How to Estimate Motor Driver Power Dissipation

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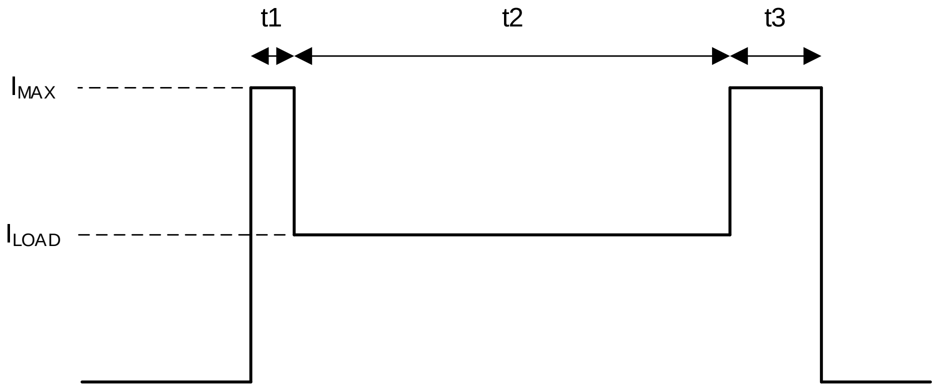
Webinar will begin at 10:00AM CET | 2:00 AM PDT | 5:00 AM EDT

MPS

Agenda

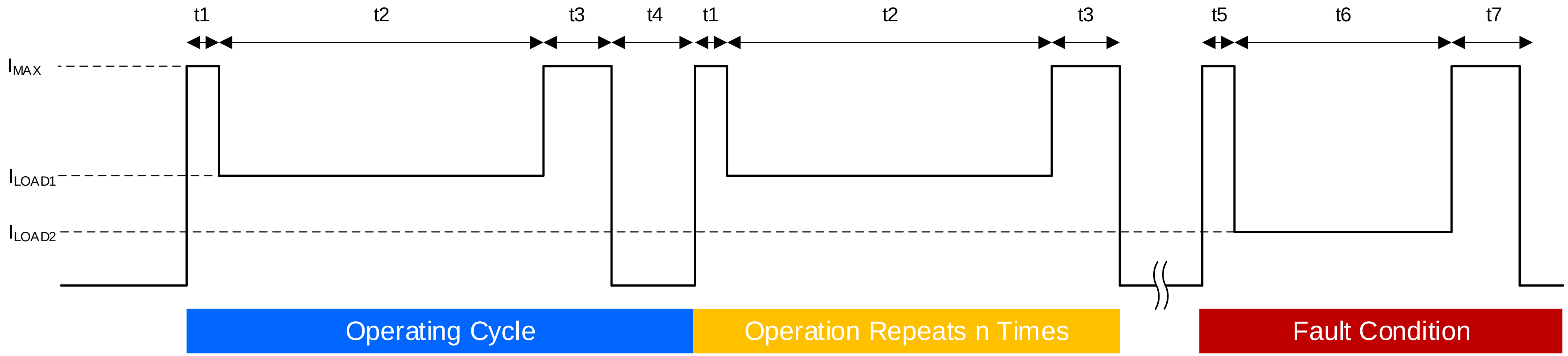
- Introduction
  - Motor current profile including stall current and application mission profile
  - Motor driver thermal challenges requiring accurate loss estimation
- Motor driver power stage basics
  - Topology (B2, B4, B6 bridges)
  - Switching waveforms
  - EMC trade-offs
  - Power stage losses introduction
- Motor driver power dissipation estimations
  - SPICE simulation
  - Lab measurements
- Conclusions

Motor Load Current Mission Profile



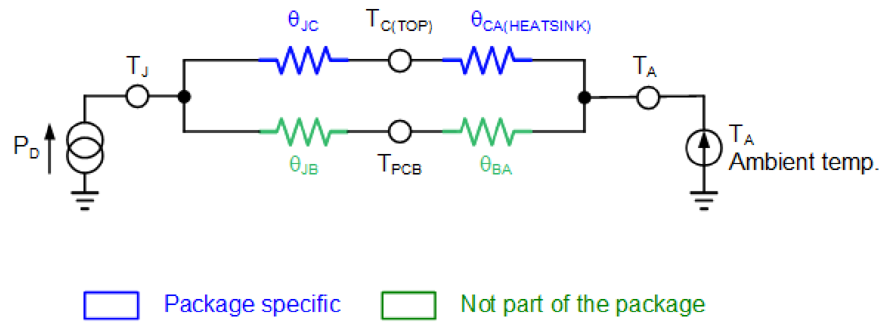
Timing	Duration (ms)
t1 (inrush current)	10 to 50 (30)
t2 (load current)	2000 to 30000 (up to ∞)
t3 (stall current)	100 to 1000

Current	
I_{LOAD}	25% to 75% I_{MAX} (30%, 50%)



Thermals and Losses Under Pulsed Operation

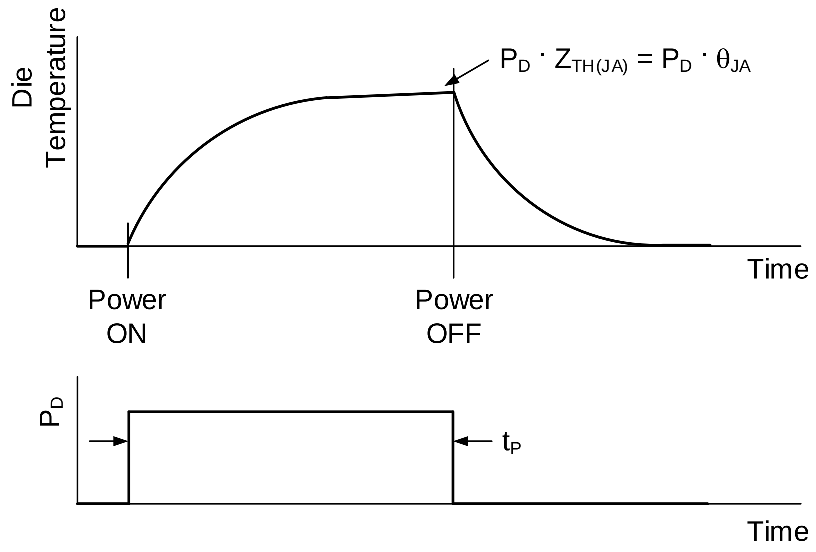
Under pulsed load operation, higher peak power dissipation can be tolerable. The critical junction temperature is not reached instantaneously, even when excessive power is being dissipated in the device.



θ_{JB}: Thermal impedance from the die to the board. θ_{JB} includes some of the board characteristics and their coupling with the package.

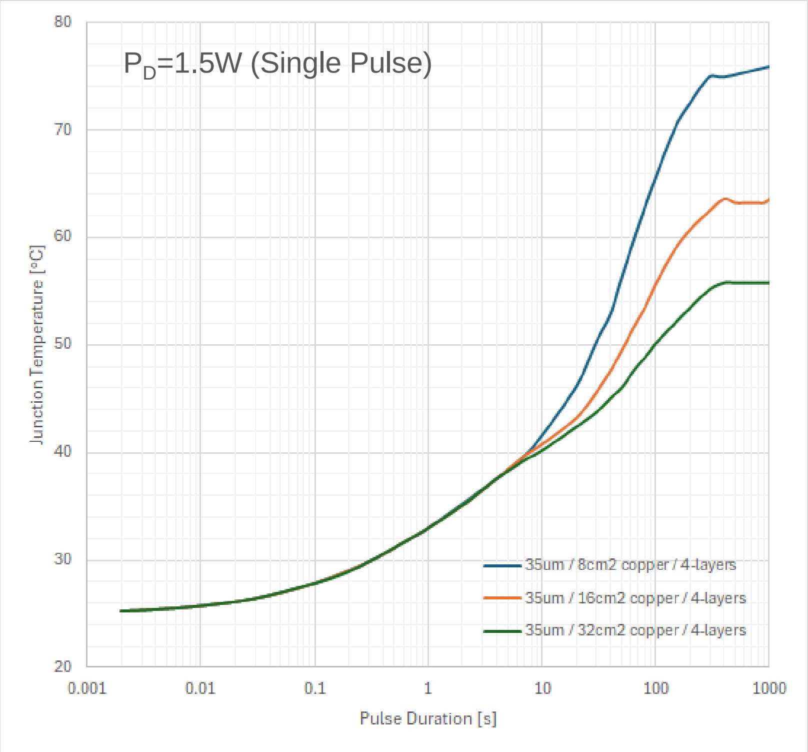
Thermal capacitance (C_{TH}) is a measure of the capability to accumulate heat and it depends on the specific heat capacity (c), volume (V), and density (ρ):

$$C_{TH} = c \cdot \rho \cdot V \quad \text{expressed in J/K}$$



Thermal Modeling

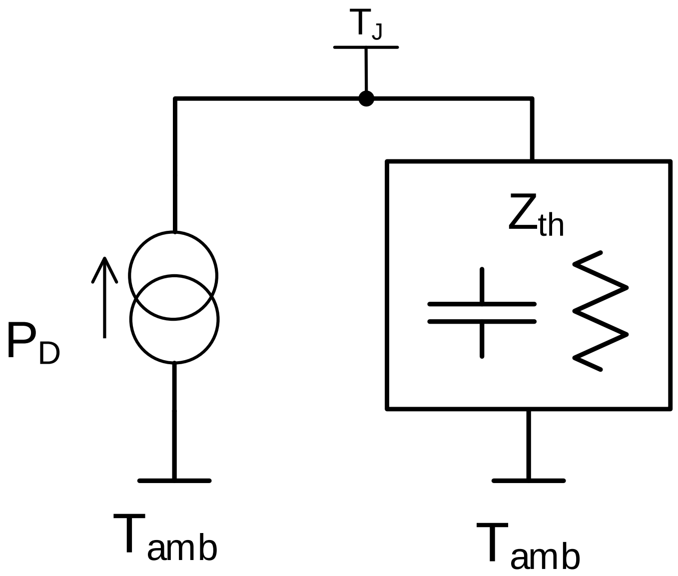
Transient Measurements



$$T_J(t) = TJ(0) + f(t)$$

$T_J(t)$ can be found using curve fitting techniques

Model



$$T_J(t) = \underbrace{Tamb}_{T(0)} + \underbrace{PD(t) * Zth(t)}_{f(t)}$$

$$\downarrow \mathcal{L}$$

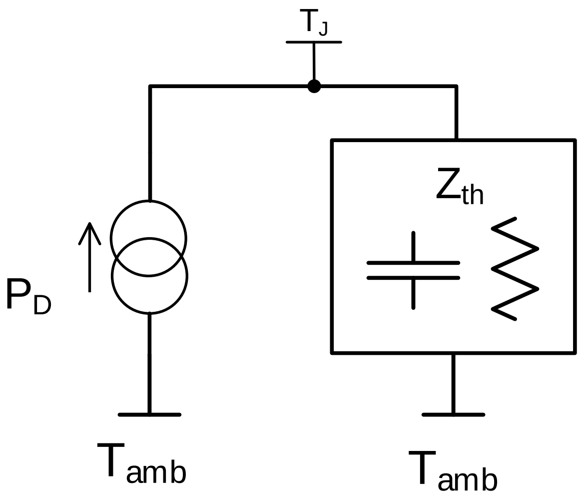
$$\mathcal{L}\{T_J(t) - TJ\ (0)\} = PD(s)\ Zth(s)$$

$$Z_{th}(s) = \frac{\mathcal{L}\{T_J(t) - TJ(0)\}}{P_D(s)}$$

To know Zth(s) one needs:
-T_J(t) time response (i.e. to step or impulse power dissipation stimuli)
-resting condition T_J(0) (temp. when no power dissipation is applied)
-stimuli function (i.e. step or impulse and its amplitude)

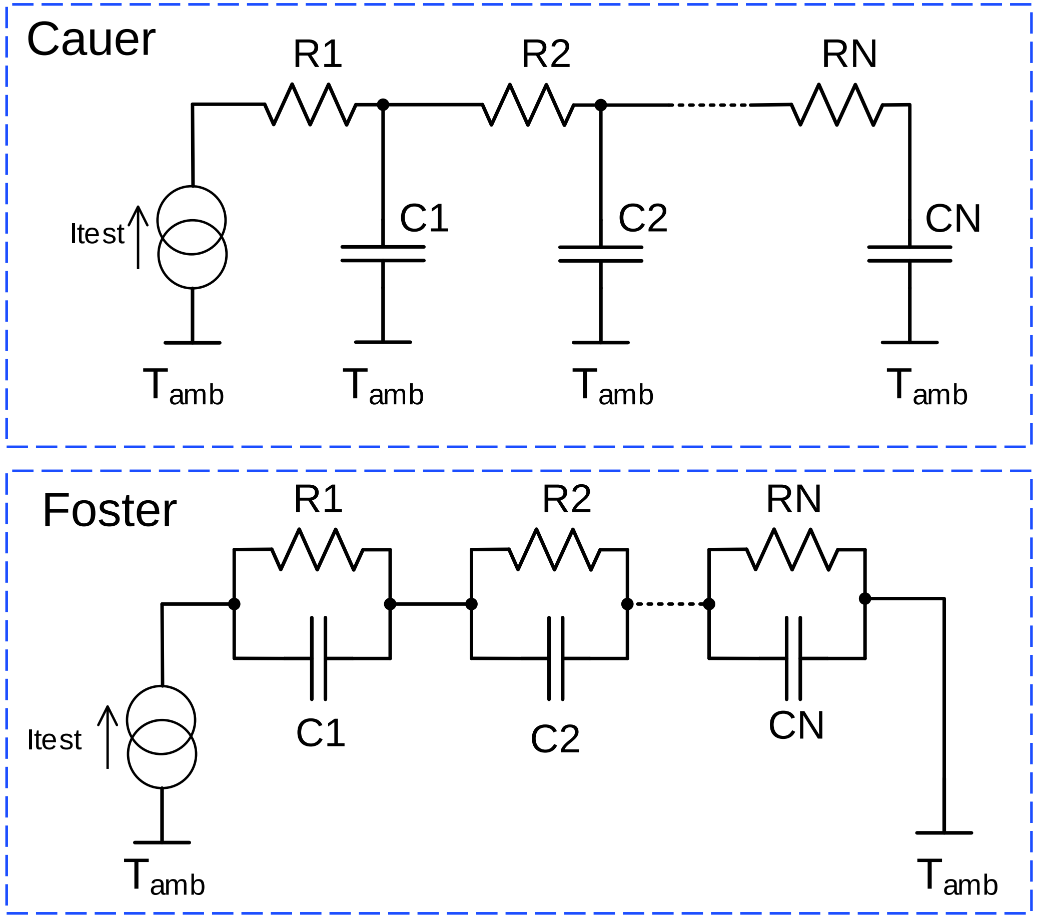
Thermal Modeling (Cont'd)

Any $Z_{th}(s)$ impedance can be synthesized in a passive network using the Cauer or Foster algorithm. For thermal models, RC networks result quite handy and representative of the reality.



$$Z_{th}(s) = \frac{N_{th}(s)}{D_{th}(s)}$$

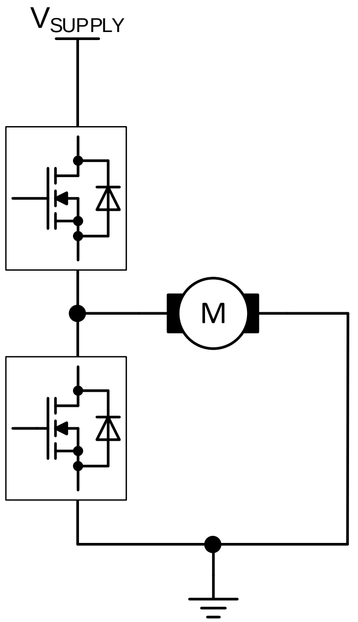
RC network extraction from $Z_{th}(s)$:
Cauer or Foster representation



Basic DC Motor Driver Topologies

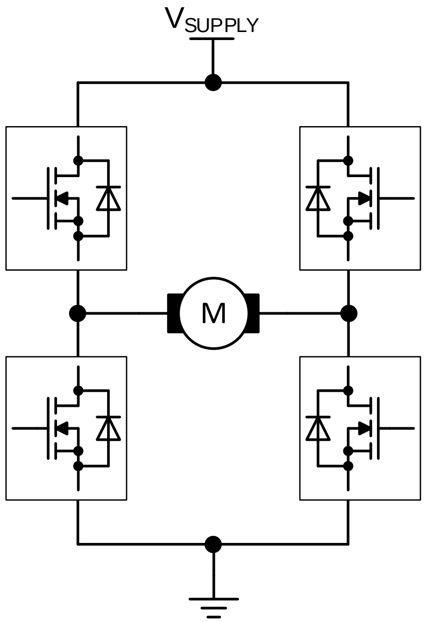
Half-Bridge

- 1-direction Brushed DC motor
- Three modes: Run, Coasting and Braking



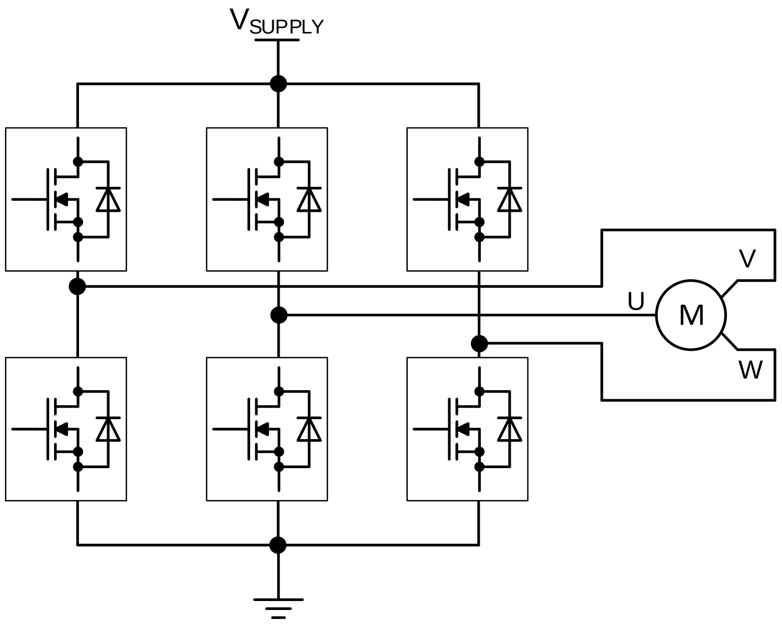
H-Bridge (B4)

- 2-Direction Brushed DC motor
- Four modes: Run, Reverse, Coasting and Braking



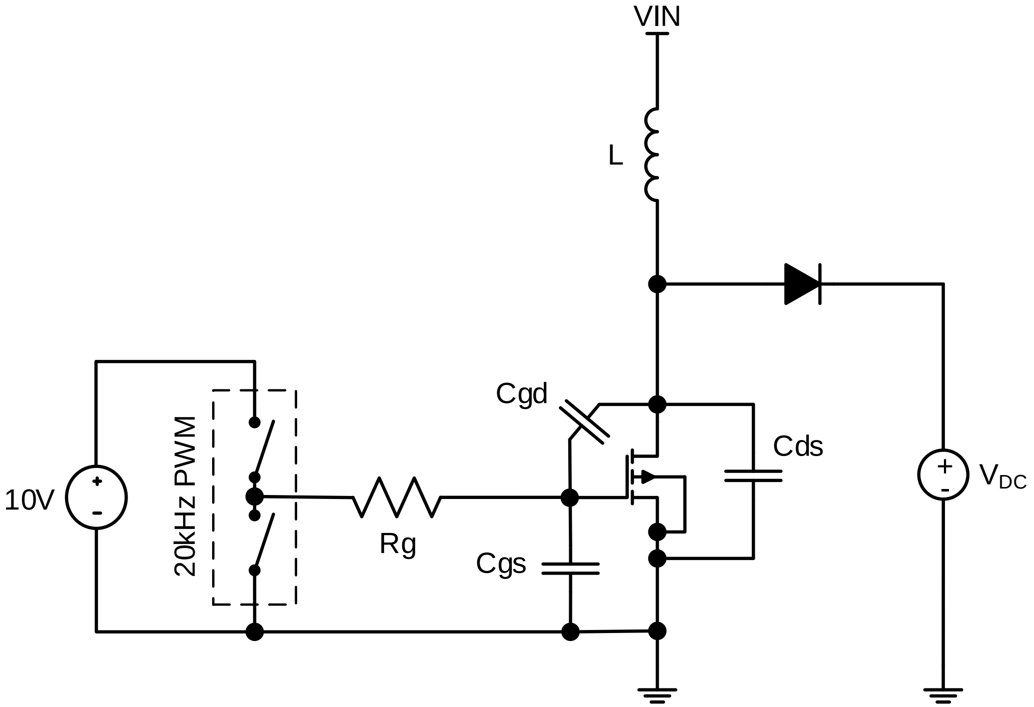
B6-Bridge

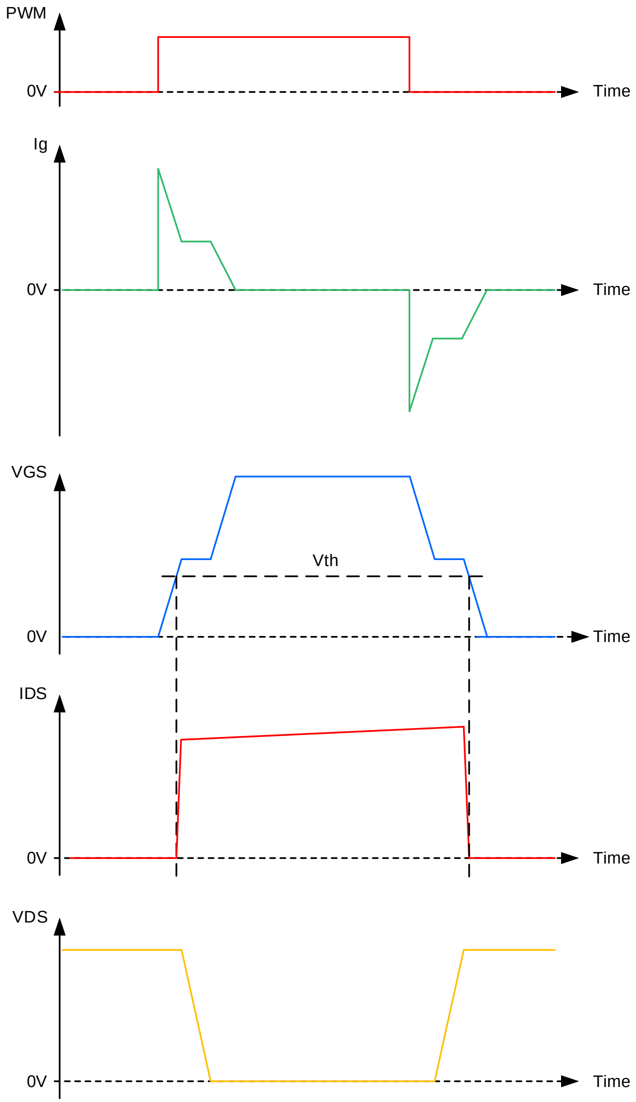
- BLDC motor – electrically commutated.
- Four modes: Run, Reverse, Coasting and Braking



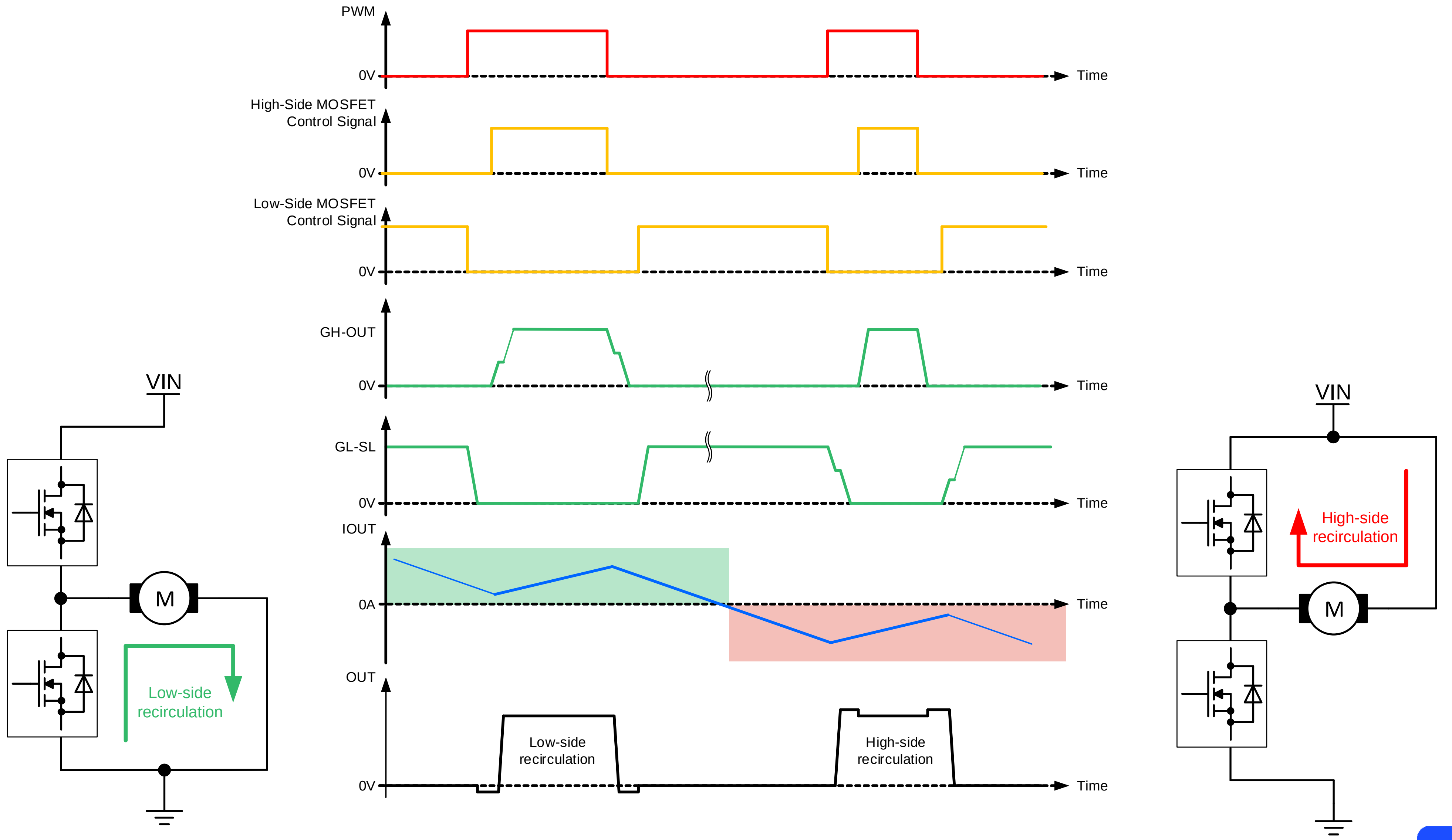
Also 2 H-bridge for **stepper**

Understanding MOSFET Basic Switching (Inductive Load)

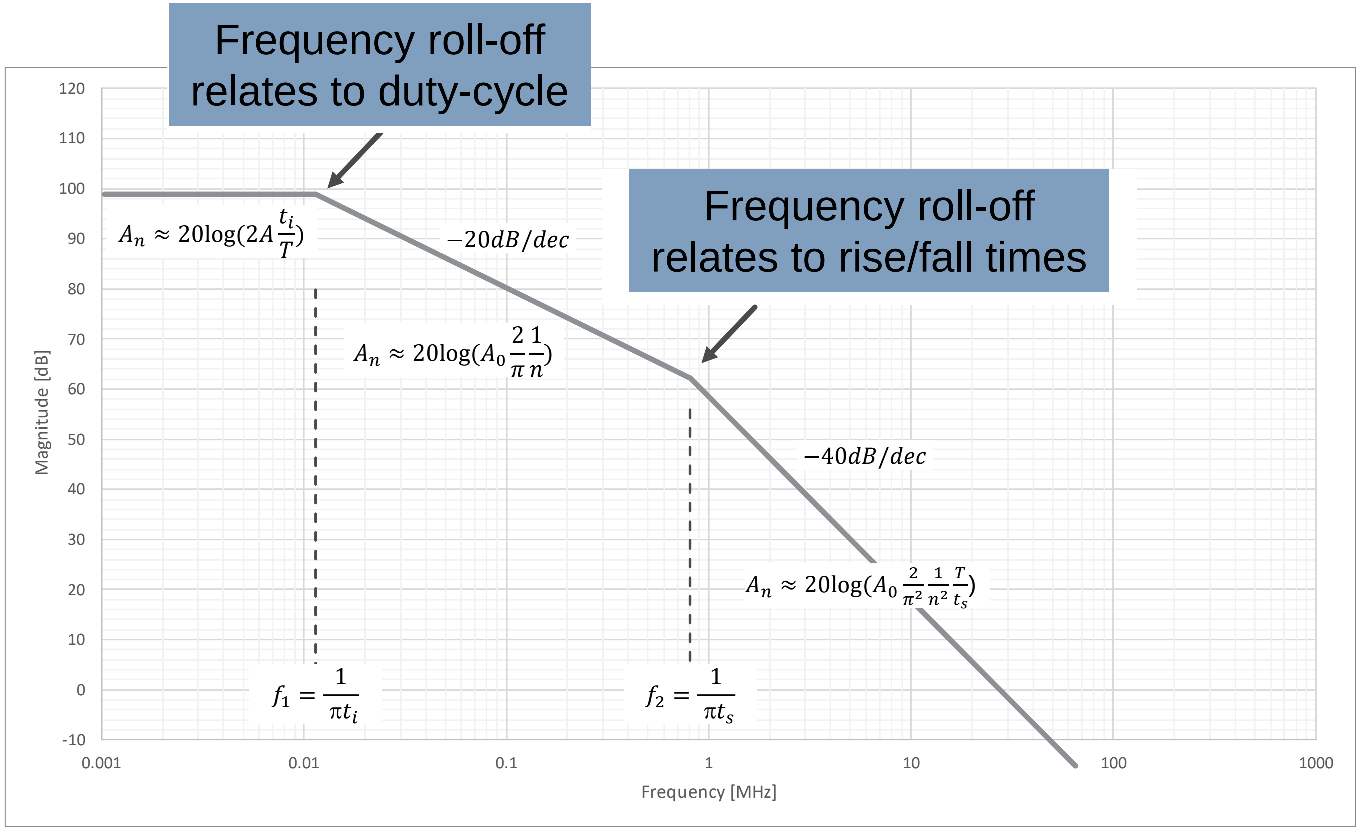




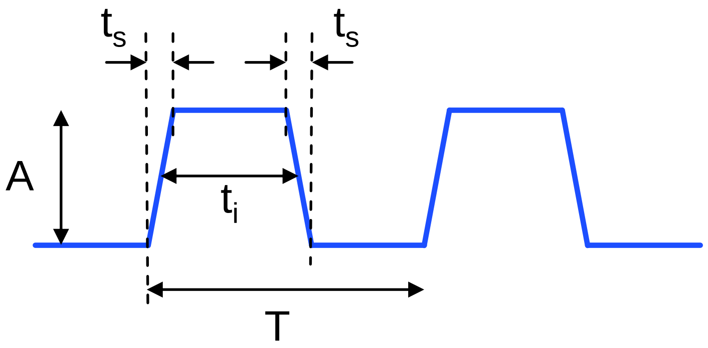
Half-Bridge Switching Waveforms



Conducted Emission Spectrum – Trapezoidal Signal



Time domain signal



Frequency roll-off vs. rise/fall times

Rise/Fall Times t_s (ns)	Roll-Off Freq. f_2 (MHz)
100	3.2
150	2.1
500	0.65
1000	0.33
1500	0.21

Half-Bridge Power Losses: 1st Order Estimation

MOSFET Turn-On Losses

$$P_D = \frac{V_{IN}}{2} \times I_{MOTOR} \times \frac{t_{RISE}}{T_{PWM}}$$

MOSFET Turn-Off Losses

$$P_D = \frac{V_{IN}}{2} \times I_{MOTOR} \times \frac{t_{FALL}}{T_{PWM}}$$

$$t_{RISE} = t_{FALL} \text{ (VDS transition)}$$

MOSFET Switching Losses

$$P_{SW} = V_{IN}^2 \times I_{MOTOR} \times f_{PWM} \times \frac{1}{SR}$$

Where I_{MOTOR} is assumed to have a very low ripple

MOSFET Conduction Losses

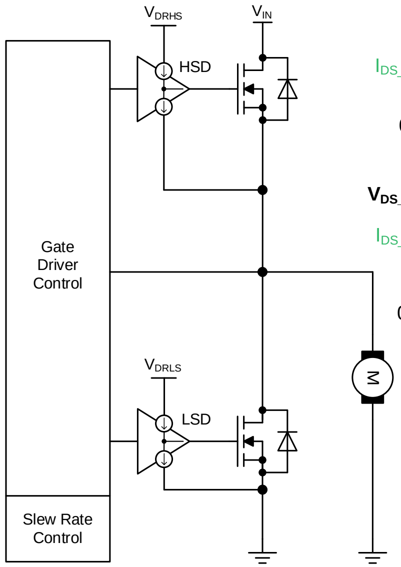
$$P_{COND} = R_{DS(ON)} \times I^2_{(RMS)} \qquad I_{RMS} = I_{MOTOR} \times \sqrt{D}$$

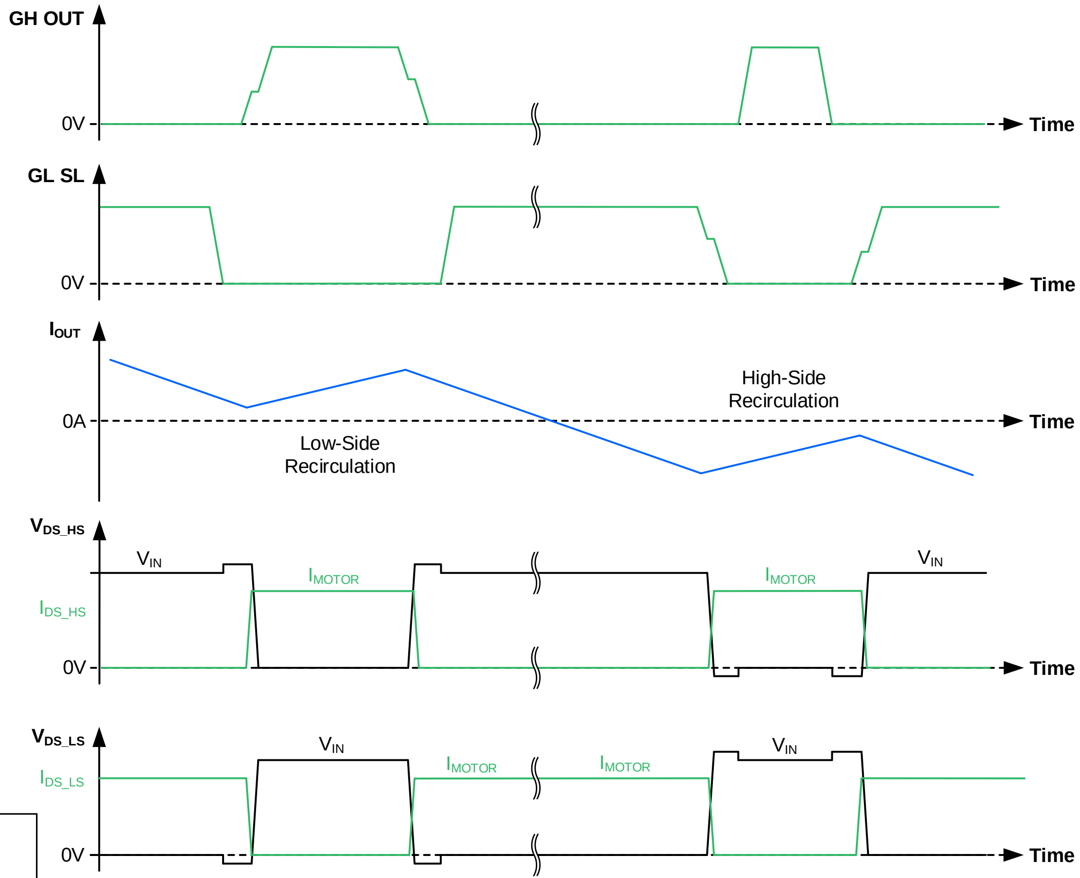
$$P_{COND} = R_{DS\,(ON)} \times I^2_{MOTOR} \times D$$

MOSFET Back-Gate Diode Losses

$$P_{BG} = 2 \times V_F \times I_{MOTOR} \times t_{BG\_TIME} \times f_{PWM}$$

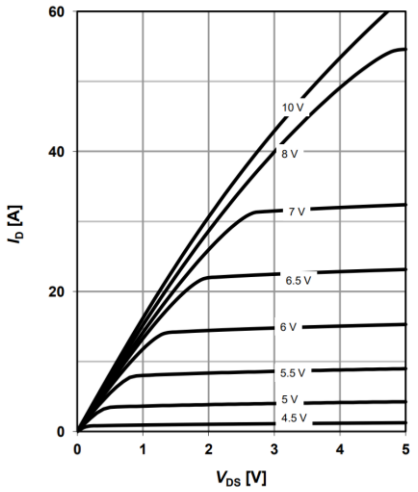
Where the I_{DS} transition is assumed to be negligible





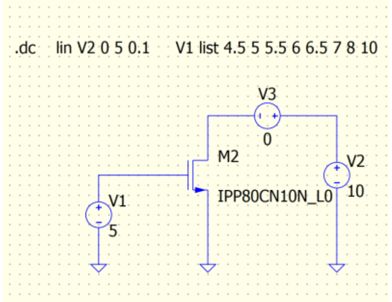
IPP80CN10N SPICE Model Level 0

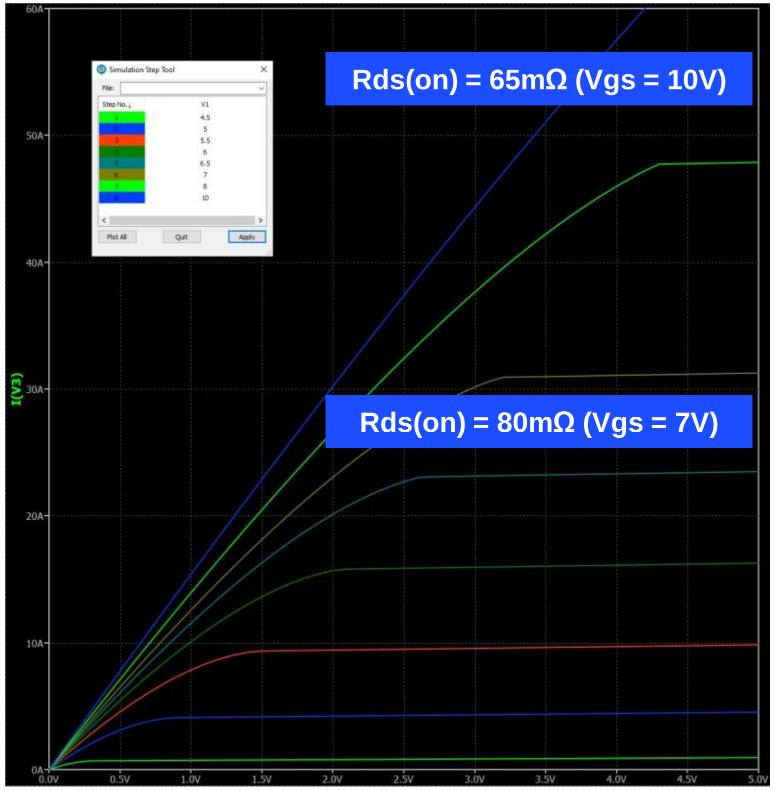
MOSFET Drain-Source On-State Resistance Datasheet Parameter



Drain-source on-state resistance	$R_{DS(on)}$	V_{GS}=10 V, I_D=13 A, (TO252)	-	59	78	mΩ

MOSFET Drain-Source On-State Resistance Model Verification

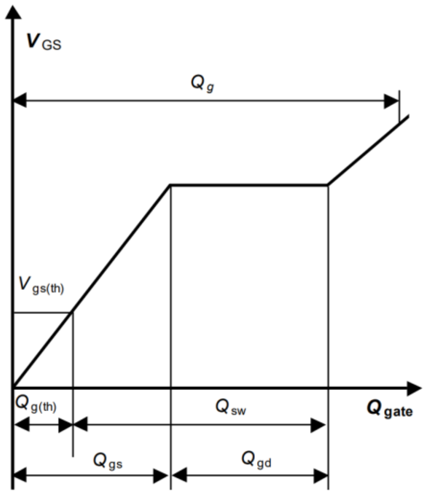


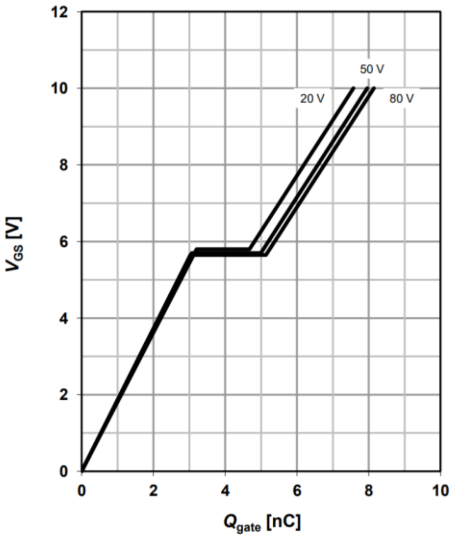


IPP80CN10N SPICE Model Level 0 (Cont‘d)

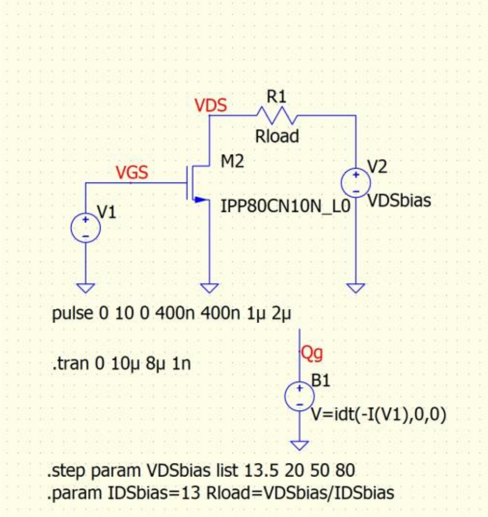
MOSFET Gate Charge Datasheet Parameters

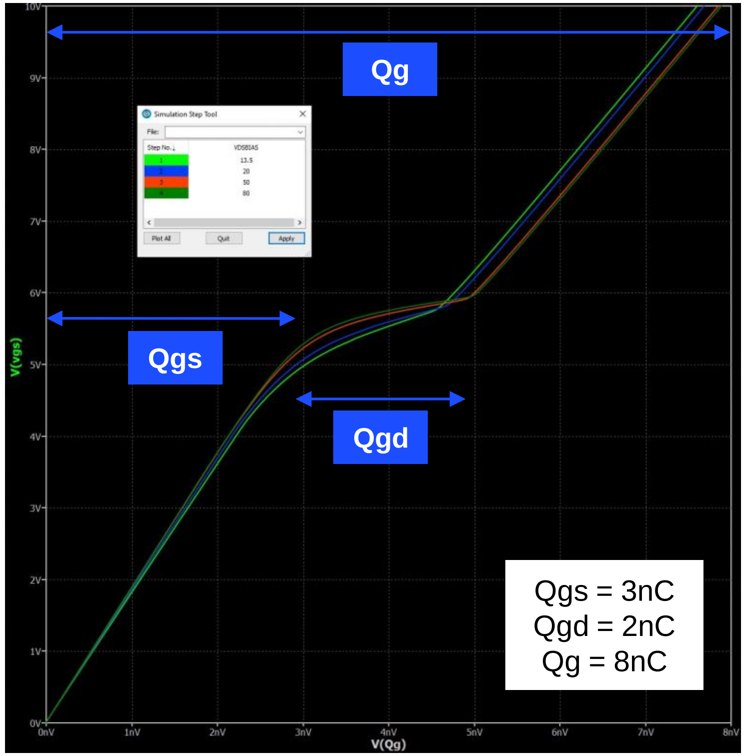
Gate to source charge	Q_{gs}	V_{DD}=50 V, I_D=13 A, V_{GS}=0 to 10 V	-	3	4	nC
Gate to drain charge	Q_{gd}		-	2	3	
Switching charge	Q_{sw}		-	3	5	
Gate charge total	Q_g		-	8	11	
Gate plateau voltage	$V_{plateau}$		-	5.7	-	V





MOSFET Gate Charge Model Verification



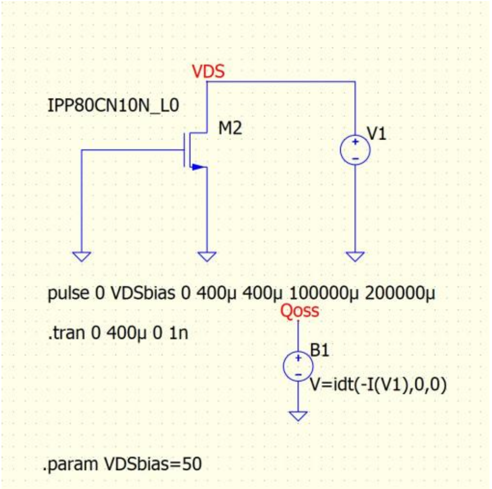


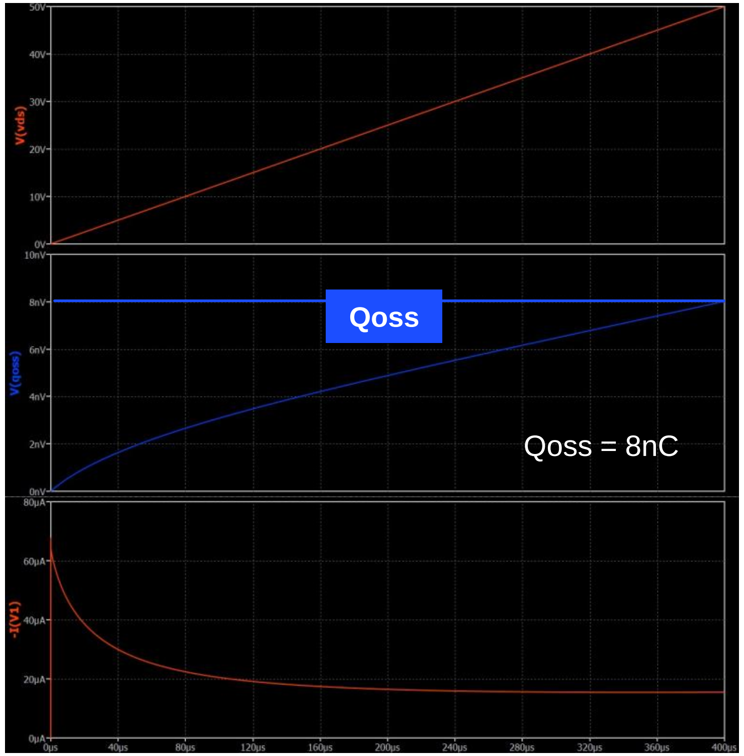
IPP80CN10N SPICE Model Level 0 (Cont‘d)

MOSFET Output Charge Datasheet Parameters

Output charge	Q_{oss}	V_{DD}=50 V, V_{GS}=0 V	-	8	10	nC

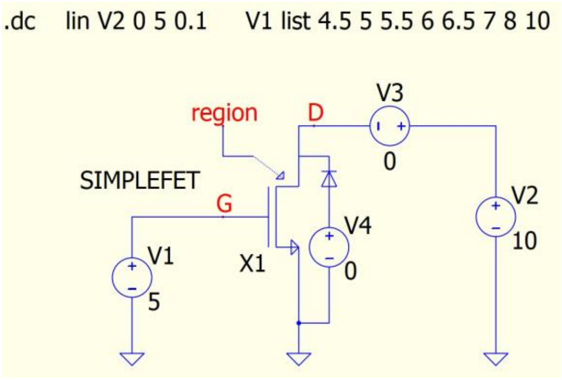
MOSFET Output Charge Model Verification





Simple Switching MOSFET SPICE Model

Testbench

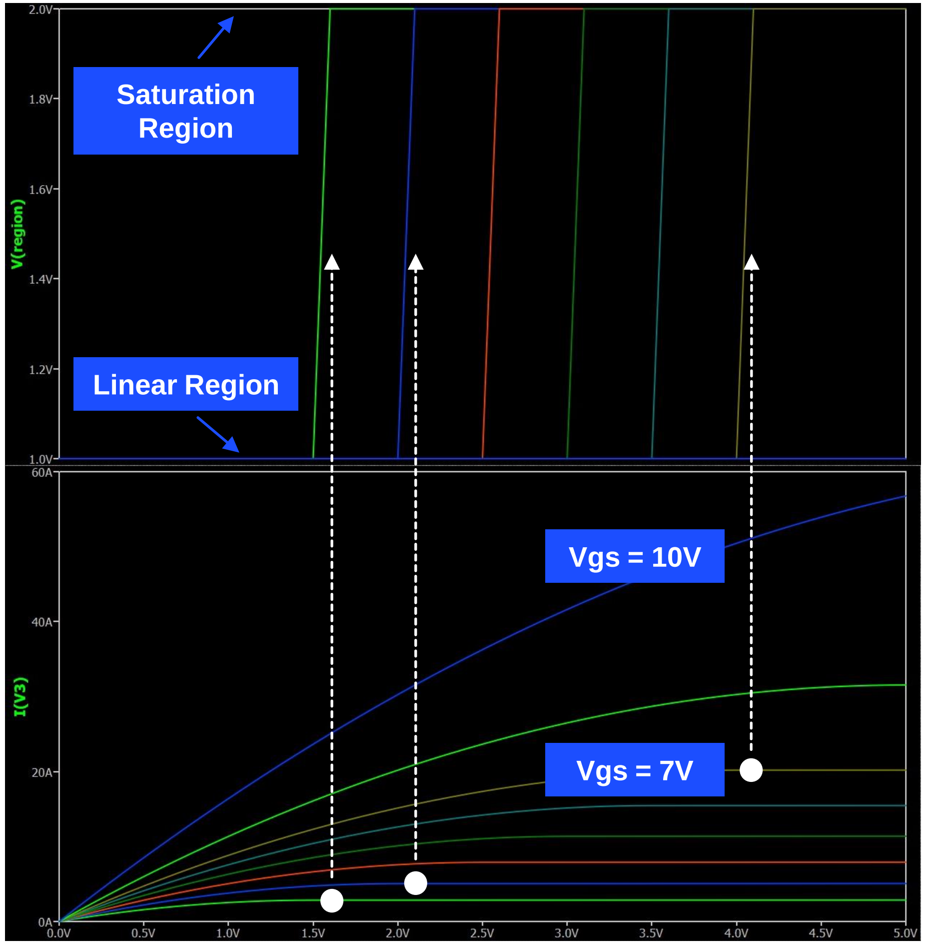


Drain-source on-state resistance	$R_{DS(on)}$	V_{GS}=10 V, I_D=13 A, (TO252)	-	59	78	mΩ
Gate threshold voltage	$V_{GS(th)}$	V_{DS}=V_{GS}, I_D=12 µA	2	3	4	V
Gate plateau voltage	$V_{plateau}$		-	5.7	-	V

```
.subckt simpleFET G Drain Source Dp region

*External resistances
R2 Drain D Rdrain
R3 Source S Rsource
R1 G S 10Meg

*Body diode model
D1 DR D Diode
R4 Dp DR RDon
.model Diode D(Ron=Rdiode Roff=RDoff Vfwd=VD Vrev=VBD EPSILON=0)

*Mosfet current
*Mosfet current
B1 D S I=if(V(G,S)<VTH, 0, if(V(G,S)-VTH>=abs(V(D,S)),
+ Kp*(V(G,S)-VTH-abs(V(D,S))/2)*V(D,S),Kp/2*((V(G,S)-VTH)**2) )) +
+ if(V(D,S)>0 & V(G,S)>VTH,V(D,S)*lambda,0)

*Mosfet operating region
B2 region 0 V=if(V(G,S)<VTH, 0, if(V(G,S)-VTH>=V(D,S),1,2 ) )

*Mosfet parameter extraction
.param Kp=Kp_lin
.param Kp_lin=IDSx/(VGSx-VTHx-VDSx/2)/VDSx
.param Kp_sat=IDSx*2/((VGSplx-VTHx)^2)
.param VDSx=(Rdsx-Rdrain-Rsource)*IDSx
.param VTH=VTHx

*Mosfet parameters
.param RDStgt=64m
.param  Rdrain=1u Rsource=1u
.param lambda=1/235
.param Rdsx=RDStgt  Rdsoff=10Meg
.param VGSx=10 IDSx=13  VTHx=4 VGSplx=5.7

*Diode parameters
.param RDon=10m Rdiode=1u RDoff=10Meg VD=0.7 VBD=1Meg
.ends simpleFET
```

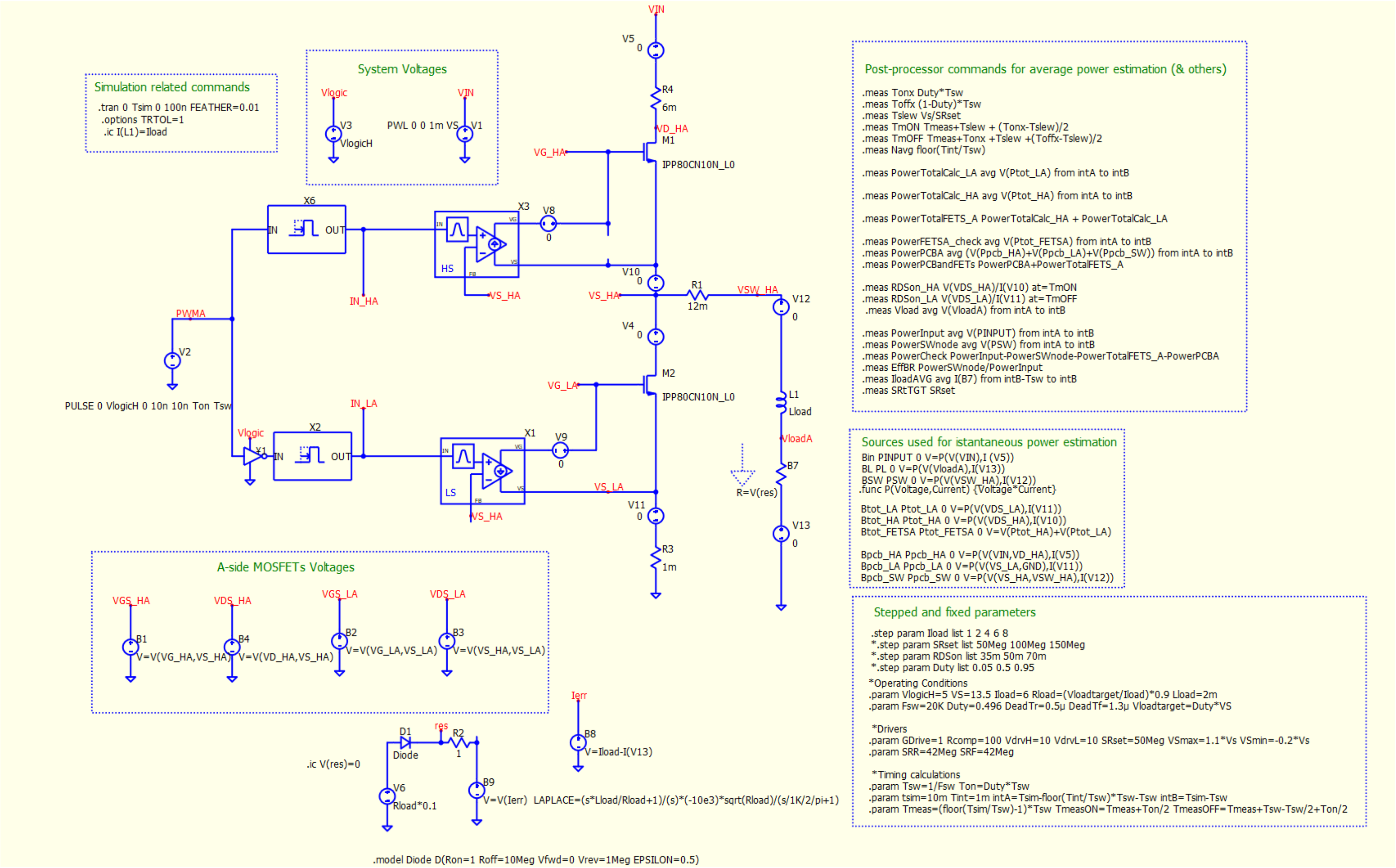
No body-diode reverse recovery modeling (Qrr)
No gate charge modeling

Model Verification



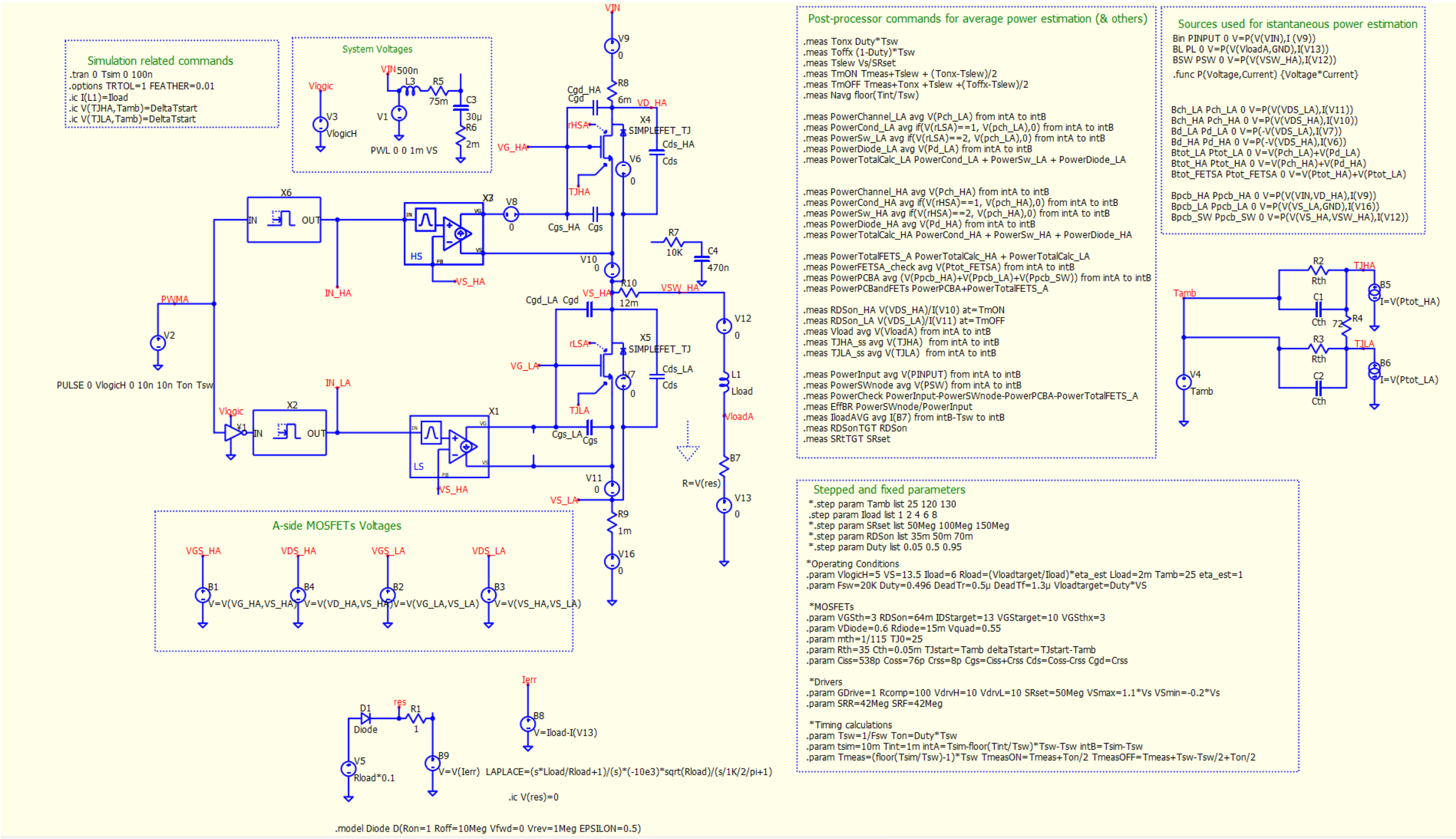
Testbench Comparison (MOSFET Level 0 Model vs. Simple MOSFET)

MOSFET Model Level 0 Testbench



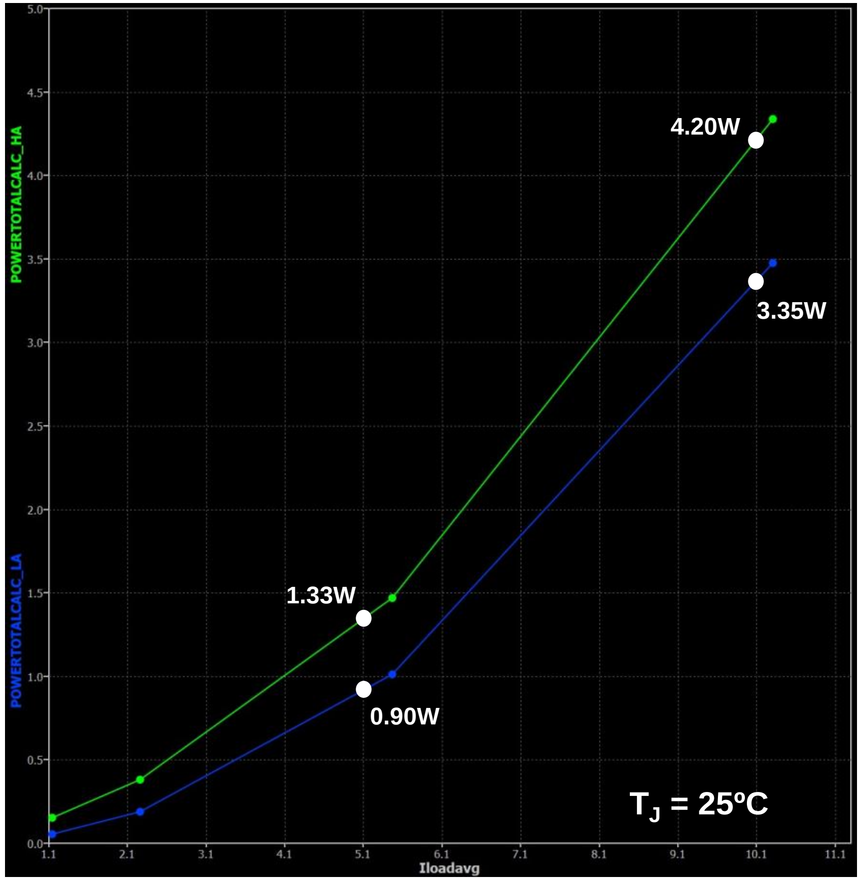
Testbench Comparison (Cont‘d)
(MOSFET Level 0 Model vs. Simple MOSFET)

Simple MOSFET Testbench

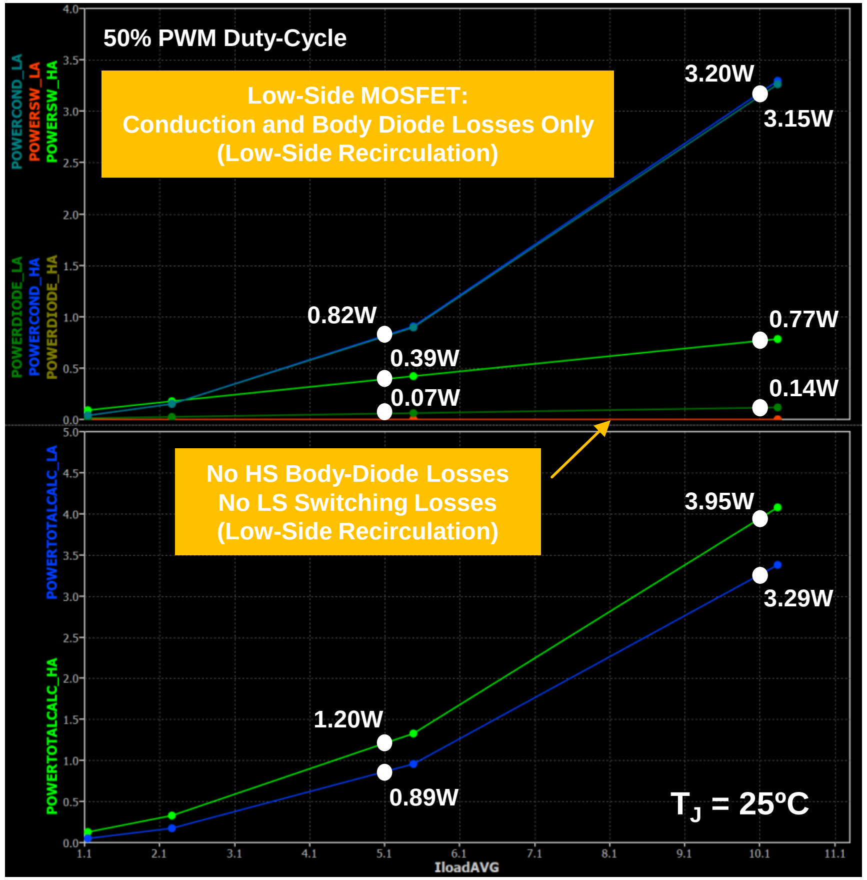


Testbench Comparison (MOSFET Level 0 Model vs. Simple MOSFET)

MOSFET Model (From Vendor) Based Testbench



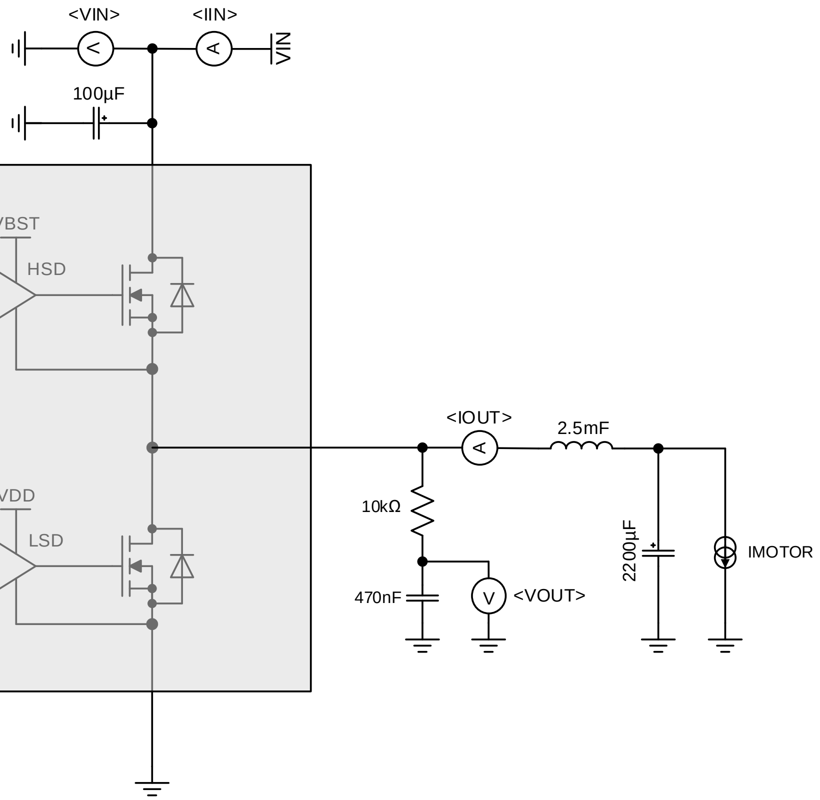
Simple MOSFET Testbench

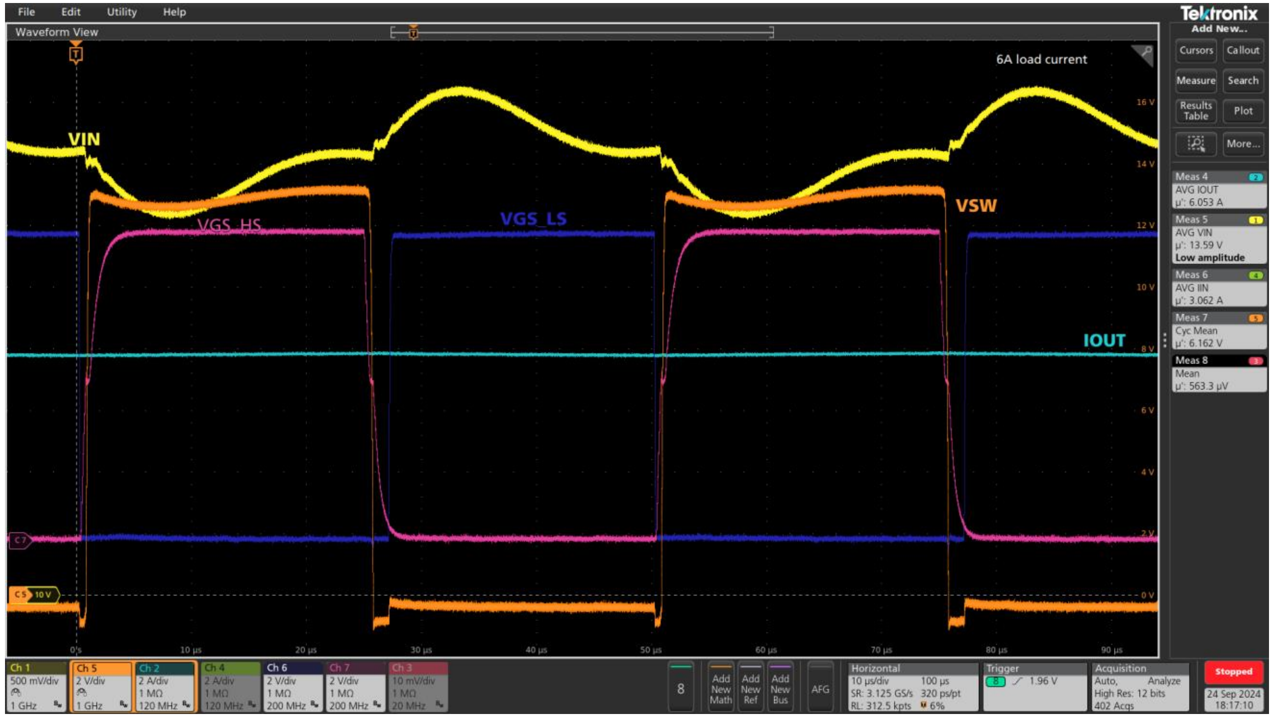


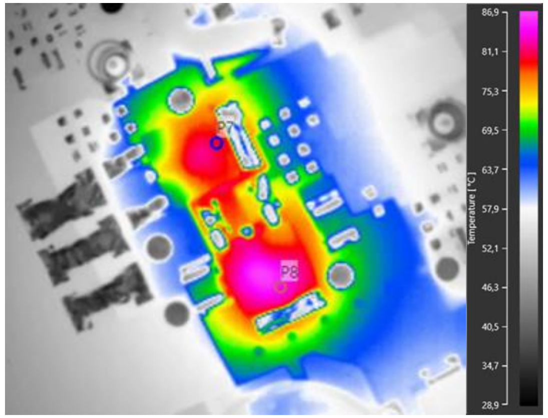
Validation Testbench

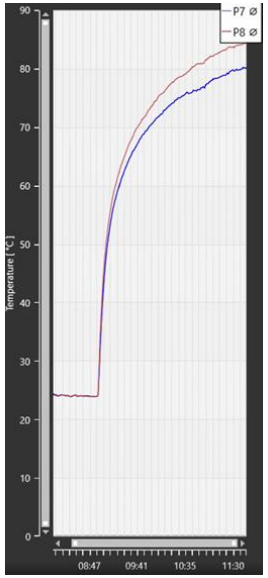
$$< P_D(t) >= \frac{1}{T_{PWM}} \int_0^{T_{PWM}} v(t) \times i(t)\, dt$$

Cycle mean value of the voltage x current product









Model Comparaison

Invalid assumption
$R_{ds(on)}$ drop > BG diode V_F

		High-Side MOSFET						Low-Side MOSFET				PCB	Low-Side + High-Side MOSFETs	MOSFETs + PCB
	Average Motor Current [A]	Conduction Losses [W]	Turn-On Switching Losses [W]	Turn-Off Switching Losses [W]	Switching Losses [W]	Back-Gate Diode Losses [W]	Total [W]	Conduction Losses [W]	Switching Losses [W]	Back-Gate Diode Losses [W]	Total [W]	Total copper losses [W]	Total losses [W]	Total losses [W]
1st order approximation	1	0.030	0.046	0.046	0.092	0	0.122	0.030	0	0.061	0.091	Not included	0.21	
	2	0.132	0.092	0.092	0.184	0	0.316	0.132	0	0.122	0.254		0.57	
	4	0.600	0.184	0.184	0.367	0	0.967	0.600	0	0.258	0.858		1.83	
	6	1.620	0.275	0.275	0.551	0	2.171	1.620	0	0.408	2.028		4.20	
	8	4.032	0.367	0.367	0.734	0	4.766	3.456	0	0.544	4.000		8.77	
IFX FET Spice Model Level 0 (T_J fixed at 25°C)	1	not available in the vendor model					0.143	not available in the vendor model			0.058	0.015	0.20	0.22
	2						0.349				0.179	0.062	0.53	0.59
	4						0.940				0.610	0.25	1.55	1.80
	6						1.780				1.280	0.56	3.07	3.63
	8						2.880				2.210	0.99	5.09	6.10
Simple FET Spice Model	1	0.030			0.093	0	0.123	0.029	0	0.026	0.055	0.015	0.18	0.20
	2	0.120			0.190	0	0.310	0.120	0	0.056	0.176	0.062	0.49	0.55
	4	0.580			0.370	0	0.950	0.540	0	0.120	0.660	0.25	1.61	1.86
	6	1.650			0.540	0	2.190	1.500	0	0.190	1.690	0.56	3.89	4.45
	8	4.390			0.690	0	5.080	1.700	0	0.950	2.650	0.99	7.73	8.72
Lab Measurement	1	Not practical to measure experimentaly						Not practical to measure experimentaly				Not practical to measure experimentaly	Not practical to measure experimentaly	0.24
	2													0.65
	4													2.15
	6													4.81
	8													9.35

<7.5% error

Notes:
- 13.5V input voltage
- 1A / 2A / 4A / 6 / 8A average motor current
- 20kHz PWM operation
- 50% duty-cycle
- 2us back-gate diode time
- 40V/us slew-rate (340ns rise time, 340ns fall time)
- 65mOhm Rds(on), 0.85V back-gate diode voltage
- ca 20mOhm PCB trace resistance

Low-side recirculation

High-side active switch (i.e. output slew-rate control)

Conclusion

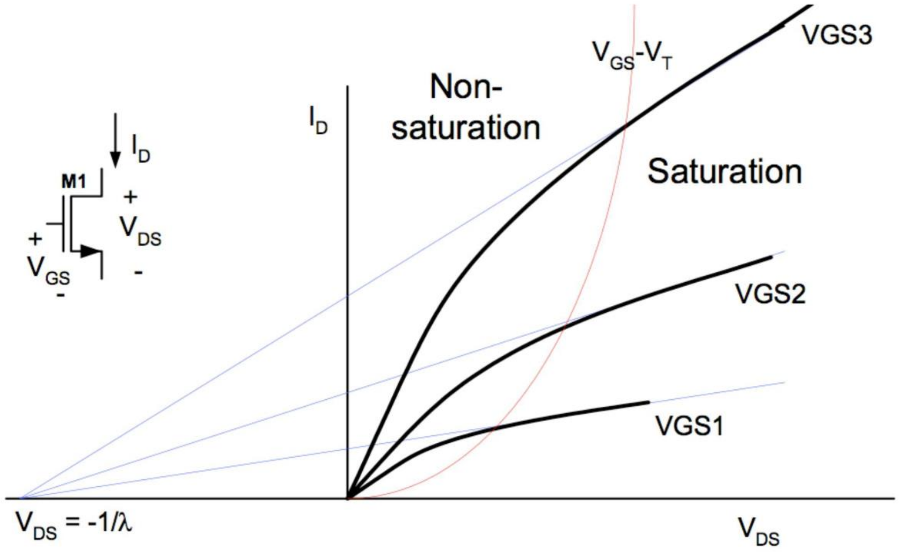
- 1^{st} order approximations are very handy to draw an initial picture of the power-stage losses
- Simple MOSFET model provides a powerful method to breakdown the losses
- Simple MOSFET model can be easily defined with datasheet parameters
- Fast simulation time
- Temperature dependencies help to improve first order estimates
- Good degree of accuracy: predicted power dissipation off by less than 10% vs. bench measurements
- Q_{rr} modeling is usually not required in motor driver applications switching at ca. 20kHz.
- Helpful to optimize the tradeoff conduction losses, switching losses and electromagnetic noise emissions
- Do not underestimate PCB copper losses

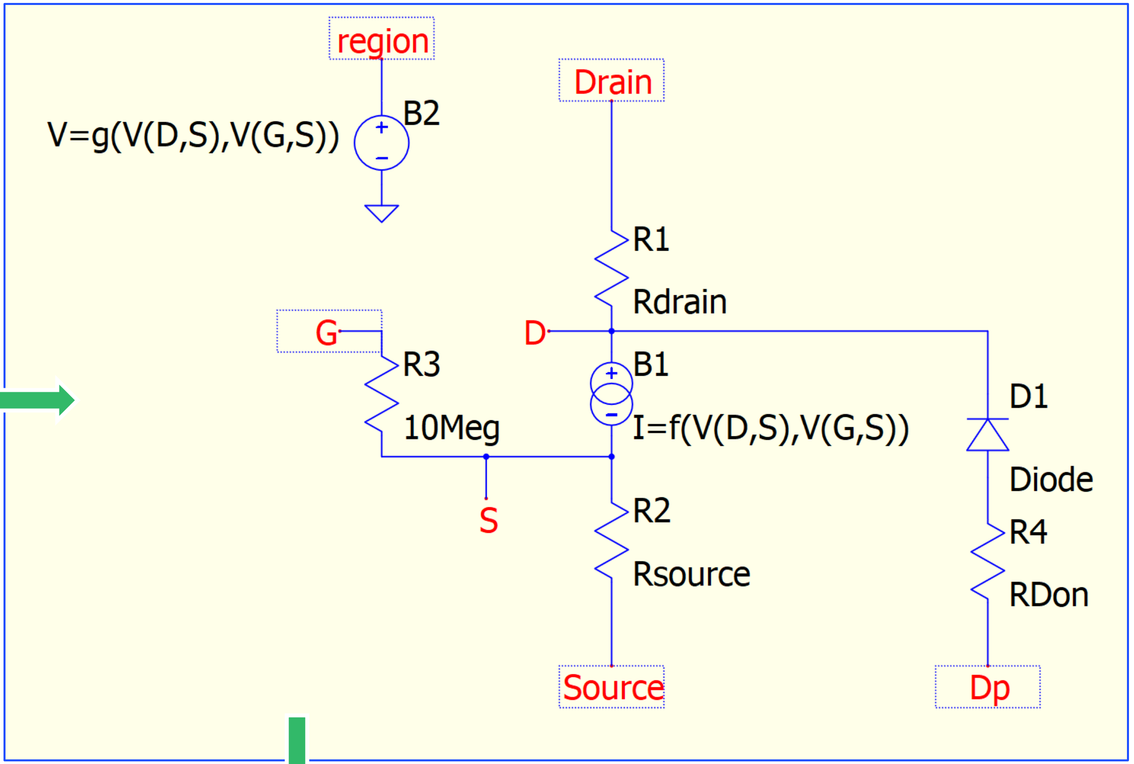
COMPLEMENTARY MATERIAL

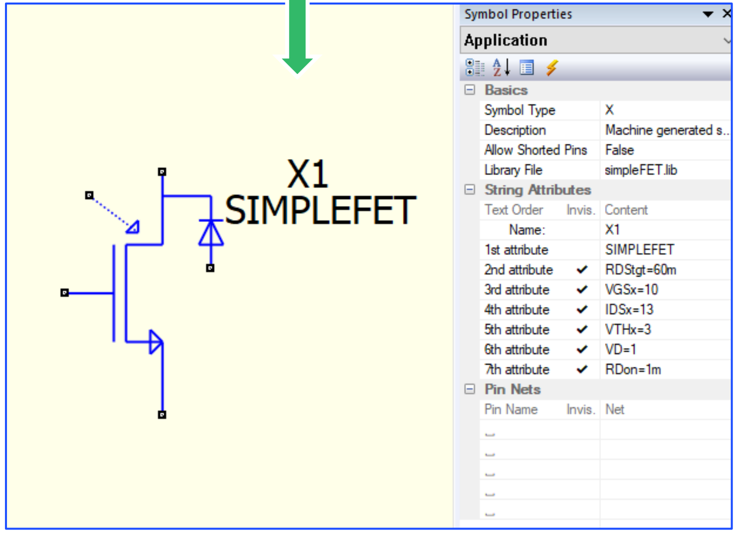
MOSFET SPICE Level (sub) 0

g(V(D,S),V(G,S)) f(V(D,S),V(G,S))

Cut Off	$V_{GS} \le V_T$	$I_{DS} = 0$
Linear	$V_{GS} > V_T$, $V_{DS} \le V_{GS} - V_T$	$I_{DS} = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right] (1 + \lambda V_{DS})$
Saturation	$V_{GS} > V_T$, $V_{DS} > V_{GS} - V_T$	$I_{DS} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$





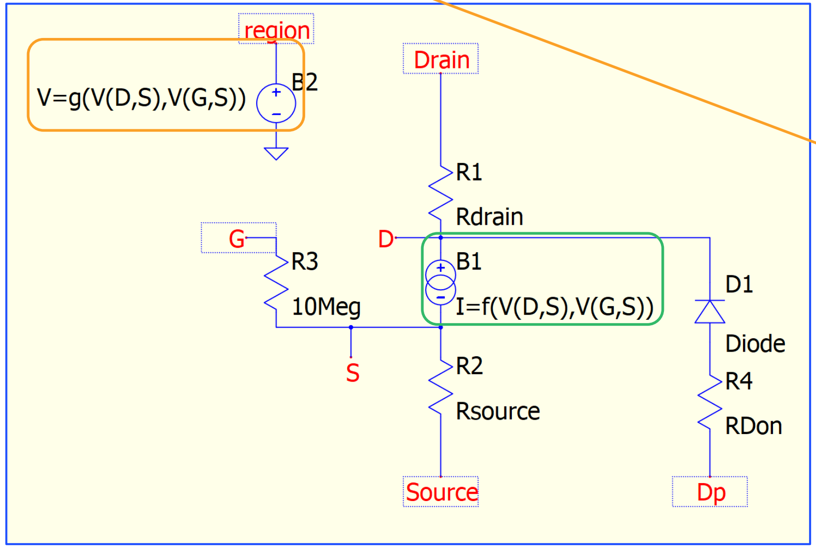


MOSFET SPICE Level (sub) 0

Cut Off	$V_{GS} \le V_T$	$I_{DS} = 0$
Linear	$V_{GS} > V_T,\ V_{DS} \le V_{GS} - V_T$	$I_{DS} = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right] (1 + \lambda V_{DS})$
Saturation	$V_{GS} > V_T,\ V_{DS} > V_{GS} - V_T$	$I_{DS} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$

Kp

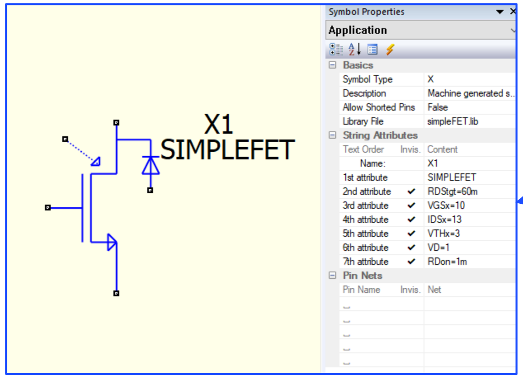
Kp




```
.subckt simpleFET G Drain Source Dp region

*External resistances
R2 Drain D Rdrain
R3 Source S Rsource
R1 G S 10Meg

*Body diode model
D1 DR D Diode
R4 Dp DR RDon
.model Diode D(Ron=Rdiode Roff=RDoff Vfwd=VD Vrev=VBD
EPSILON=quad)

*Mosfet current
B1 D S I=if(V(G,S)<VTH, 0, if(V(G,S)-VTH>=abs(V(D,S)),
+ Kp*(V(G,S)-VTH-abs(V(D,S))/2)*V(D,S),Kp/2*((V(G,S)-VTH)**2)
)) +
+ if(V(D,S)>0 & V(G,S)>VTH,V(D,S)*lambda,0)
B2 region 0 V=if(V(G,S)<VTH, 0, if(V(G,S)-VTH>=V(D,S),1,2 ) )

*Mosfet parameter extraction
.param Kp=Kp_lin
.param Kp_lin=IDSx/(VGSx-VTHx-VDSx/2)/VDSx
.param Kp_sat=IDSx*2/((VGSplx-VTHx)^2)
.param VDSx=(Rdsx-Rdrain-Rsource)*IDSx
.param VTH=VTHx

*Mosfet parameters
.param RDStgt=65m
.param Rdrain=1u Rsource=1u
.param lambda=1/235
.param Rdsx=RDStgt  Rdsoff=10Meg
.param VGSx=10 IDSx=12  VTHx=4 VGSplx=5.7

*Diode parameters
.param RDon=7m Rdiode=1m RDoff=10Meg VD=10 VBD=1Meg quad=1
.ends simpleFET
```

Simple PWL diode model

To be extracted from MOSFET datasheet



Params in subckt are overwritten when new values are passed through symbol