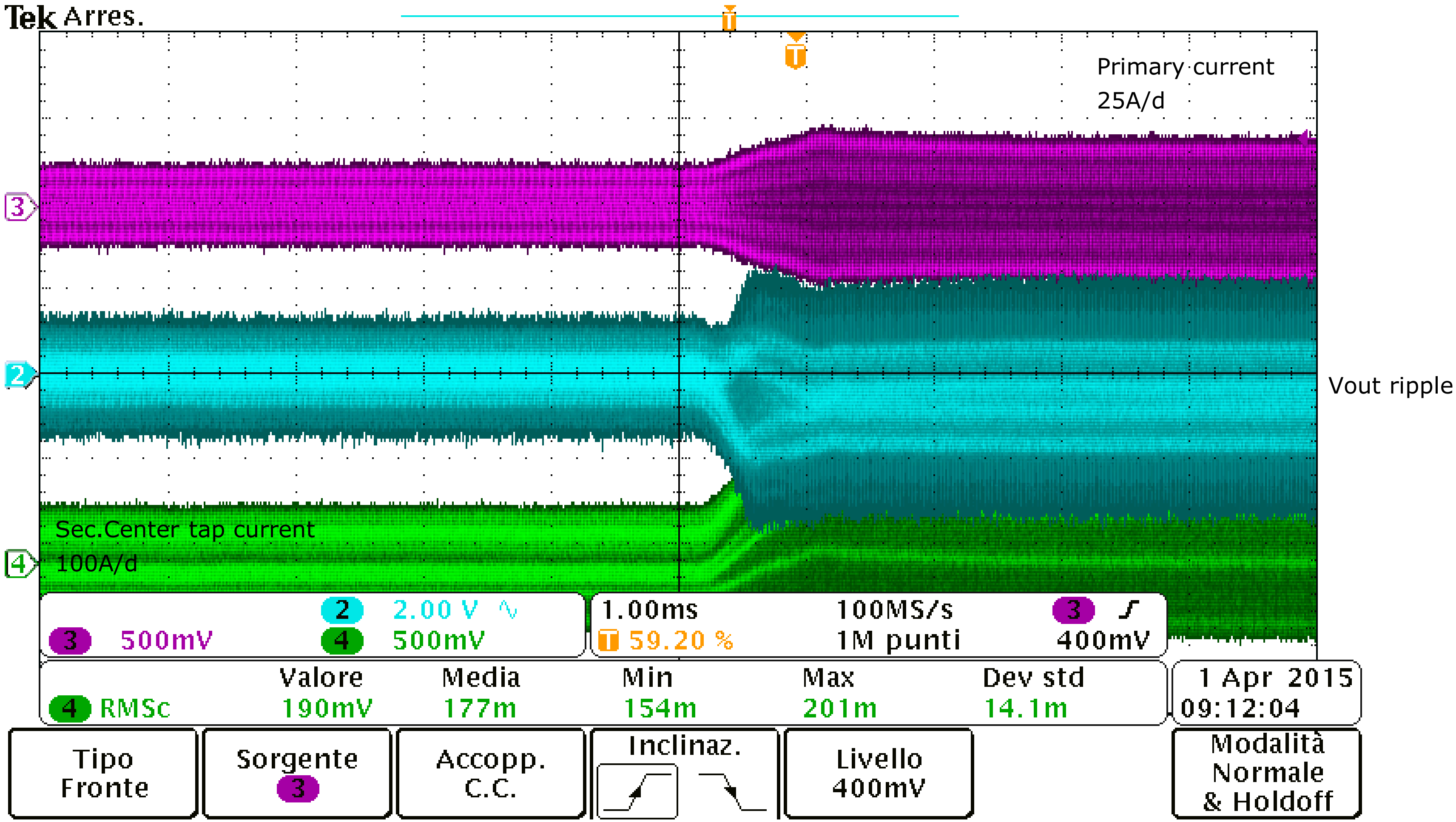
Fast start: Vin rise time is only limited by the Lab power supply
Vin=400V, Io=25A

Experimental results: load transient



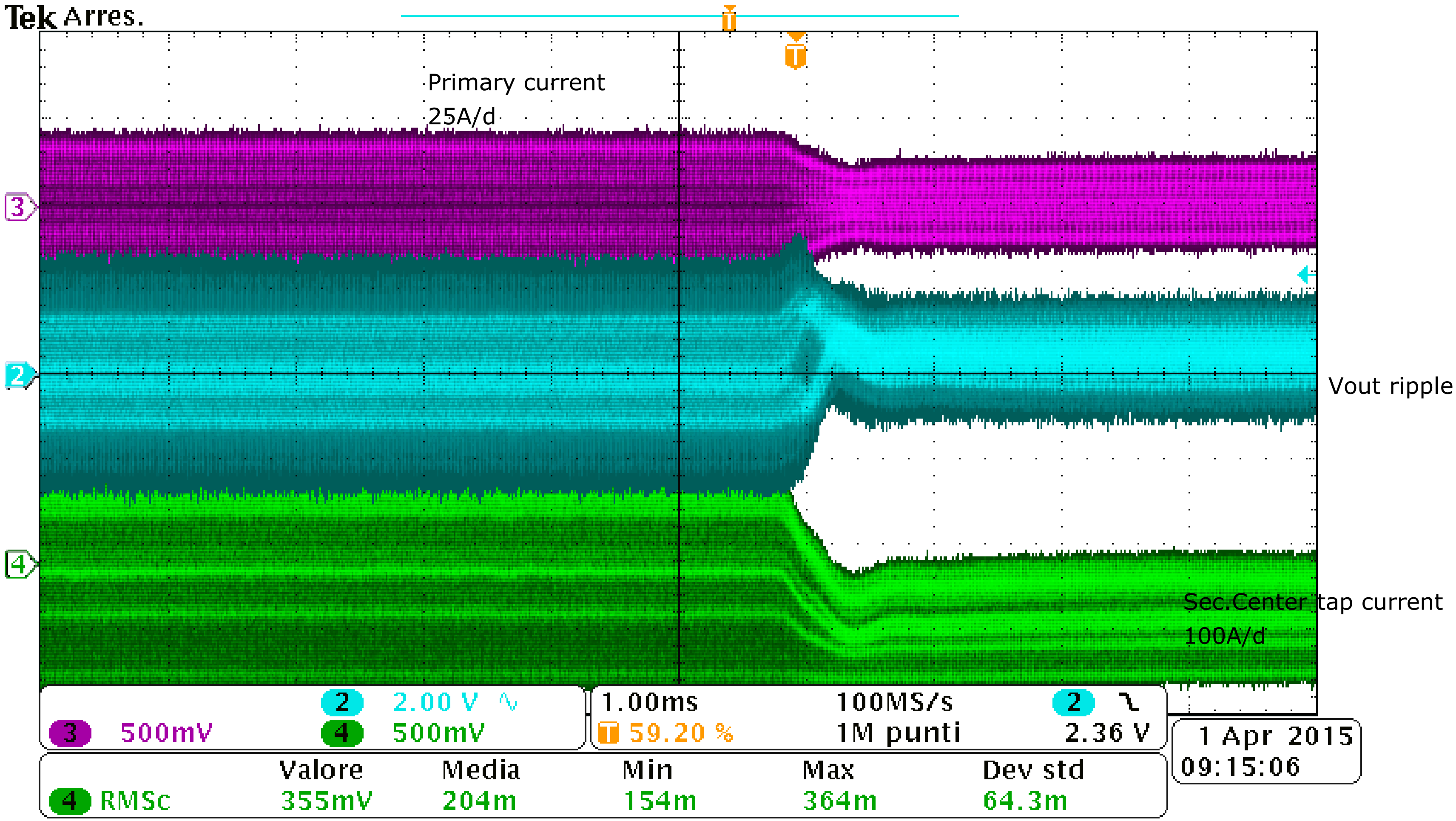
Low ESR output caps provide very low output voltage variation at load transients

Load transients : Iout from 70 to 140A



Load increase to 140A (traces 2 and 3 with AC coupling)

Load transients : Iout from 140 to 70A



Load decrease to 70A (traces 2 and 3 with AC coupling)

Conclusions

1. An Auxiliary DC-DC converter has been designed by using the uncommon LLC ZCS topology
2. System design flow with mathematical and electrical models have been utilized to tune the resonant tank and converter frequency operation range
3. Prototype has been built and verified
4. System efficiency over 90%, limited by high Vce_sat of IGBTs and inductor losses
5. Robustness to load transients has been verified
6. Prototype Max power is limited to around 2.0kW with air forced cooling, because of PCB and heat sinks limitations.
7. Next step: evaluate Super-Junction Mosfets performances in the same topology, adding Ultrafast diodes in parallel.