Thermal considerations in integrated MOSFET drivers

TI Precision Labs – Motor Drivers

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Overview

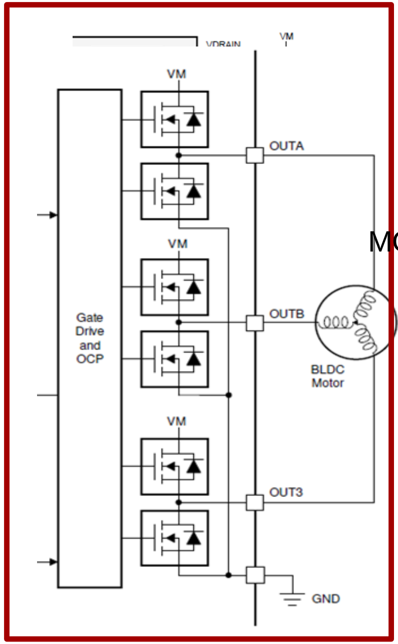
- Integrated MOSFET drivers vs gate drivers
- Importance of thermals in motor driver systems
- Relationship between power and thermals
- RMS current vs peak current
- Final junction temperature
- Major sources of power loss
- Applying total power loss to thermal calculation
- Major mechanisms of thermal dissipation
  - Ways to improve thermal dissipation
- Estimating thermal performance
  - Example calculation

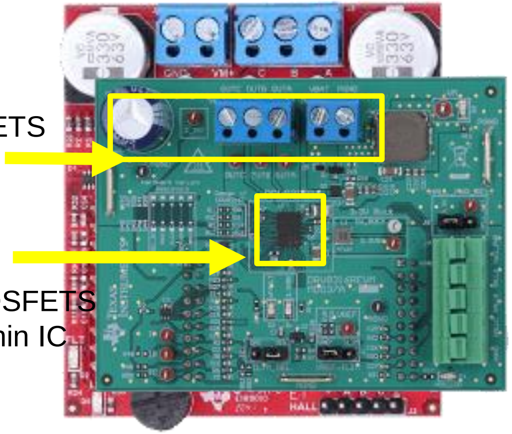
Gate driver vs. integrated MOSFET drivers

- **Gate driver:** MOSFETs placed outside the package
- **Integrated driver:** MOSFETS placed within the IC

Advantages
- Less expensive
- Smaller board space

Disadvantages
- More thermal considerations
- Limited power capability



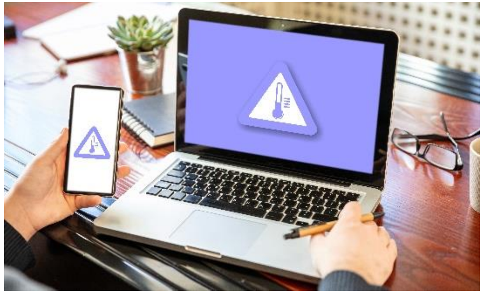


Integrated MOSFETs / Gate Driver

Importance of thermals

User-experience

- High-heat accumulation affects usability
- Heat leads to discomfort



Device reliability

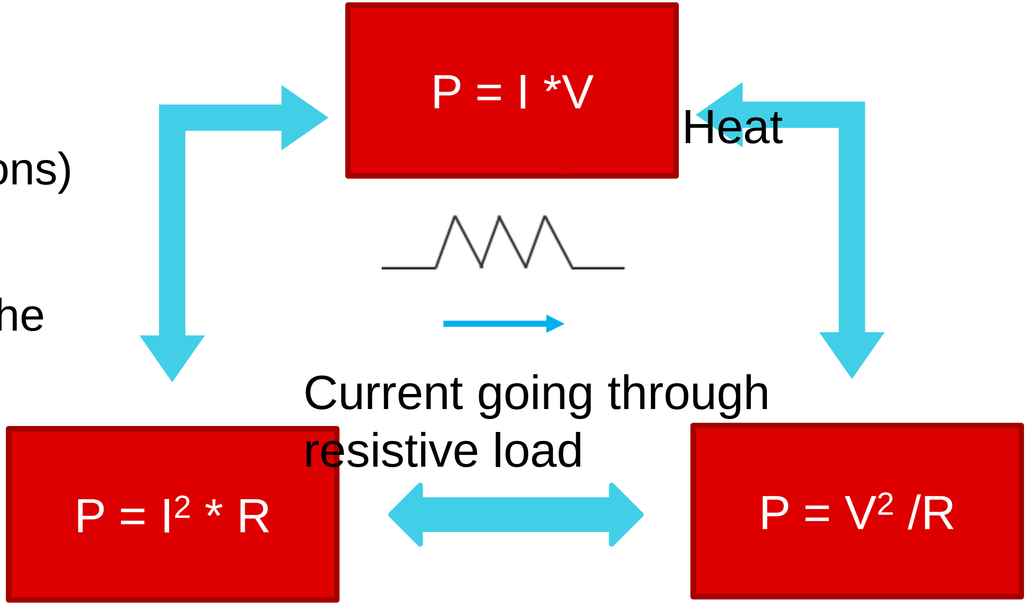
- Hot device operation leads to accelerated wear and tear
- Heat leads to inconsistent performance

Power efficiency

- Decrease in battery life
- Increased electrical expense due to energy loss

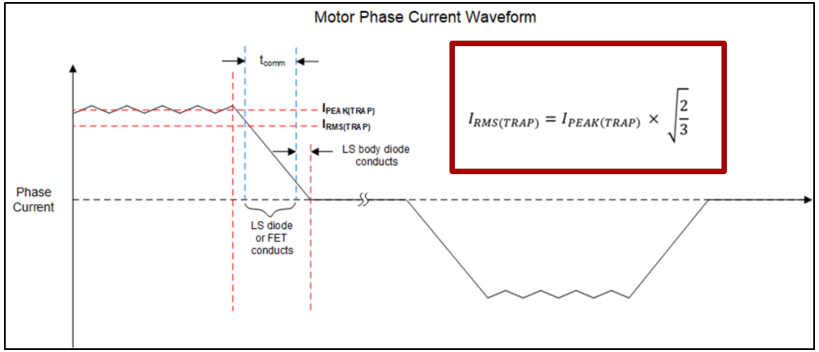
Introduction to power

- Power = energy/time
- Power losses release energy which generates heat (thermal considerations)
- Heat results in thermal issues
- Power loss depends on features of the device, commutation mode, physical characteristics etc.
- Energy rate depends on electrical signals from current and voltage



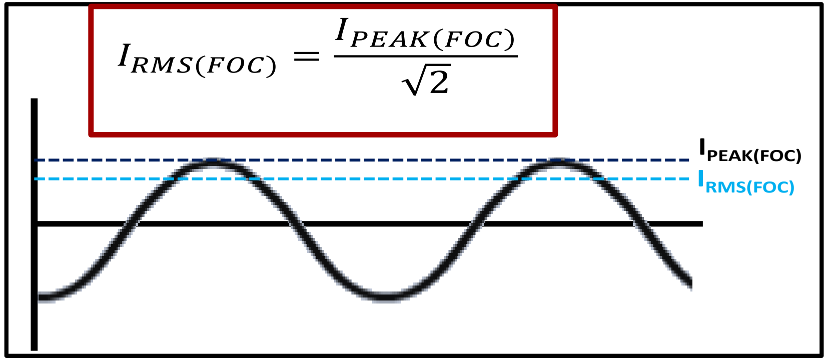
I_{RMS} calculation from I_{PEAK} for trapezoidal vs FOC

- Current is constantly changing in a motor driver application, so we use RMS current to approximate this in power calculations
- RMS current is dependent upon commutation type (trap, sine, FOC)



$$I_{RMS(TRAP)} = I_{PEAK(TRAP)} \times \sqrt{\frac{2}{3}}$$

Trapezoidal

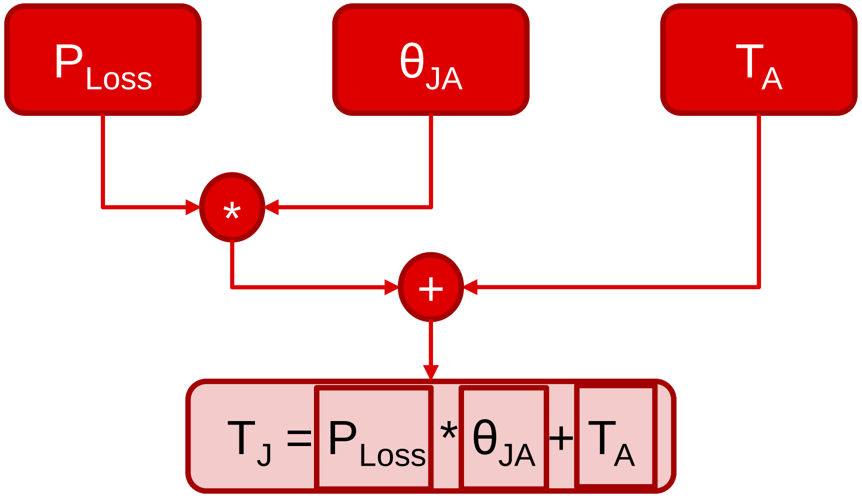


$$I_{RMS(FOC)} = \frac{I_{PEAK(FOC)}}{\sqrt{2}}$$

FOC

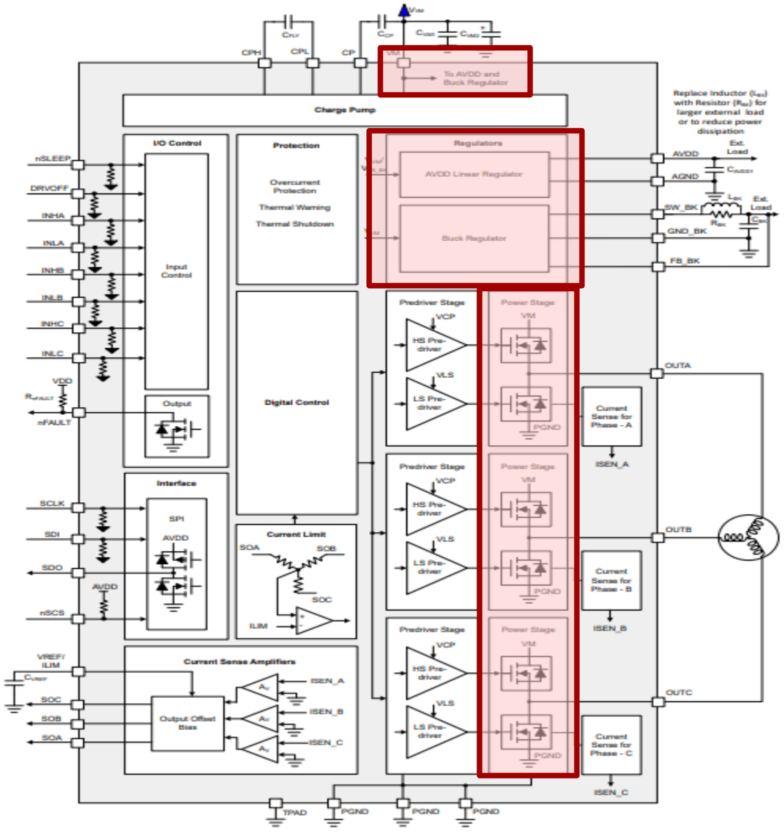
Factors determining the final junction temperature

Variable	Units	Explanation
Power loss	W	The total combined power loss of all components inside the driver and on the PCB
θ_{JA}	°C/W	Junction to air thermal resistance
Ambient temperature	°C	Average temperature of the environment where the device is being used



Power loss sources

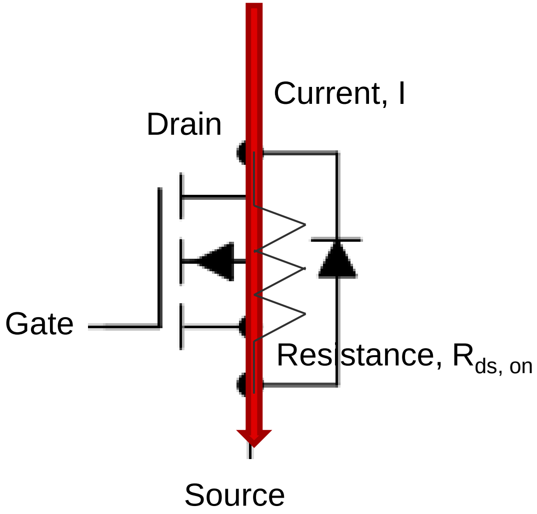
- In a motor driver application, some power losses you may encounter are:
  - MOSFET losses
    - Conduction
    - Switching
    - Diode
      - Active demagnetization
  - Other losses
    - Integrated regulator (LDOs and Bucks)
    - Standby



Conduction losses

- MOSFET losses when the current is conducting from drain to source through the MOSFET's on state resistance, $R_{ds, on}$

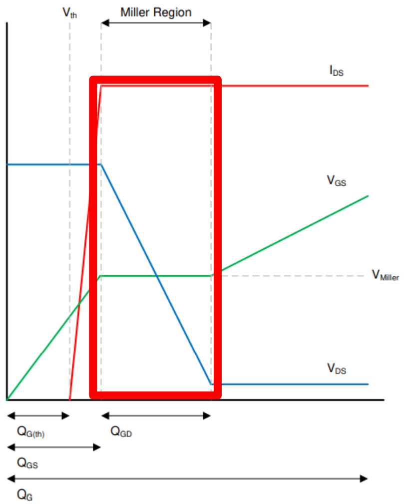
Commutation Type	Equation
Trapezoidal	$P_{CON} = 2 * (I_{PK(trap)})^2 * R_{ds, on(TA)*}$
FOC	$P_{CON} = 3 * (I_{RMS(FOC)})^2 * R_{ds, on(TA)}$



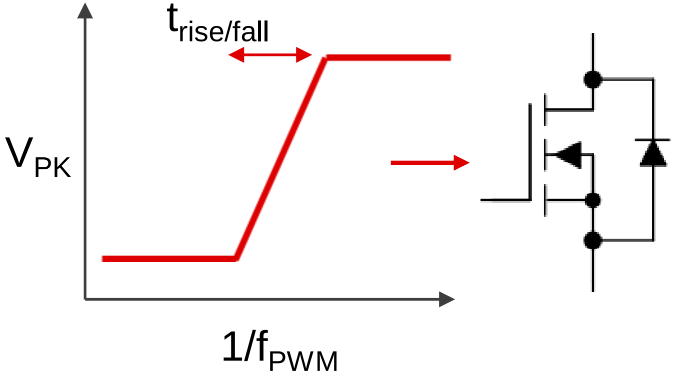
*TA: ambient temperature

Switching losses

- The loss associated with MOSFET turn on and turn off slew rate.
- Switching losses are affected by the PWM frequency.



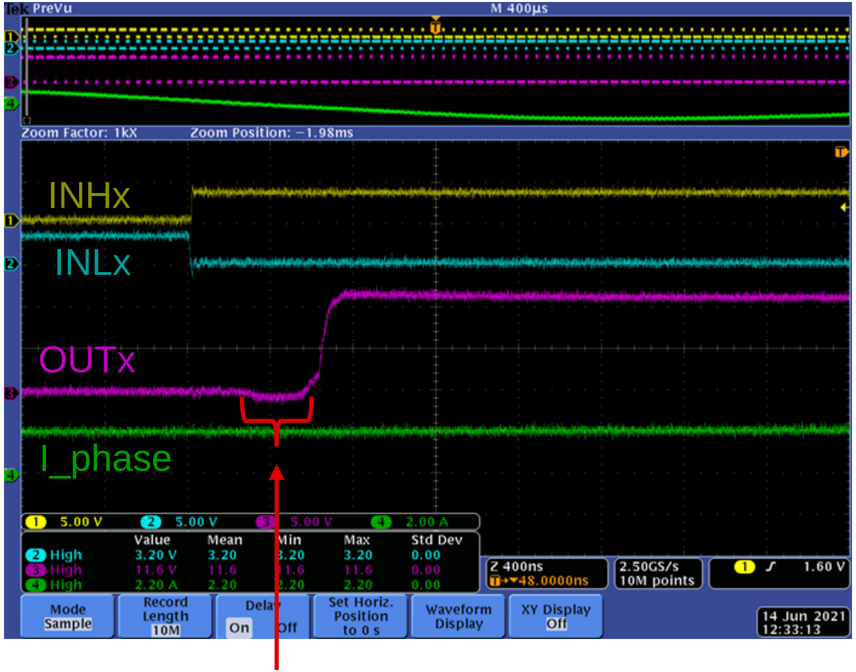
Commutation Type	Equation
Trapezoidal	$P_{SW} = I_{PK(trap)} * V_{PK(trap)} * t_{rise/fall} * f_{PWM}$
FOC	$P_{Sw} = 3 * I_{RMS(FOC)} * V_{PK(FOC)} * t_{rise/fall} * f_{PWM}$



Body diode losses

- The power loss happening across the body diode of the MOSFET.
- Typically occurring during coasting and deadtime

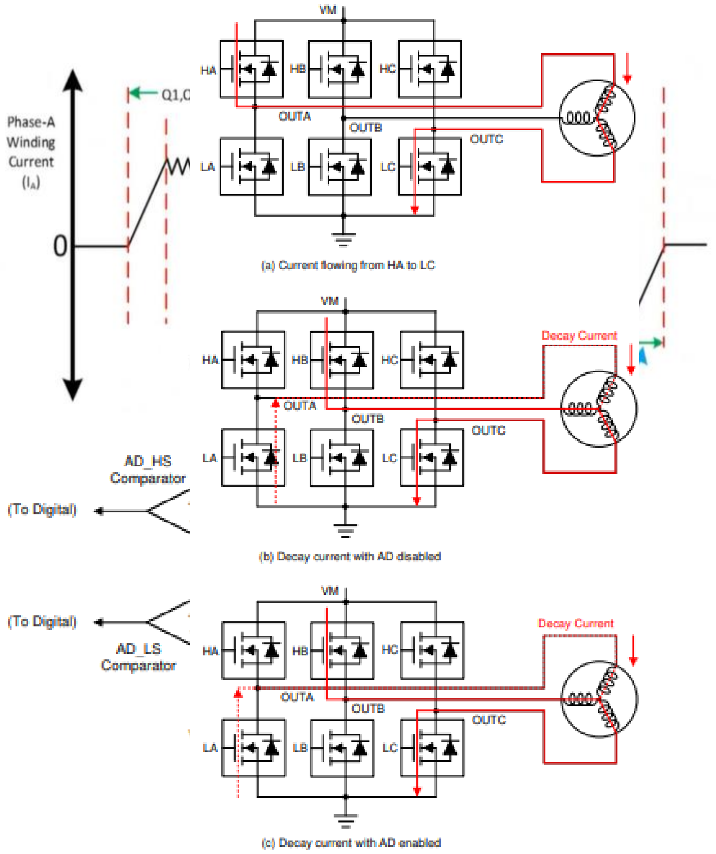
Commutation Type	Equation
Trapezoidal	$P_{diode} = 2 * I_{PK(trap)} * V_{F(diode)} * t_{DEADTIME} * f_{PWM}$
FOC	$P_{diode} = 6 * I_{RMS(FOC)} * V_{F(diode)} * t_{DEADTIME} * f_{PWM}$



$t_{DEADTIME}$

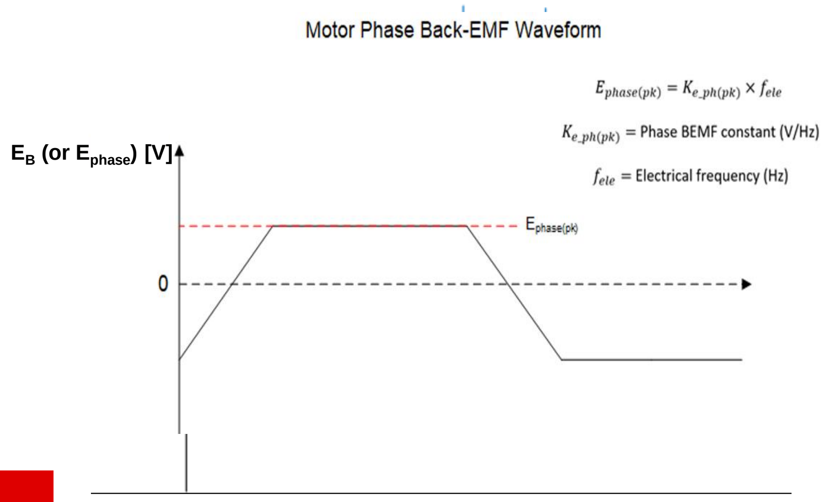
Active demagnetization

- This is a special consideration for trapezoidal commutation
- The benefit of this technique is to reduce diode losses by redirecting the current through the active channel of the MOSFET instead of the diode



Active demagnetization equations

Feature	Equation
Enabled	$P_{FET} = 6 * (\frac{1}{3}) * (I_{PK(trap)})^2 * R_{ds,\ on(TA)} * t_{comm} * f_{ele}$
Disabled	$P_{diode} = 6 * 0.5 * I_{PK(trap)} * V_{F(diode)} * f_{ele} * t_{comm}$



Motor	Equation
Back - EMF	$E_B = K_e * f_{ele}$
Wye	$t_{comm} = I_{PK(trap)} * 3 * L_{motor} / (VM + (2 * E_B))$
Delta	$t_{comm} = I_{PK(trap)} * L_{motor} / (VM + E_B)$

*Note:

- K_e = motor Back – EMF constant (D/S)
- F_{ele} = motor electrical frequency (D/S)
- L_{motor} = motor inductance (D/S)

Integrated regulators

Linear-dropout regulator (LDO)

- Lower efficiency
- Low current output capability

Buck regulator

- Higher efficiency
- Higher current output capability

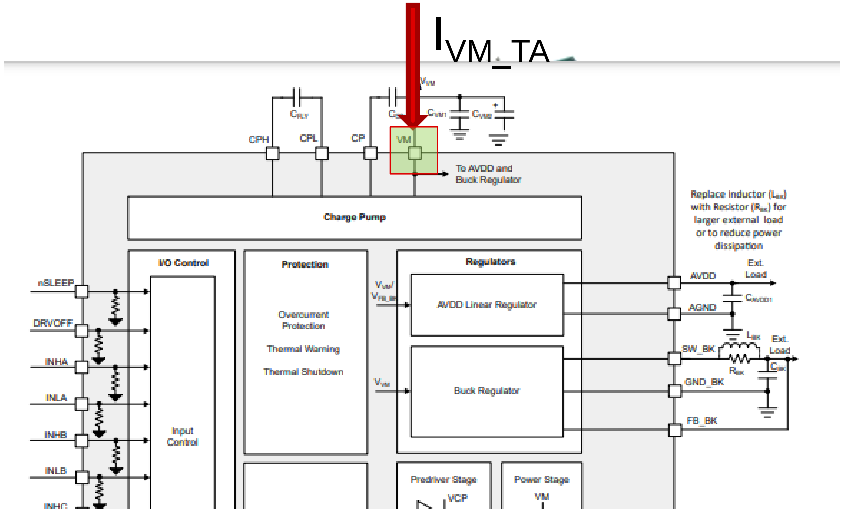
Loss Type	Equation
LDO*	P_{LDO} = (VM - V_{AVDD}) * I_{AVDD}, if power sequencing = off P_{LDO} = (V_{BK} - V_{AVDD}) * I_{AVDD}, if power sequencing = on
Buck	P_{BK} = 0.1 * VBK * IBK (assuming η_{BK} = 90%)

*certain devices offer a feature called power sequencing in which the LDO input volt comes from VBK rather than VM to decrease the power losses

Standby power loss

- Power consumed by the device in IDLE mode

Loss Type	Equation
Standby Power	$P_{Standby} = VM * I_{VM\_TA}$



Applying power loss to thermal calculation

- Combine total power loss of the system within the integrated MOSFET driver package
- Reference the θ_{JA} of the driver package in the thermal equation to calculate the final junction temperature

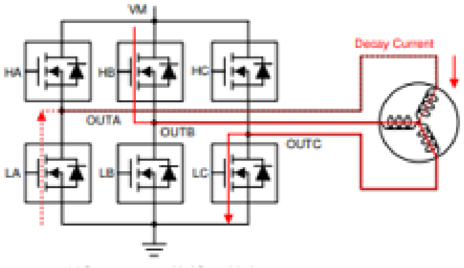
$$T_J[°C] = P_{Loss}[W] * \theta_{JA}[°C/W] + T_A[°C]$$

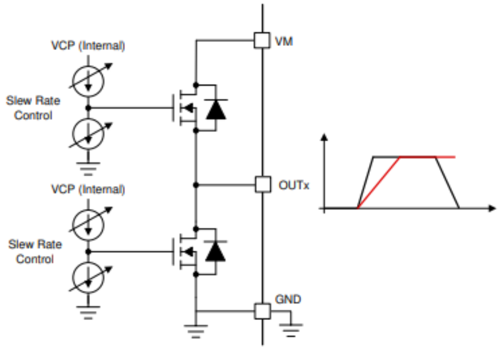
Loss Type	Equation
Total power loss	$P_{Loss} = P_{CON} + P_{SW} + P_{diode} + P_{LDO} + P_{BK} + P_{Standby}$

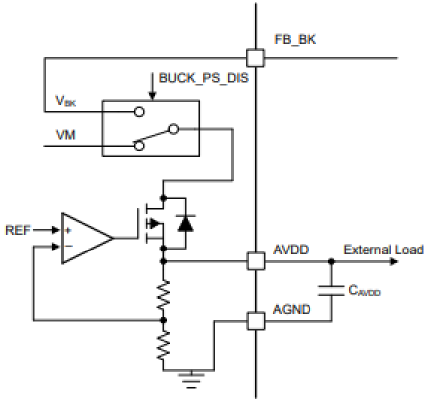
Improving thermal performance

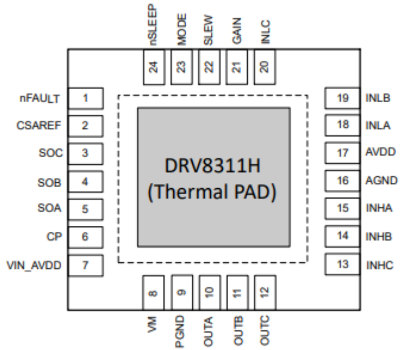
Using device features

- Active demagnetization
- Slew rate control
- Power sequencing
- Thermal pad





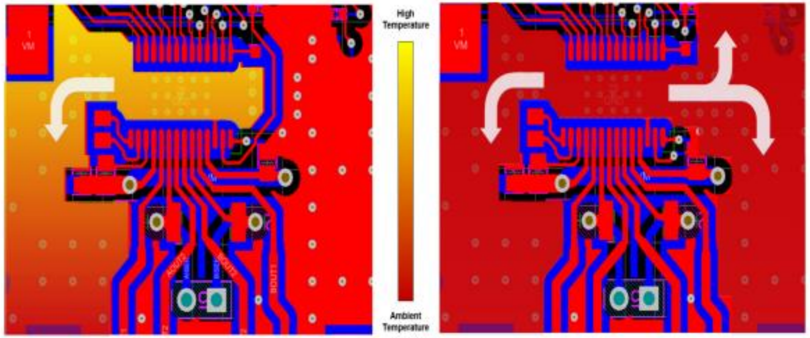


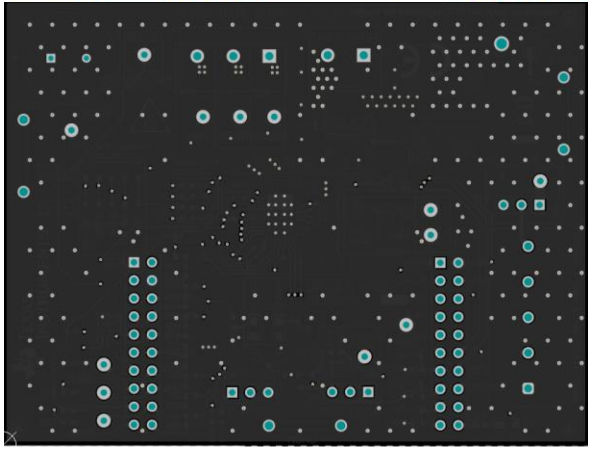


Improving thermal performance

Improving layout

- Wide copper pours
- Stitching vias

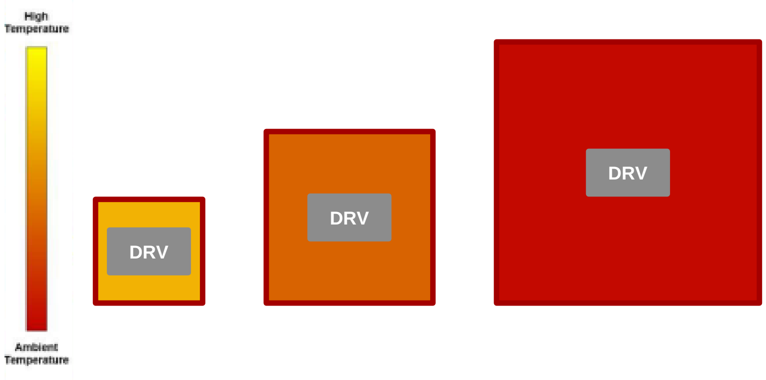


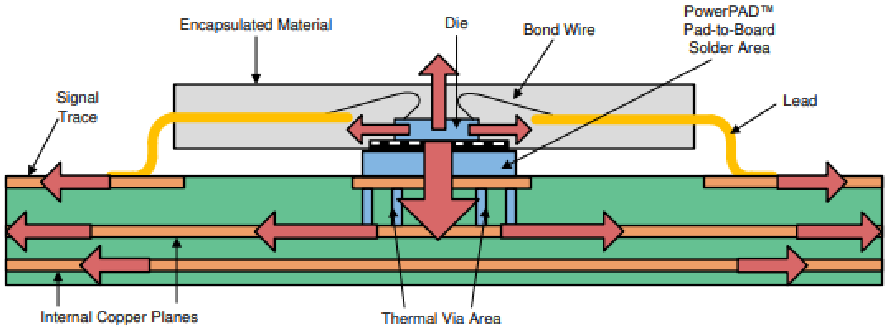


Improving thermal performance

PCB specifications

- More layers
- Thicker layers
- Larger board area





er Name	Type	Material	Thickness (mil)	Dielectric Material	Dielectric Constant	Pullback (mil)	Orientation	Cover Expan
Overlay	Overlay							
Solder	Solder Mask/...	Surface Mat...	0.4	Solder Resist	3.5			0
Layer	Signal	Copper	4.2				Top	
ectric1	Dielectric	Prepreg	8	FR-4	4.2			
und	Signal	Copper	1.4				Not Allowed	
ectric 2	Dielectric	Core	40	FR-4	4.2			
er	Signal	Copper	1.4				Not Allowed	
ectric 3	Dielectric	Prepreg	8	FR-4	4.2			
tom Layer	Signal	Copper	4.2				Bottom	
tom Solder	Solder Mask/...	Surface Mat...	0.4	Solder Resist	3.5			0
tom Over...	Overlay							

Estimating thermal performance

- Integrated MOSFET thermal calculator
  - Pre-built equations
  - Device specific
  - Enter your own test condition values for better accuracy
  - For devices such as: DRV8316, MCT8316, MCF8316, DRV8311

DRV8311 Field-Oriented Control (FOC) Thermal Calculator

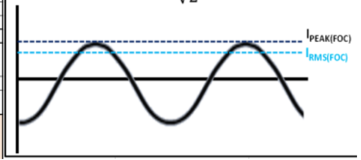
Directions - Fill in all yellow boxes with known motor system parameters for the DRV8311.

Electrical Parameters	DRV8311	Unit
DC Input Voltage [V_M]	12	V
Motor Winding RMS Current [$I_{rms(FOC)}$]	1	A
PWM Modulation	Continuous	
PWM Frequency [f_{pwm}]	20	kHz
Switching Slew Rate (SR)	230	V/us
Dead Time [t_{dead}] (SPI/tSPI variant only)	600	ns
AVDD output current (I_{AVDD})	10	mA
Ambient Temperature	25	°C
PCB Specification		
PCB Layers	4	#
Top/Bottom Layers Cu Thickness (if PCB more than 2 layers, internal	2	oz
PCB Area	16	cm²

Estimated Results	Value	Unit
Total Losses	0.67	W
Junction Temperature	60.43	C

NOTE: DRV8311 FOC thermal calculator assumes synchronous modulation switching and typical datasheet values.

$$I_{RMS(FOC)} = \frac{I_{PEAK(FOC)}}{\sqrt{2}}$$



Example calculation

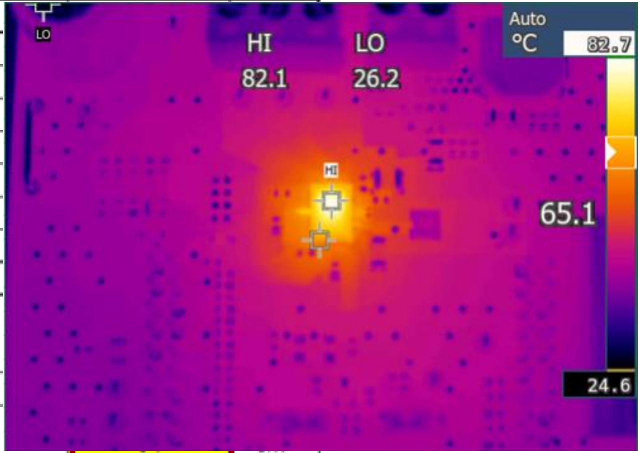
Input
- Electrical parameters
- PCB specifications

Processing (Thermal calculator)

Output
- Total losses
- Junction temperature

DRV8316 Field-Oriented Control (FOC) Thermal Calculator	Directions - Fill in
Electrical Parameters	
DC Input Voltage [V_M]	
Motor Winding RMS Current [$I_{rms(FOC)}$]	
PWM Modulation	
PWM Frequency [f_{pwm}]	
PCB Layers	
Top/Bottom Layers Cu Thickness (if PCB more than 2 layers,	
PCB Area	

Estimated Results	Value	Unit
Total Losses	2.72	W
Junction Temperature	83.93	C



For more information

- Motor drives website: ti.com/motordrivers
- Excel calculator: ti.com/lit/zip/slvrbi8
- Thermal considerations for PCB: ti.com/lit/an/slva938a/slva938a.pdf
- Delay and dead time: ti.com/lit/an/slvaf84/slvaf84.pdf