Thermally aware high-power inverter board for battery-powered applications

Prospero LOMBARDI

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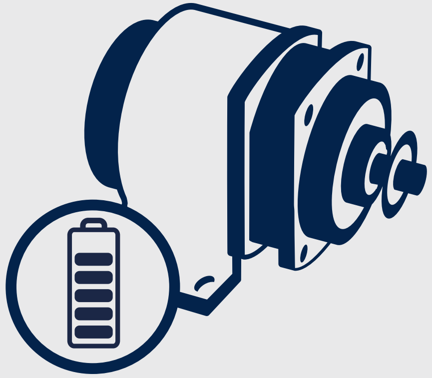
Introduction



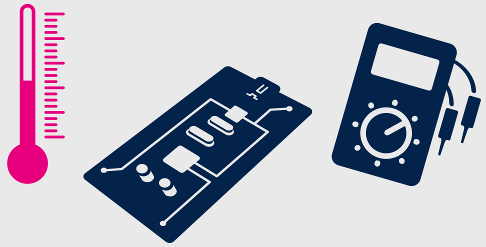
High power at low voltage

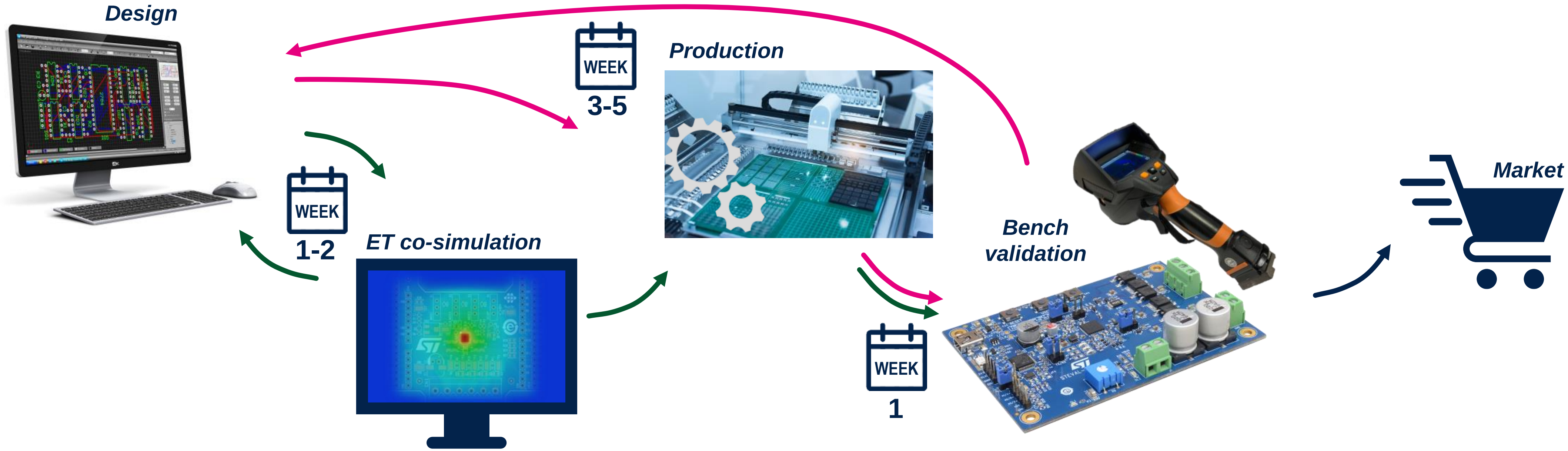
Best efficiency and reliability

Compact form factor

but…

Challenging PCB design





➔ EVALSTDRIVE101 evaluation board optimized by Celsius™ Thermal Solver

We are creators and makers of technology

One of the world's largest semiconductor companies

48,000 employees of which **8,400** in R&D

$12.8 billion revenues in 2021

Over **80** sales & marketing offices serving over **200,000** customers across the globe

14 manufacturing sites

Signatory of the United Nations Global Compact (UNGC)
Member of the Responsible Business Alliance (RBA)

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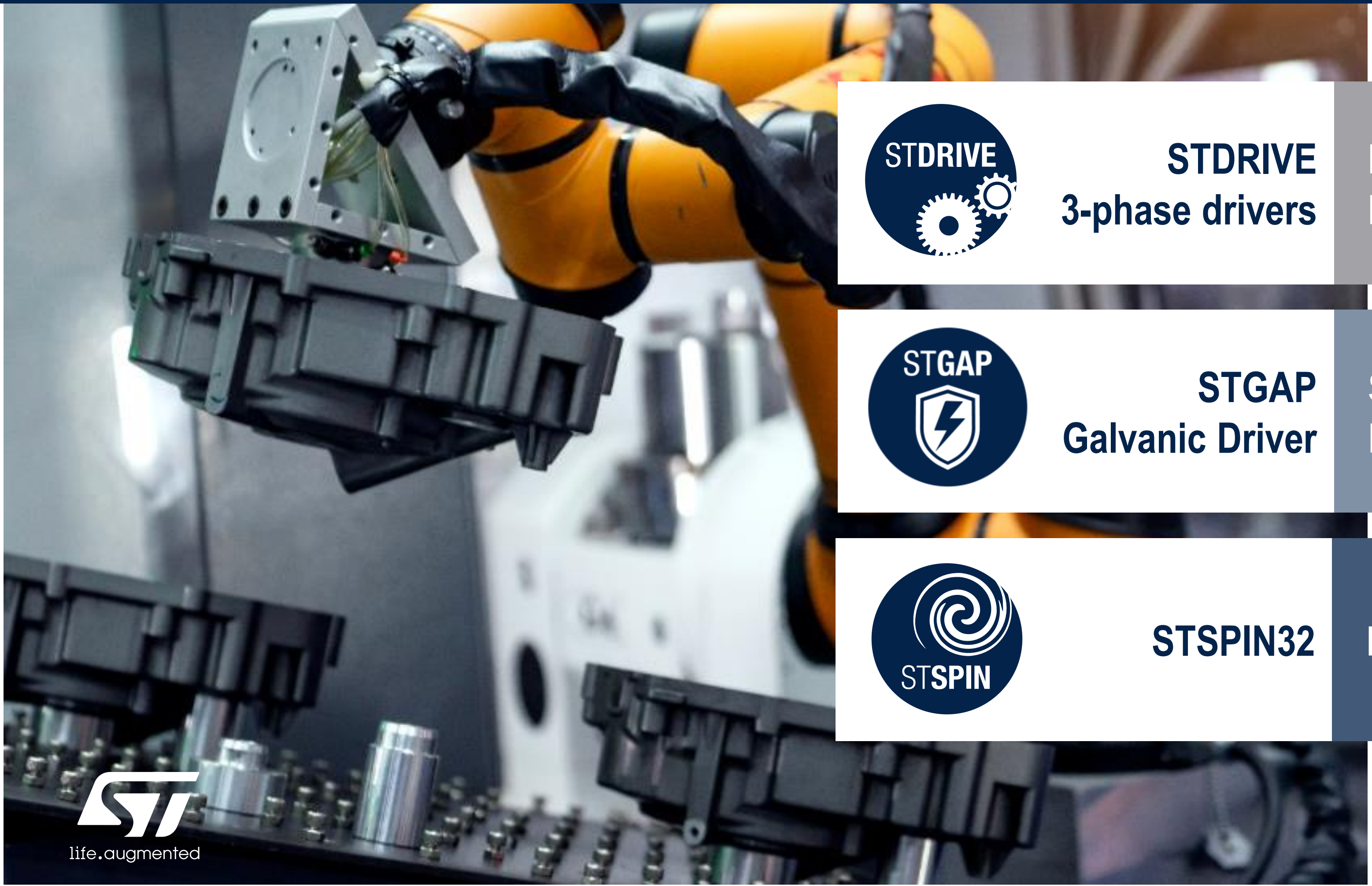
As of December 31, 2021

ST addresses the industrial market with application driven, high added-value ASSPs & ASICs

Motor control leadership areas



STDRIVE 3-phase drivers	Motion 3-phase Low Voltage	Best-in-class motor driving, high efficiency and low consumption
STGAP Galvanic Driver	Safety & High voltage	6 kV galvanic isolated drivers optimized for SiC, GaN & IGBT
STSPIN32	Digital motion	High system integration, Flexibility, performance

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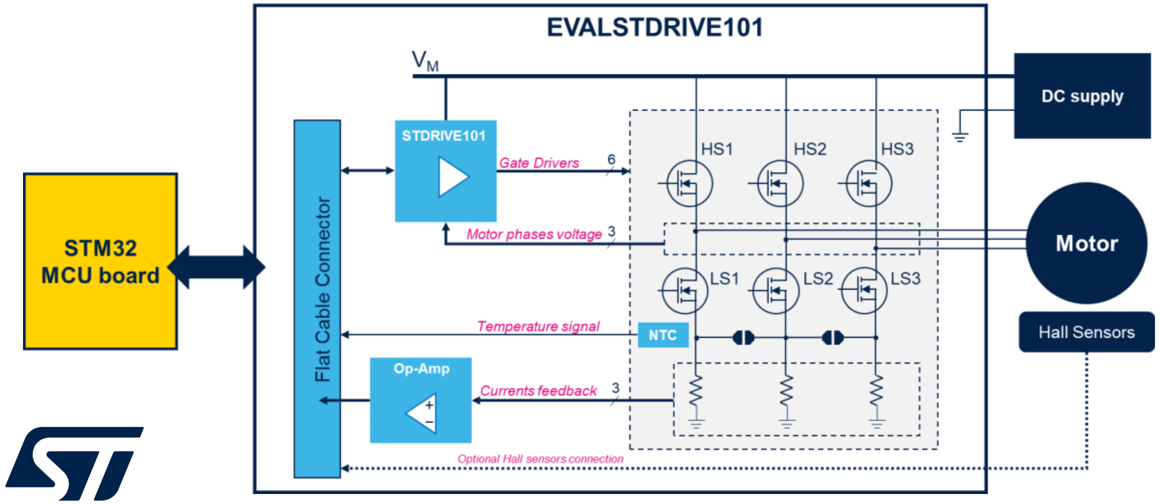
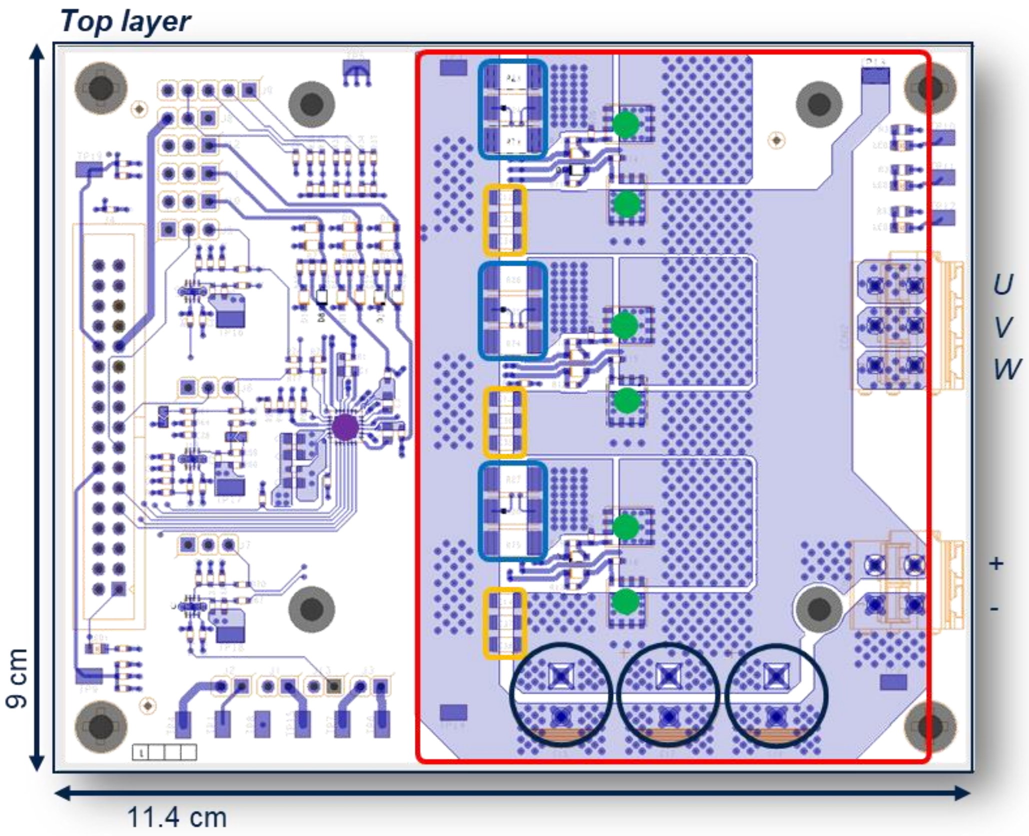
EVALSTDRIVE101

- STDRIVE101 gate driver and STL110N10F7 MOSFETs
- 15A_{rms} output current (20A_{rms} with heatsink) at 75V
- Three or single shunt
- Sensor and sensor less algorithms
- Bus voltage and temperature monitoring
- Overcurrent / short circuit protection
- NUCLEO board interfacing
- Free software libraries



Drive three-phase brushless DC motors
FOC and six-step algorithms

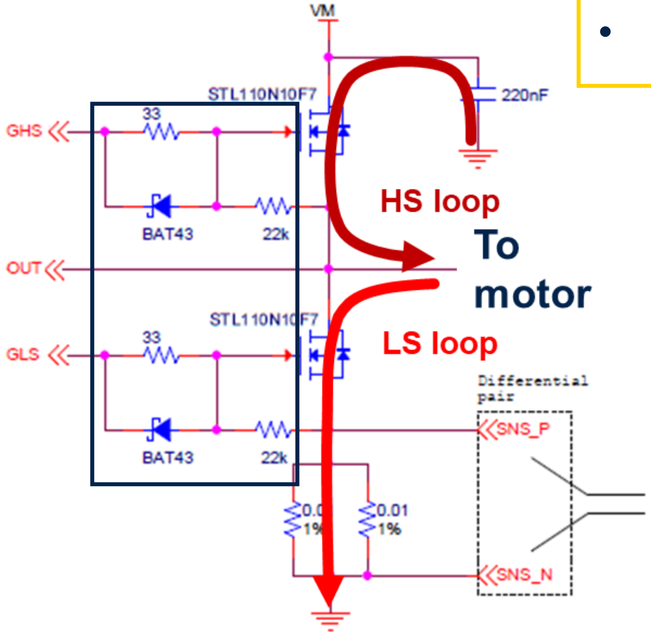
Layout improvements

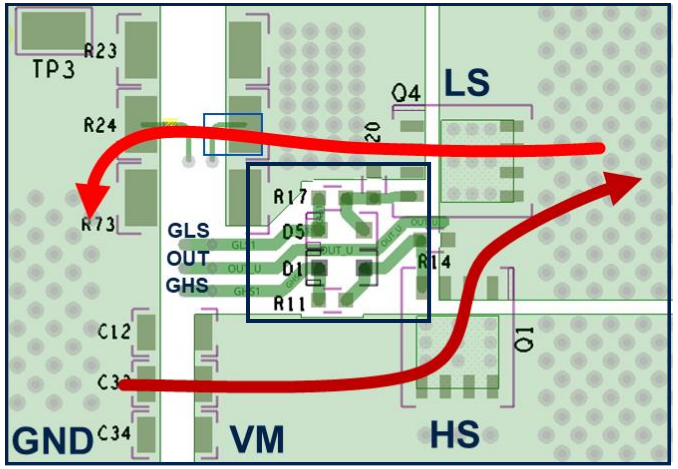


- STDRIVE101
- STL110N10F7
- 50 cm^2 power stage
- Shunt resistors
- Ceramic capacitors
- Electrolytic capacitors

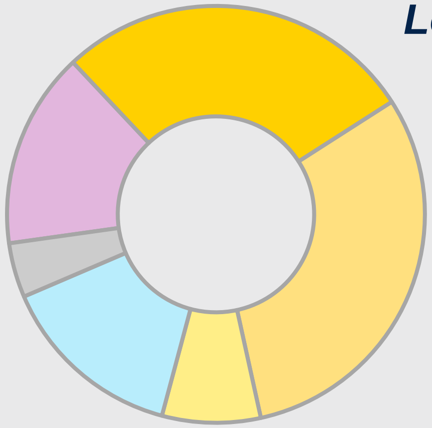
- Better heat spreading
- Max dissipation area
- Dual side cooling

- Reduced current density
- Small loops placement
- Fast switching





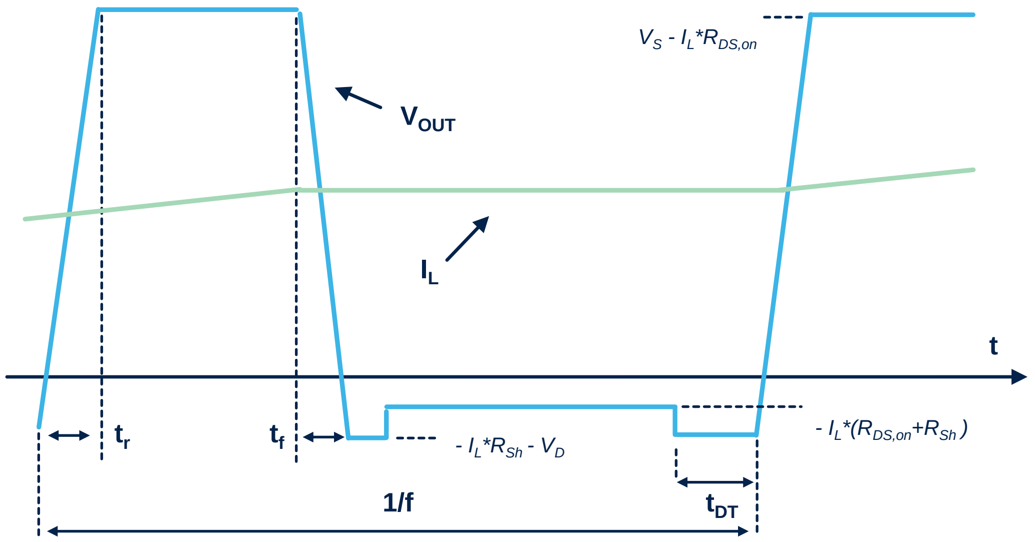
Estimate of power losses



Losses composition

- PCB traces → By Celsius™ from layout data
- MOSFETEs:
  - Conduction
  - Switching
  - Body diode
- Shunt resistors
- Others

(Conduction, Switching, Body diode, Shunt resistors:) By formulae with datasheet parameters



551 mW

$$P_{cond} \sim \frac{R_{on} \cdot I_l^2 \cdot (1-2 \cdot t_{dt} \cdot f)}{2}$$

602 mW

$$P_{sw} \sim \frac{f \cdot V_s \cdot I_l \cdot \left(\frac{Q_p \cdot R_g}{V_{gd}-V_p} + \frac{Q_p}{I_{gd}} + R_g \cdot C_{iss} \cdot ln\left(\frac{V_{gd}-V_{th}}{V_{gd}-V_p}\right) + \frac{C_{iss} \cdot (V_p - V_{th})}{I_{gd}} \right)}{4}$$

150 mW

$$P_{dt} \sim V_d \cdot I_l \cdot t_{dt} \cdot f$$

281 mW

$$P_{sh} = \frac{R_{sh} \cdot I_l^2}{2}$$

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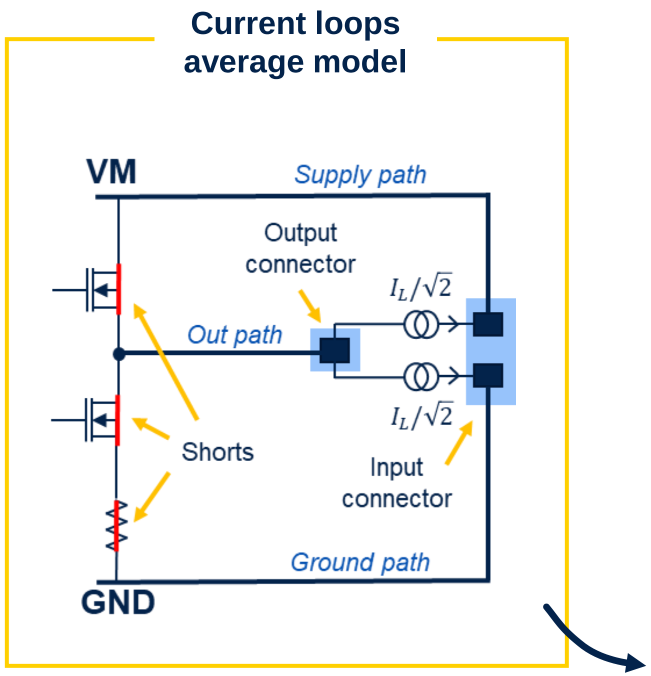
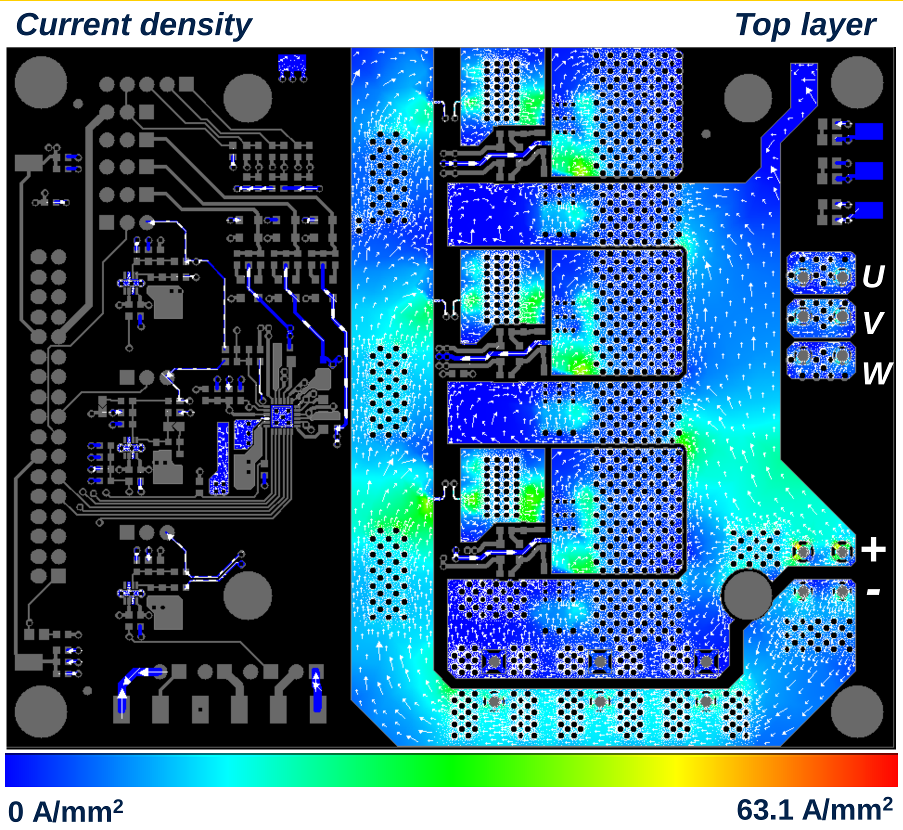
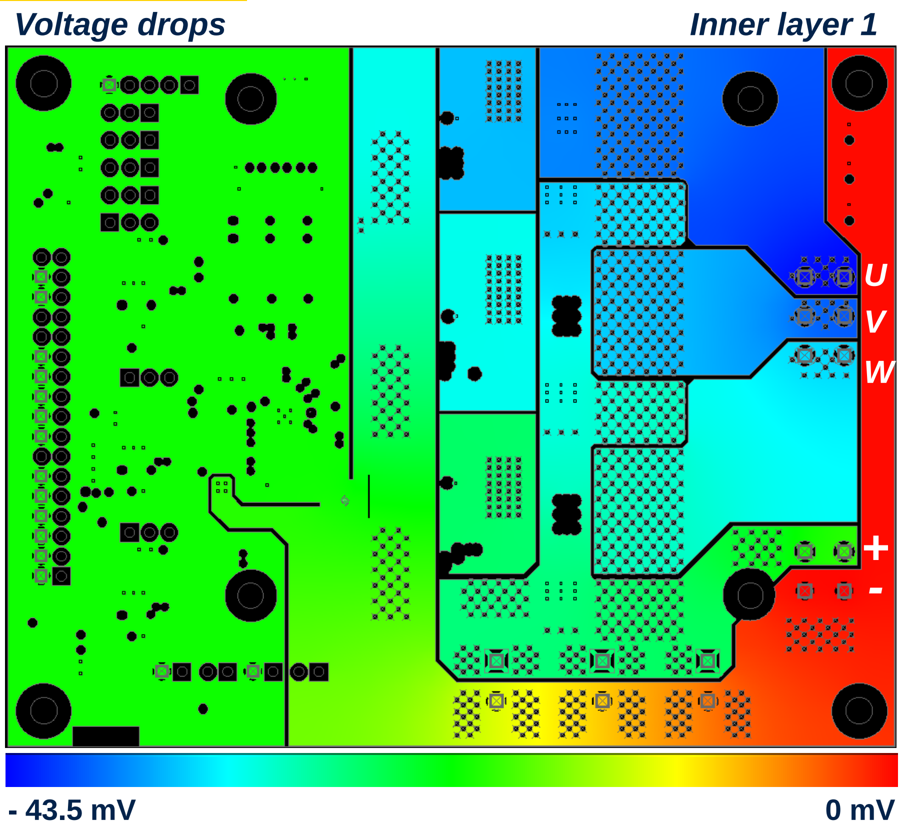
Celsius simulation

Electrical analysis @ 15 A_{rms}



Only effects on traces





- Current density below 25 A/mm2
- Hotspots not of concern
- No bottleneck and balanced outputs

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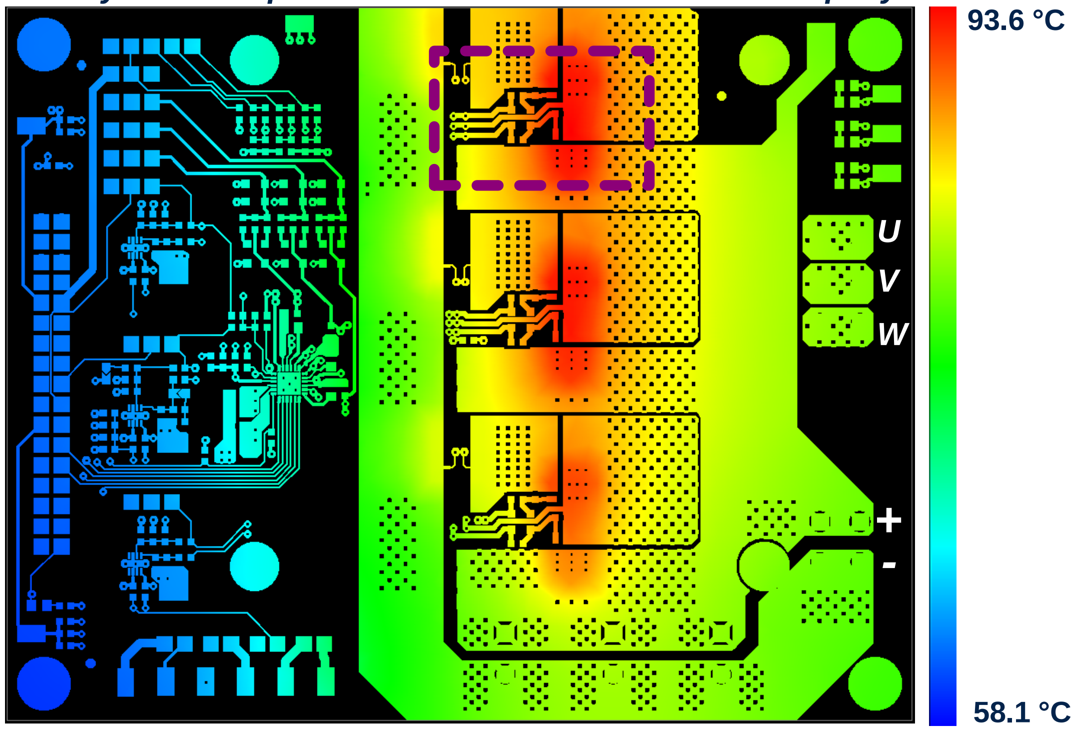
Celsius simulation

Thermal analysis @ 15 A_{rms}

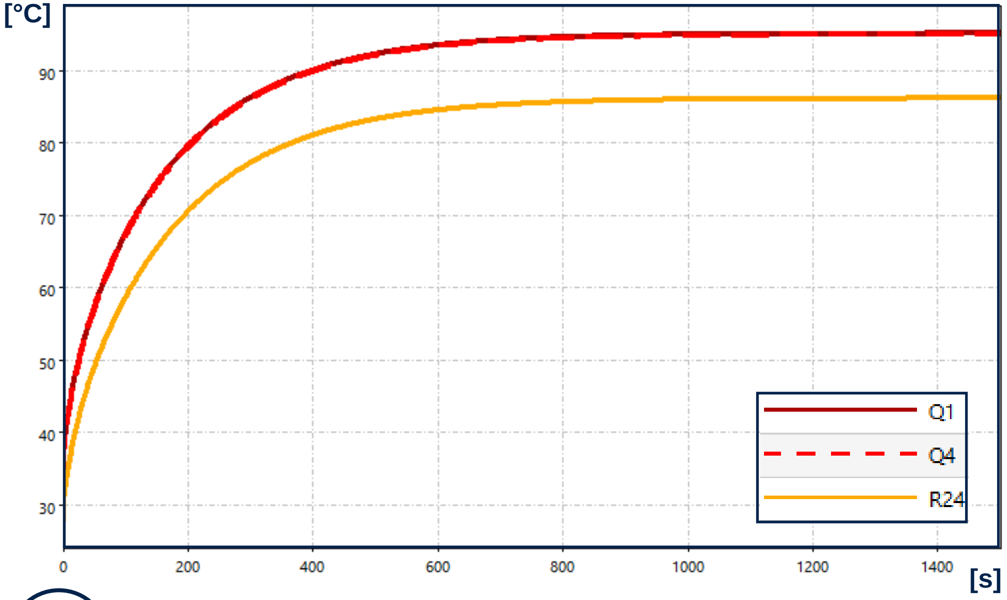
Settings

- 28 °C ambient temperature
- Fixed heat transfer coefficients
- 2-R model for MOSFETs
- Step functions for sources

Steady state temperatures ***Top layer***



Transient temperatures



- Hottest U half bridge
- MOSFETs at 95 °C and shunts at 86 °C
- 13 minutes warm up
- 5 °C delta - top vs bottom

Very good design margin

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Bench validation

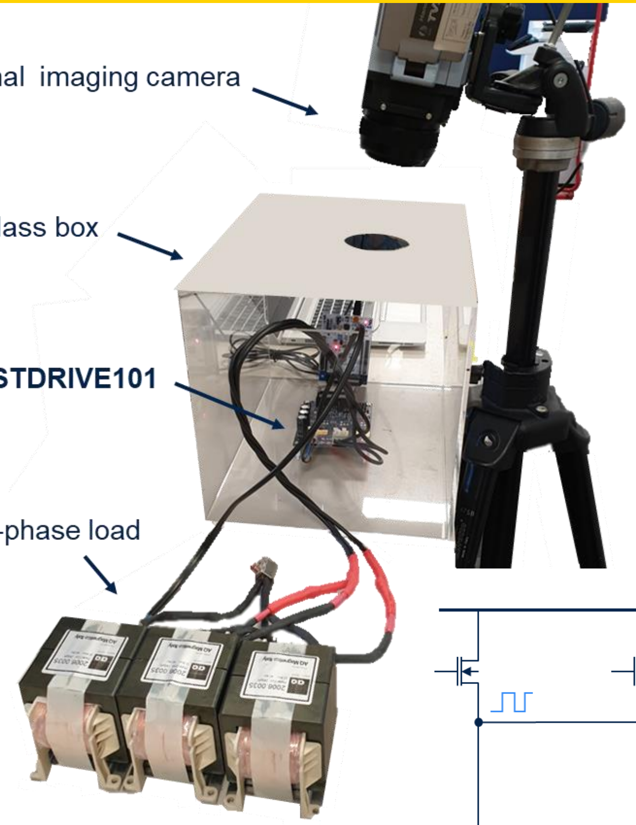
Setup description

Thermal imaging camera

Plexiglass box

EVALSTDRIVE101

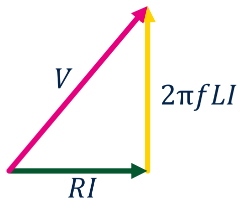
Three-phase load

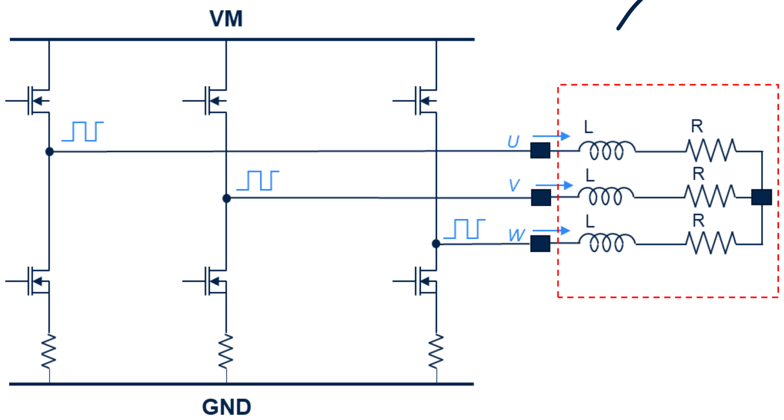


Equivalent to motor

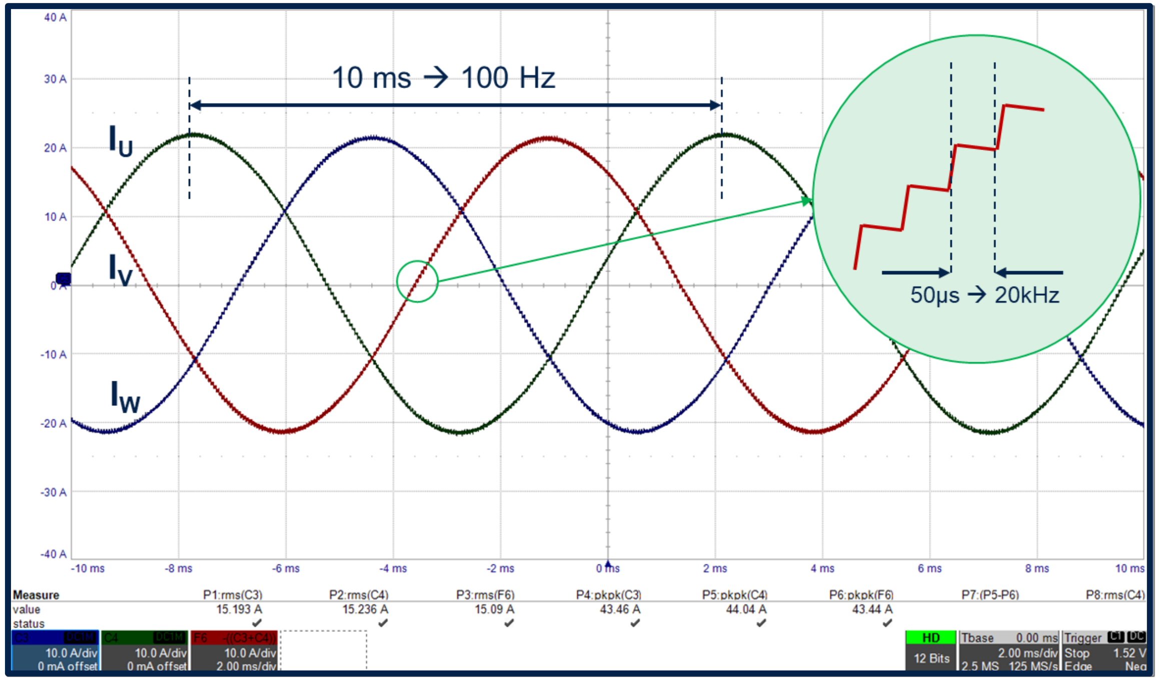
V - I drops

$$I = \frac{V}{\sqrt{(2\pi f L)^2 + R^2}}$$





Configurable sinusoidal currents



- Power stage as in application
- Easier to implement
- Fast tuning

Bench validation

Power losses measurement

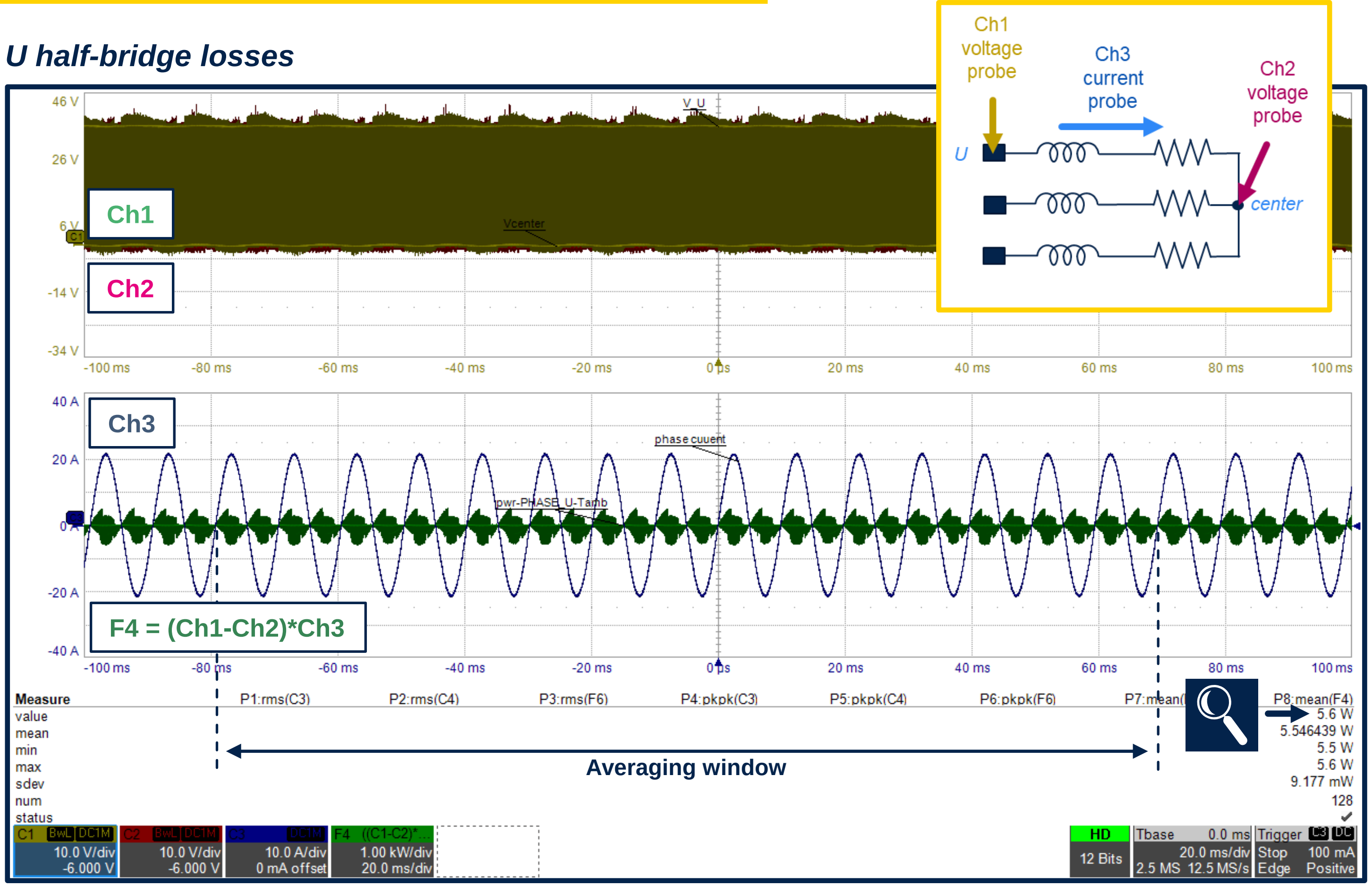
Correlate estimated data with real losses

By oscilloscope

$$P_{loss} = P_{in} - P_{out} = \overline{V_{in} \cdot I_{in}} - \sum_{i=1}^{3} \overline{(V_i - V_c) \cdot I_i}$$

Power	Estimate [W]	Measure @ T_{amb} [W]	Measure @ T_{hot} [W]
P_{in}	-	27.51	28.39
P_{out}^{U}	-	5.6	5.7
P_{out}^{V}	-	6.5	6.6
P_{out}^{W}	-	6.1	6.2
P_{loss}	9.5	9.36	9.89

U half-bridge losses



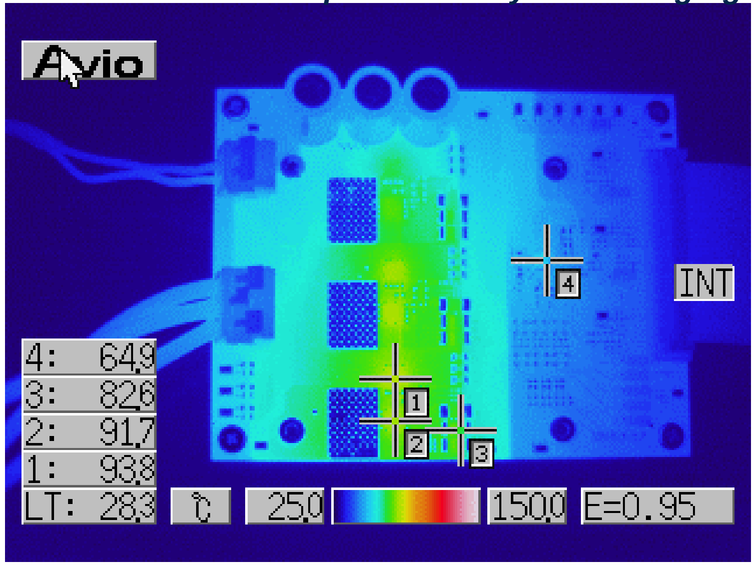
- Spread hot vs ambient
- Slight load unbalancing
- Estimate in line with measures

Bench validation

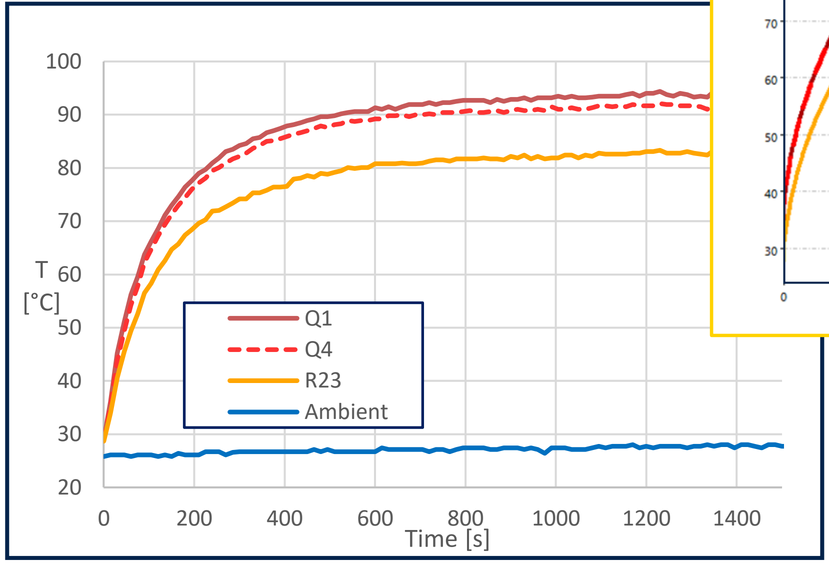
Thermal characterization

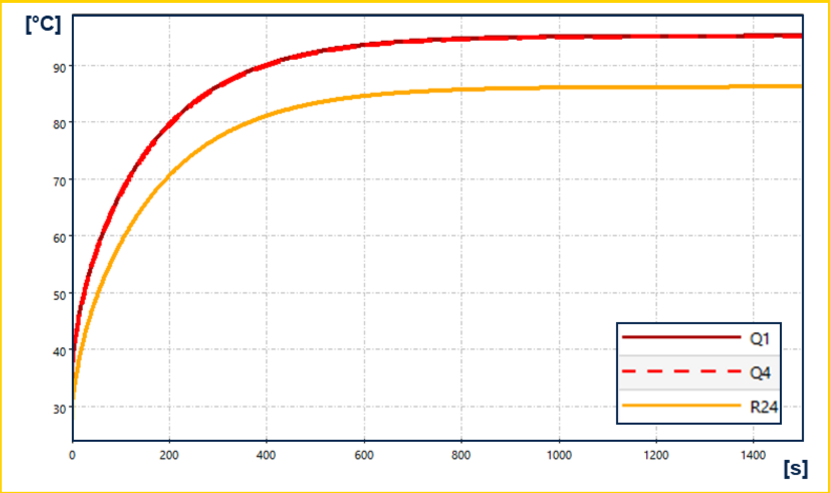
Correlate simulations with real heating

Top side steady state imaging



Half-bridge U components warm up





Simulated transient temperatures

Component	Simulation [°C]	Measure [°C]
HS MOSFET Q1	95.1	93.8
LS MOSEFT Q4	94.9	91.7
Shunt resistor R23	86.3	82.6

- Confirmed hottest half bridge
- Same transient
- Very good temperatures matching

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Conclusions

EVALSTDRIVE101 optimized by Celsius™

High power & low voltage BLDC motors
Battery-powered applications

- Fine tuned layout
- Detailed voltage drops and current density
- Foreseen temperature profile and hotspots
- Certified performance by thermal imaging

Find more on:
https://www.st.com/resource/en/technical_article/ta0361-thermally-aware-highpower-inverter-board-for-batterypowered-applications--stmicroelectronics.pdf
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STDRIVE

STDRIVE101

75 V 3-phase low voltage brushless gate driver

Compactness

- Compact design with 4x4mm QFN
- Integrated bootstrap diodes

Robustness

- VDS monitoring for each Power MOSFET
- Fully protected (UVLO, OCP, Thermal shutdown)
- nFAULT open-drain for fault signaling

Performance

- Operating Voltage: 5.5 V to 75 V
- I = 600 mA sink/source driving capability
- 12 V LDO embedded
- Two Flexible inputs driving: Enable / Input with adjustable dead-time generation or Direct driving with interlocking
- Very short 70 ns propagation delay / 20 ns phases matching
- Standby mode for low consumption

VFQFPN4x4 24 leads

Key applications

- Power tools
- E-bike
- Drones, Robotics
- Home appliance, Air purifiers
- Fans

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