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Low-Side MOSFET Drivers Application and Lab Evaluation

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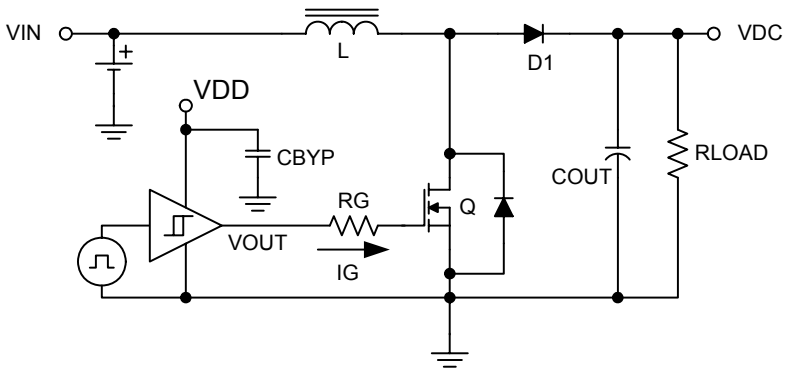
Overview

- Overview of low-side driver applications
  - Clamped Inductive switching
  - Synchronous rectifier switching
  - Transformer drive applications
- Discrete and integrated driver solutions
- Driver datasheet current ratings
- Techniques for evaluating driver current capability in the lab

When are External Drivers Needed?

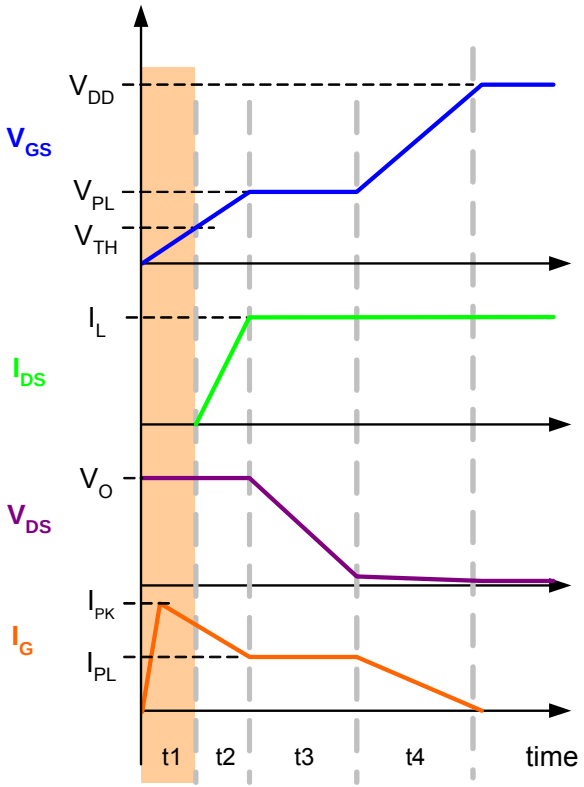
- Direct low-side driver in PWM controller
  - PWM output in low to mid power applications (100 to 200W)
  - Flyback, boost, forward applications
- When is PWM onboard driver acceptable?
  - MOSFET switching times provide acceptable efficiency
  - Control circuit not disrupted by noise
  - Heat dissipation is within acceptable limits
- When are external drivers needed?
  - Higher power requires more current capability
  - Need translation from logic levels to higher gate drive voltage
  - IGBTs need high voltage drive (>15V)
  - Grounding, noise and heat issues affect operation
  - Application requires driving gate or pulse transformers

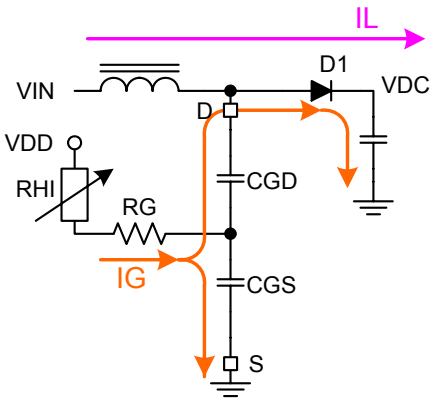
Examine Boost with Clamped Inductive Load



- Non-isolated boost stage
- Illustrates clamped inductive load switching
- Inductor L is large, constant current during switching intervals
- Switching intervals are examined in following slides as in [1], [2]
- Allow user to estimate I_G requirements

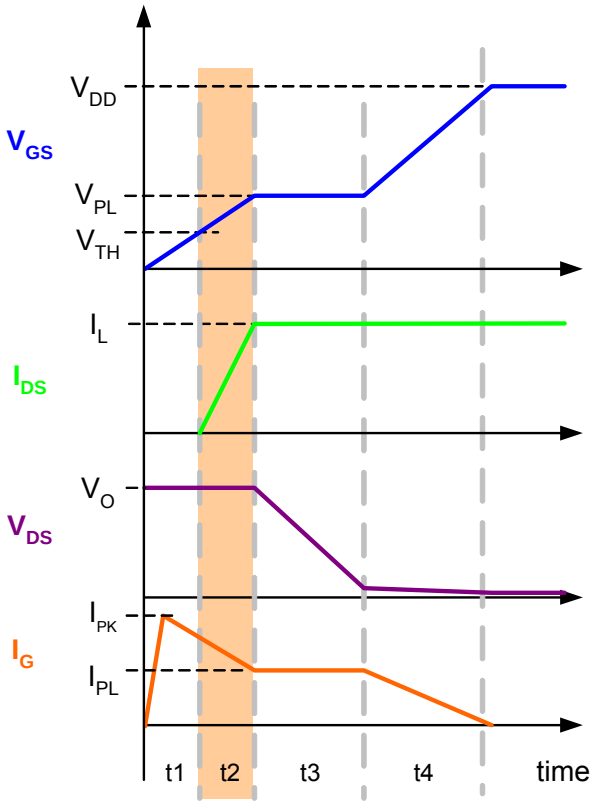
MOSFET Turn on in Interval t1

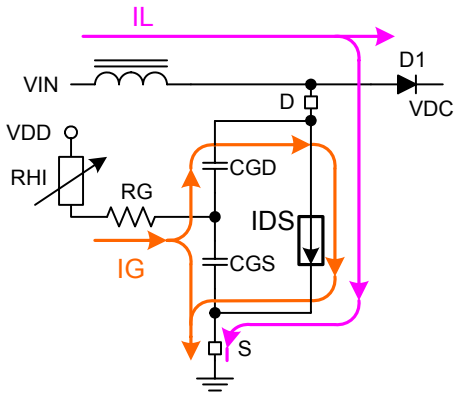




- Initially MOSFET is off, $V_{DS} = V_{OUT}$
- I_G charges $C_{GS}||C_{GD}$ to V_{TH}
- I_G amplitude is limited by
  - driver output current capability
  - external resistance
  - parasitic inductance

MOSFET Turn on Interval t2





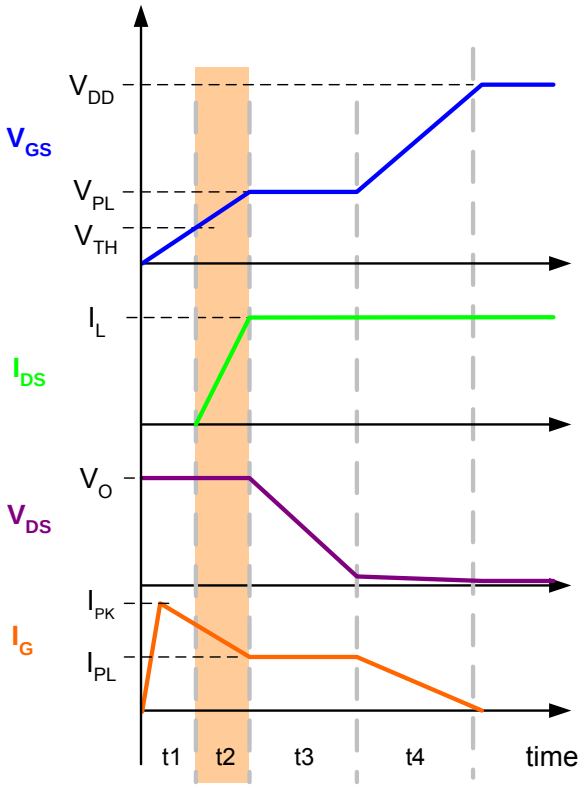
- V_{TH} is exceeded and MOSFET starts conducting in linear mode:

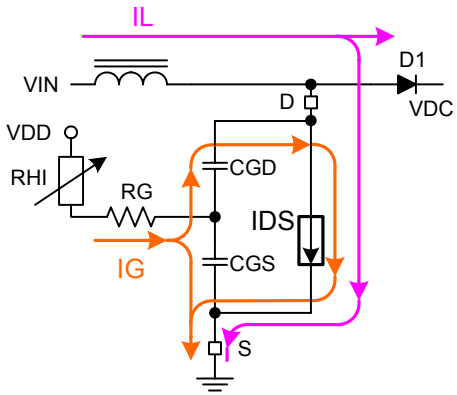
$$I_D = g_m (V_{gs} - V_{TH})$$

- I_{DS} rises in MOSFET channel from 0 to I_L
- During t2 C_{GD} and C_{GS} are charged to a level:

$$V_{PL} = \frac{I_L}{g_m} + V_{TH}$$

What is the Length of Interval t2?



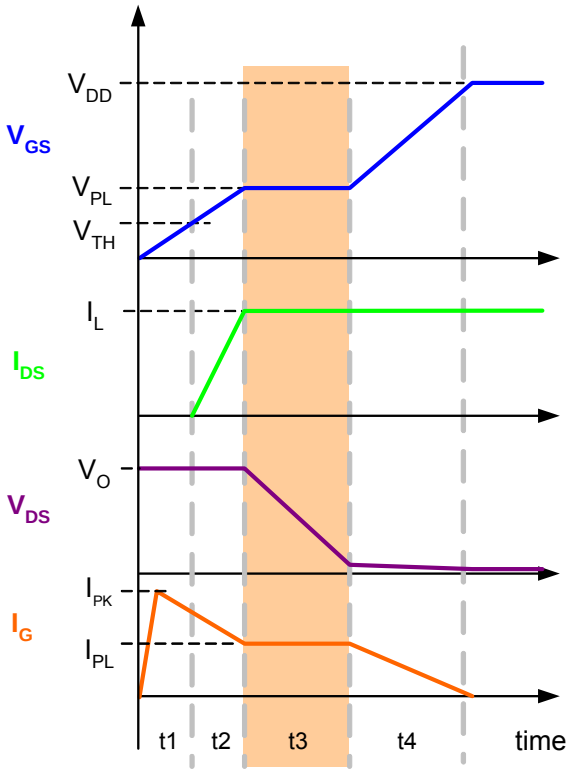


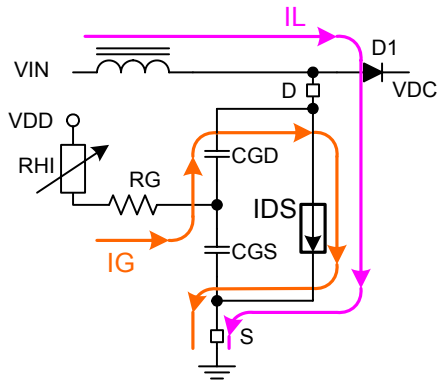
- I_{DS} rises in MOSFET channel from 0 to I_L
- t2 interval length can be defined as

$$t2 = T_{IDS,rise} = \frac{Q_{gs2}}{I_G}$$

- Q_{GS2} specified by MOSFET datasheet
- I_G is the current delivered during t2

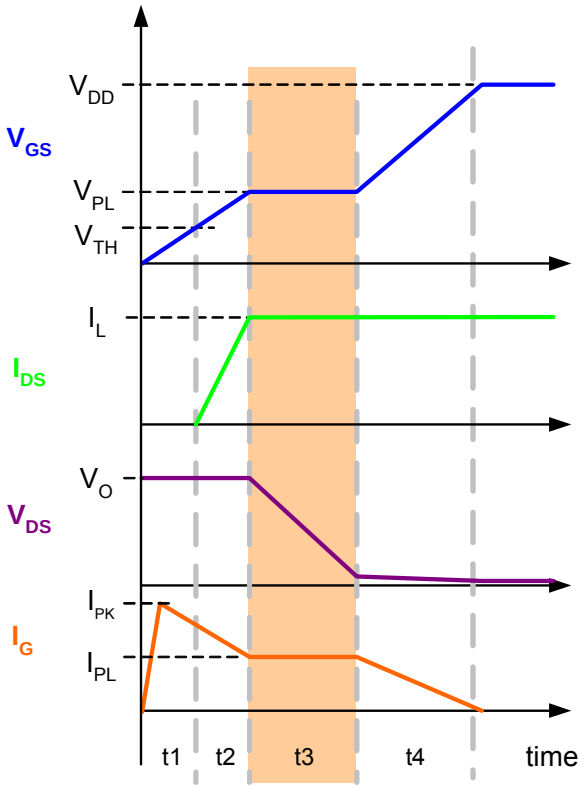
Interval t3 – Known as “Miller” region

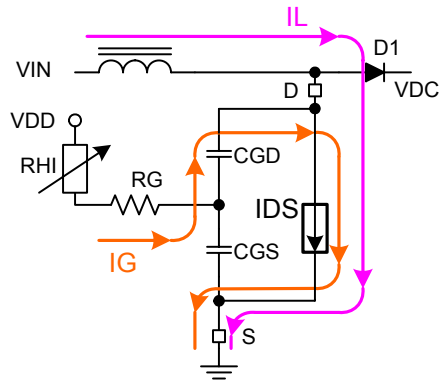




- I_G flows through C_{GD} while V_{GS} remains at V_{PL}
- MOSFET conducts full I_L while V_{DS} falls from V_{DC} toward GND
- How can we determine driver current capability (Amps) required?

What is the Length of Interval t3?



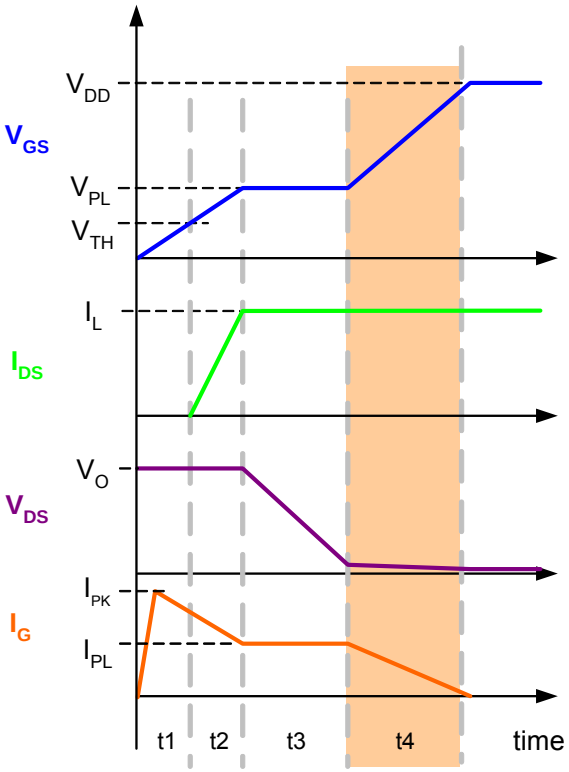


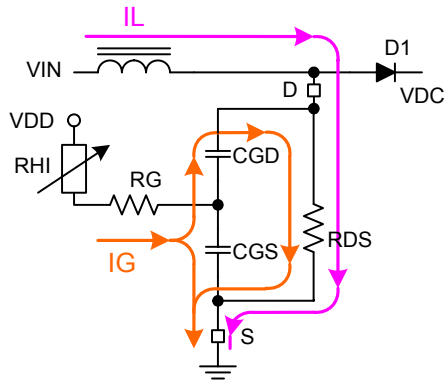
- t3 interval approximated by

$$t3 = T_{vds,f} = \frac{Q_{GD}}{I_G}$$

- Q_{GD} derived from MOSFET datasheet
- I_G is a function of
  - driver current source capability
  - external impedances

MOSFET Turn on Interval t4

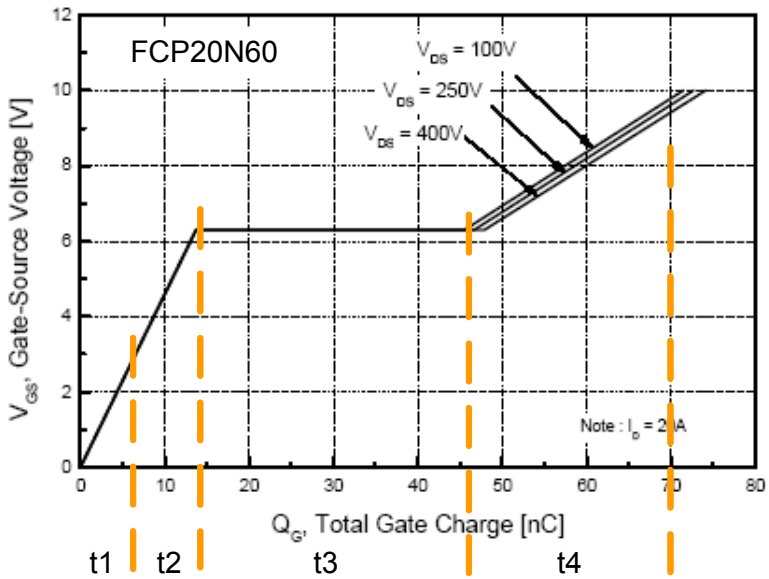




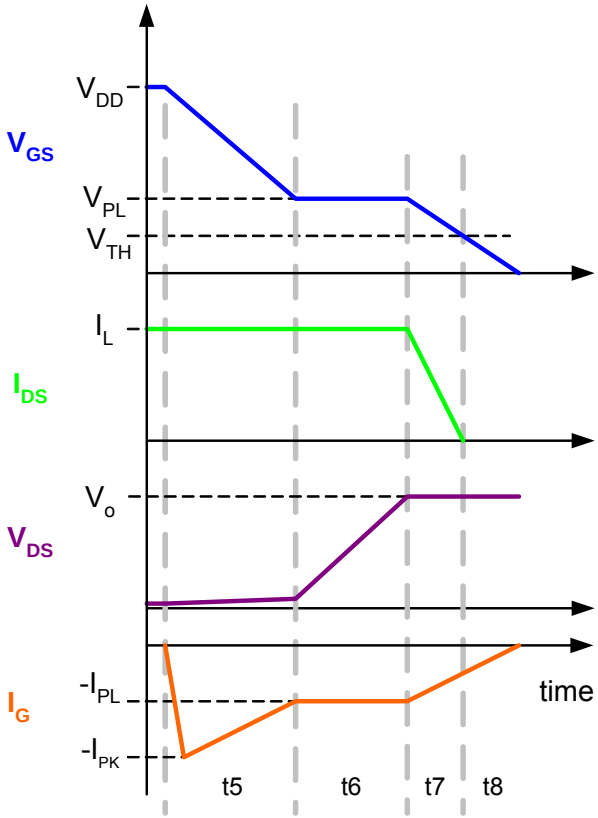
- V_{GS} rises from V_{PL} to V_{DD}
- I_G charges $C_{GD}||C_{GS}$
- R_{DS} reaches low value

Equate Intervals to Datasheet Gate Charge Curve

- t1 – V_{GS} reaches V_{TH} (3V)
- t2 – V_{GS} reaches V_{PL} (6.2V)
- t3 – Q_{GD} delivered as V_{DS} swings low (32 nC)
- t4 – V_{GS} enhanced to 9.5V with $Q_{G,T}$ = 70 nC
- Average current from V_{DD} is $I_{DD} = Q_G \times f_{SW}$

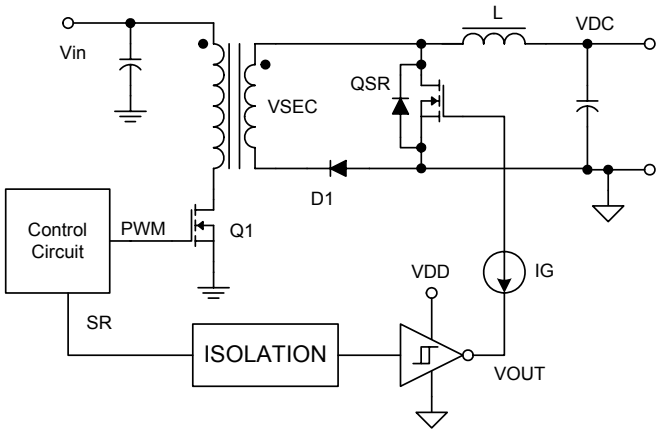


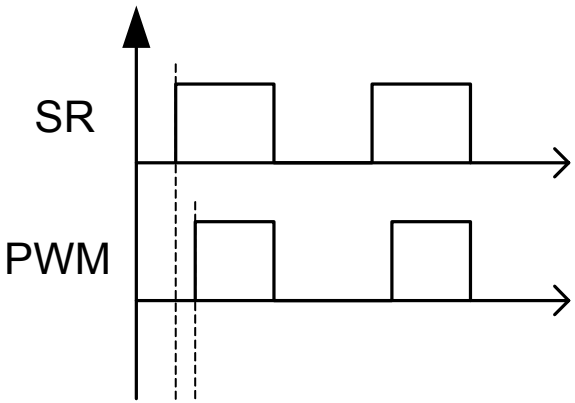
Boost Turn off waveforms



- Turn off proceeds in reverse order from turn on
- t5 – V_{GS} discharges to V_{PL}
- t6 – I_G constant as V_{DS} rises
- t7 – V_{GS} decrease reduces I_{DS}
- t8 – V_{GS} is discharged to 0V

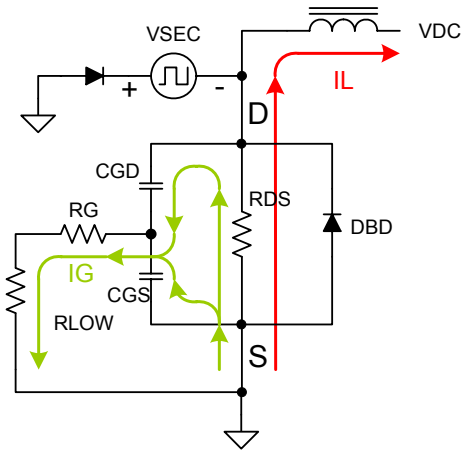
Forward Converter with Secondary Sync. Rectifier

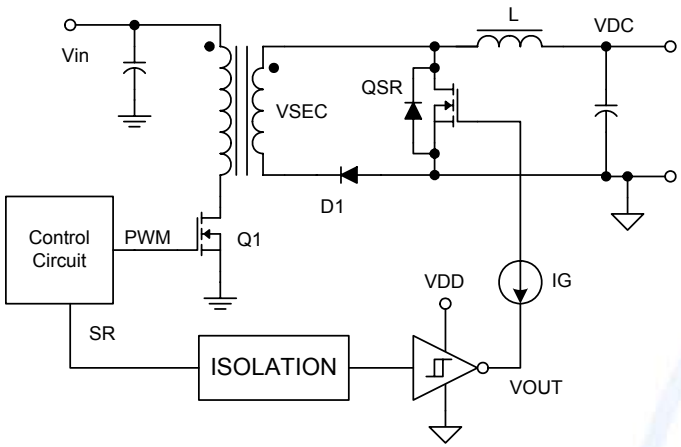




- Simplified forward converter with freewheel diode replaced by Q_{SR}
- Q_{SR} conducts when Q1 is off
- Q_{SR} must turn off before Q1 turns on
- SR signal leads PWM as indicated
- SR signal generation
  - primary controller
  - external timing circuitry

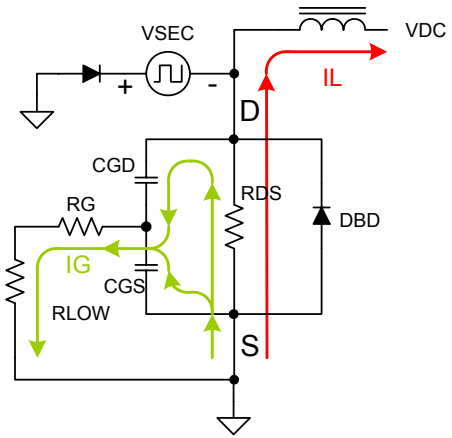
SR MOSFET Turn off operation

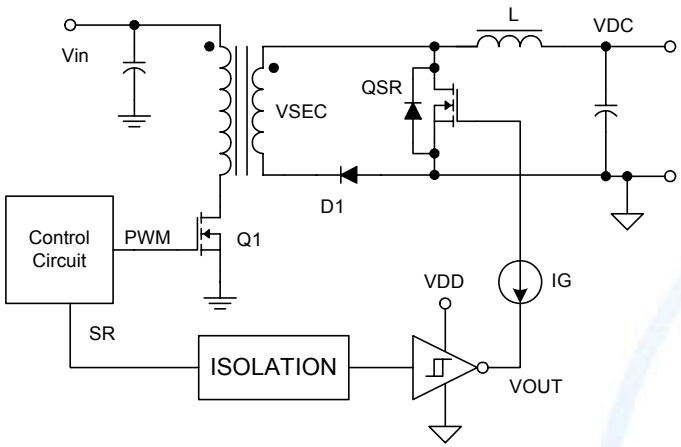




- Initially, inductor current flows through MOSFET channel R_{DS}
- Driver output goes low and sinks current I_G shown
- In many applications there is no external resistor between driver and MOSFET
- How can we determine driver current capability (Amps) required?

What Driver is Needed for SR MOSFET?





- Turn-off time can be estimated using $Q_{Q,SR}$ as determined in [3]

$$t_{off} = \frac{Q_{Q,SR}}{I_G}$$

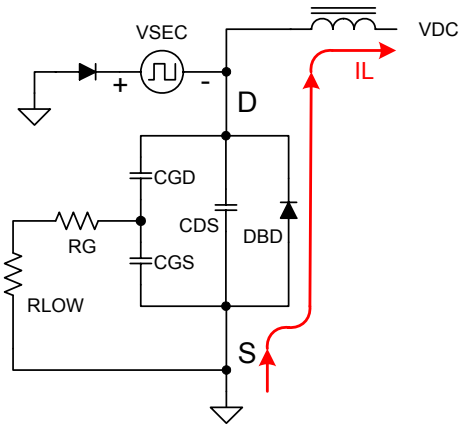
- With $Q_{Q,SR} = (C_{GS} + C_{GD,SR}) \cdot V_{DRV}$

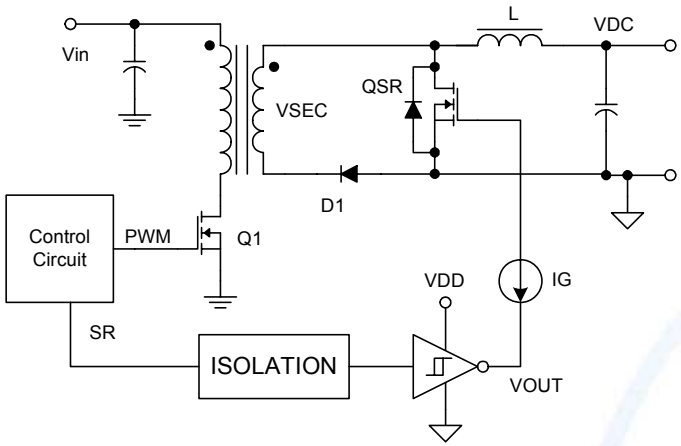
$$C_{GD,SR} = 2 \cdot C_{RSS,SPEC} \cdot \sqrt{\frac{V_{DS,SPEC}}{0.5 \cdot V_{DRV}}}$$

$$C_{GS} = C_{ISS} - C_{RSS}$$

- C_{ISS} and C_{RSS} found on datasheet curves, C_{GS} approximately constant
- What value should be used for I_G?

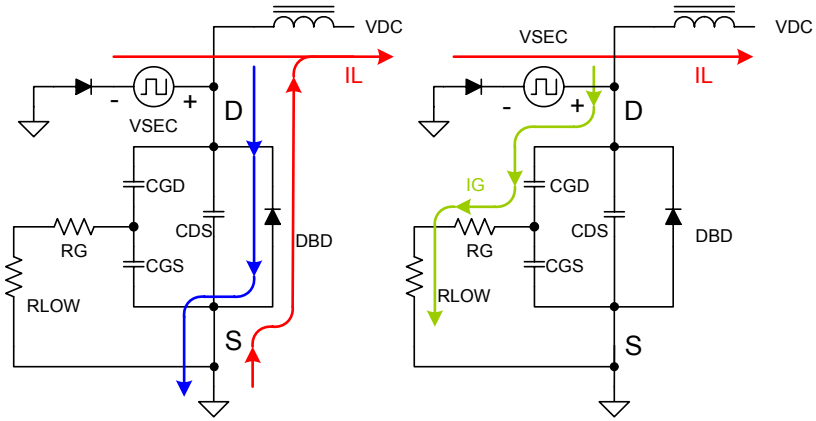
SR MOSFET with Vgs = 0

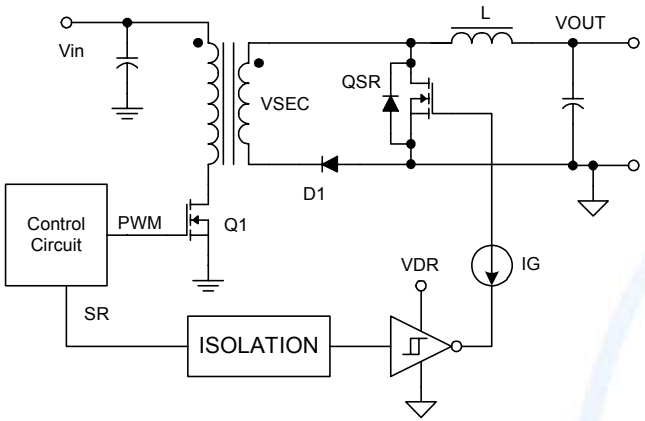




- With MOSFET OFF, I_L flows through body diode D_{BD}
- This current flow is determined by external circuit, not MOSFET gate-source voltage
- No gate current flows

SR MOSFET dV/dT interval





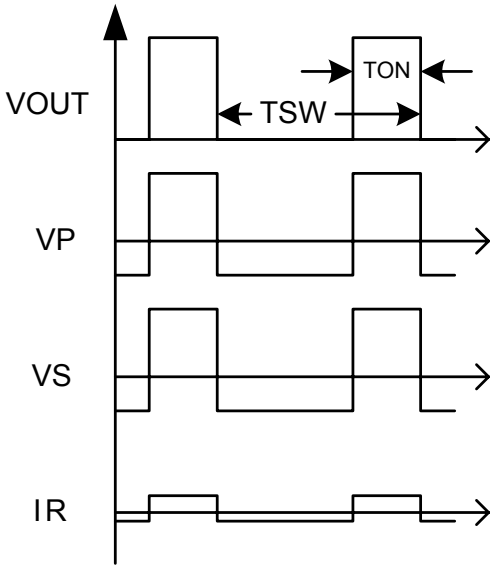
- V_{SEC} polarity switches as shown with V_{SEC} (-) clamped by diode
- This forces reverse recovery current (blue) through body diode and I_L transfers to V_{SEC} (left)
- After D_{BD} recovers V_{DS} rises
- With no current in C_{GS}, driver sinks current (right)

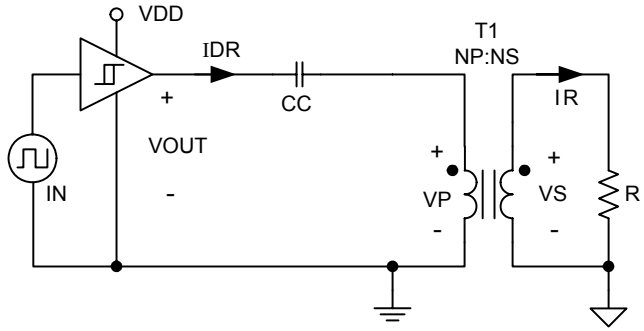
$$I_G = C_{GD} \cdot \left(\frac{dV_{DS}}{dT} \right)$$

Using Drivers in Transformer Applications

- Gate drive transformer applications
  - Higher power converters often have high/low switches
  - High voltage or primary-secondary isolation may be needed
  - Short propagation delays resulting from small leakage inductance improves protection [4]
  - Competition: half-bridge gate drive ICs
- Pulse transformers used for communication
  - communication needed for enhanced performance
  - competition: high speed opto-isolators with digital outputs
- These two applications can look similar

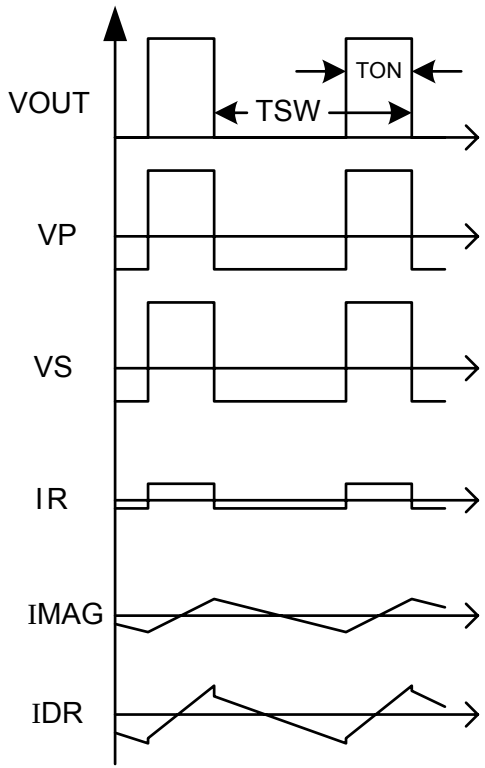
Pulse Transformer With Resistive Load

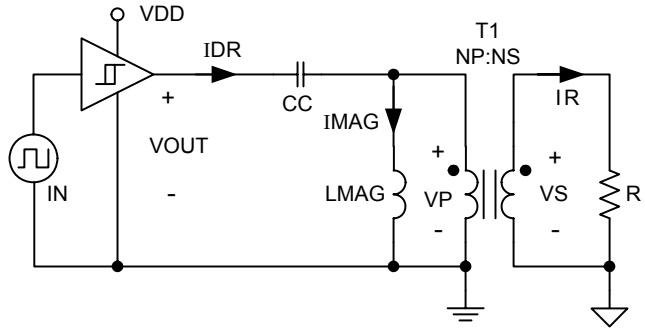




- V_{OUT} has DC voltage component
- Transformer cannot support DC voltage
- C_C blocks DC voltage but passes AC
- C_C selected with ripple voltage <<V_{OUT} while passing I_{DR}
- With Np=Ns, V_P and V_S are centered at 0V and amplitudes change with duty cycle
- Positive Volt-sec = negative Volt-sec

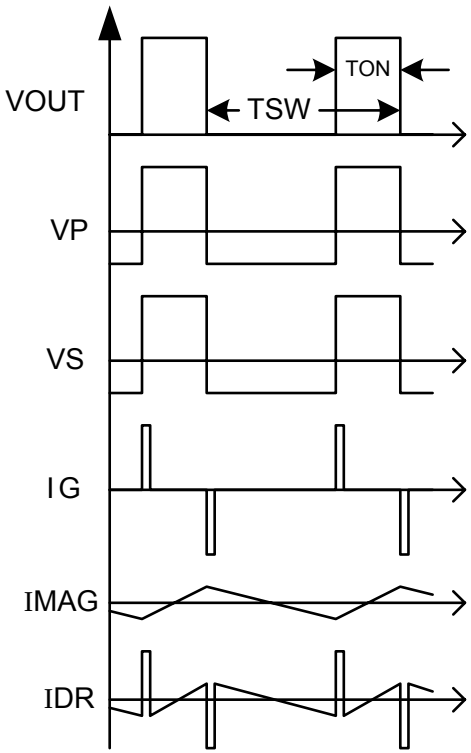
Pulse Transformer With Resistive Load-2

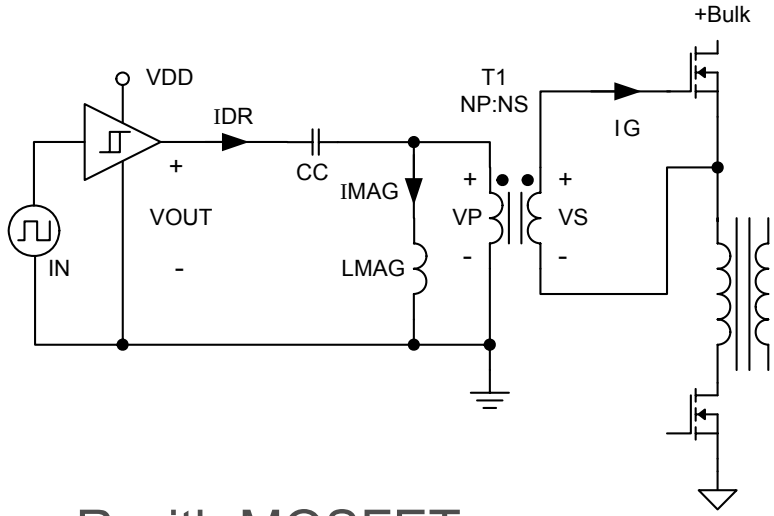




- Transformer is replaced by magnetizing inductance in parallel with ideal transformer
- I_{DR} is equal to magnetizing current I_{MAG} plus reflected resistive current I_R
- I_{MAG} is defined by L_{MAG}, voltage, and time (not load)

Change to MOSFET Gate Drive Application

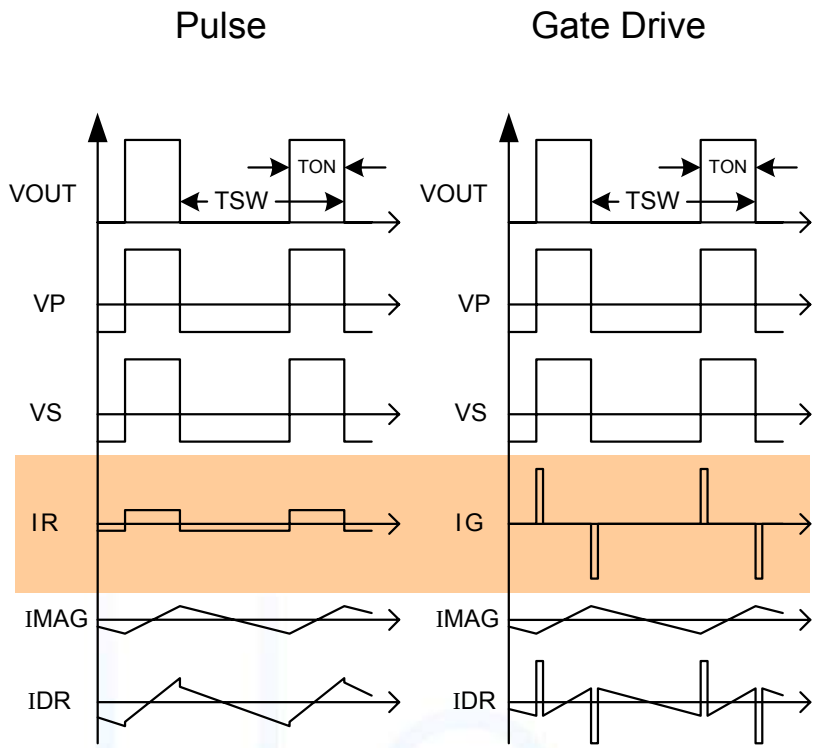




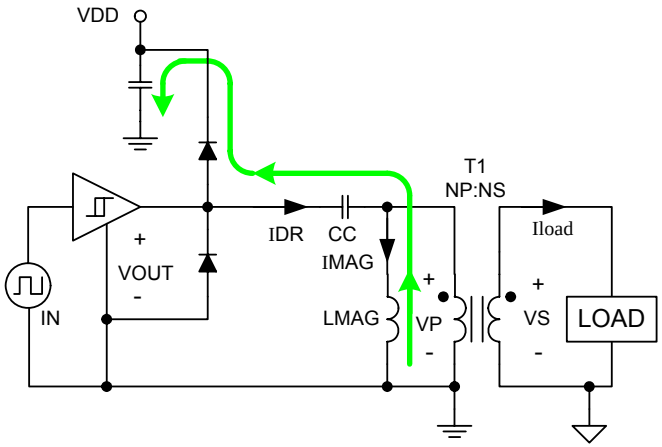
- Exchange R with MOSFET on high side in bridge circuit
- I_{DR} is a combination of pulses to switch MOSFET I_G and magnetizing current I_{MAG}
- Driver must supply I_G pulses for acceptable switching operation

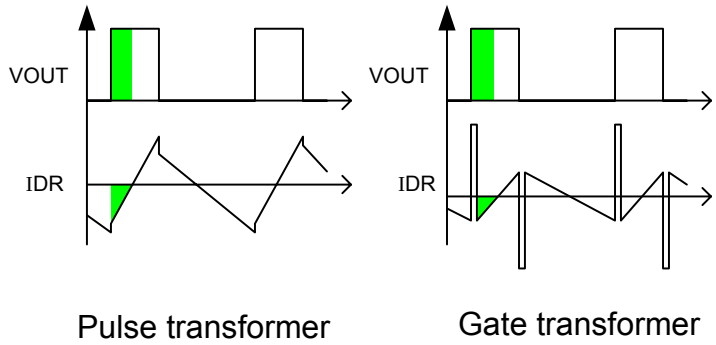
Comparison of Pulse to Gate Drive operation

- For these applications V_{OUT}, V_P, V_S, and I_{MAG} are the same
- I_R and I_G are very different
- Winding DC resistance (DCR) should be checked for voltage drop and losses
- Same transformer often works in either circuit
- Transformer E-T Product (V-us) calculated on secondary side



Driver Reverse Current - V_{OUT} High



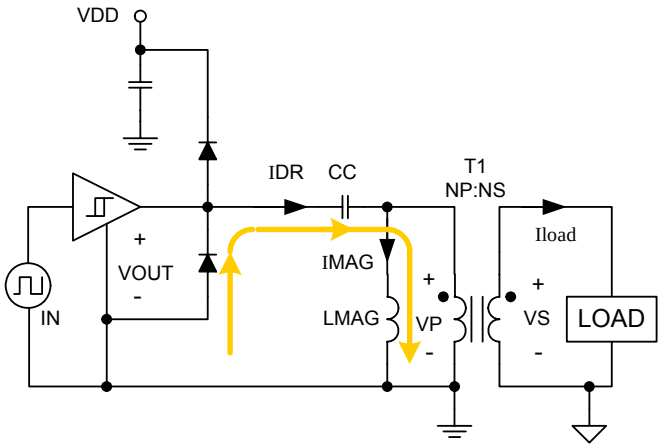


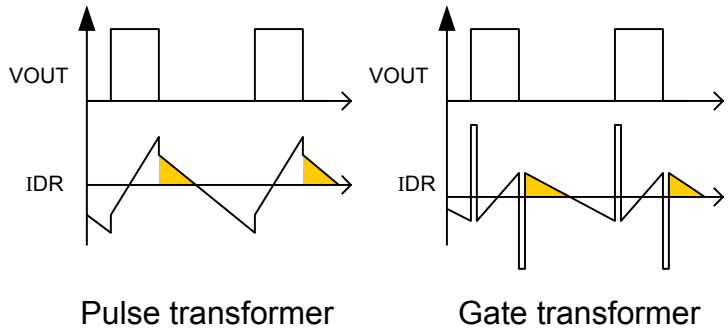
Pulse transformer

Gate transformer

- Before V_{OUT} goes HIGH, I_{MAG} is negative and driver sinks current
- When V_{OUT} goes HIGH driver must continue to sink current
- Bipolar drivers need external diodes, MOSFET drivers can conduct reverse current through channel, body diode

Driver Reverse Current Vout - Low



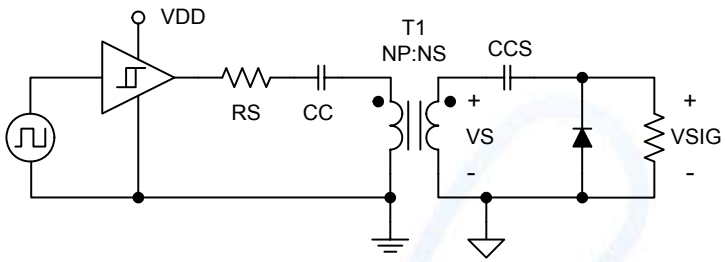


- Before V_{OUT} goes LOW, I_{MAG} is positive and driver sources current
- When V_{OUT} goes LOW driver must continue to source current
- Bipolar drivers need external diodes, MOSFET drivers can conduct reverse current through channel, body diode

Modified Pulse Transformer Circuit

- In initial pulse transformer circuit V_S is related to V_{DD} by turns ratio, and varies with duty cycle
- C_{CS} and D clamp V_{SIG} with GND reference
- C_C and L_{MAG} undergo startup transient
- Series R_S can be selected to provide critical damping

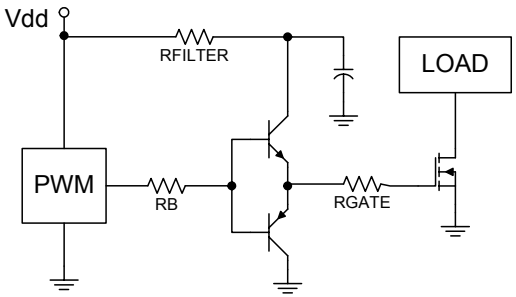
$$R_S = 2 \cdot \sqrt{\frac{L_{MAG}}{C_C}}$$

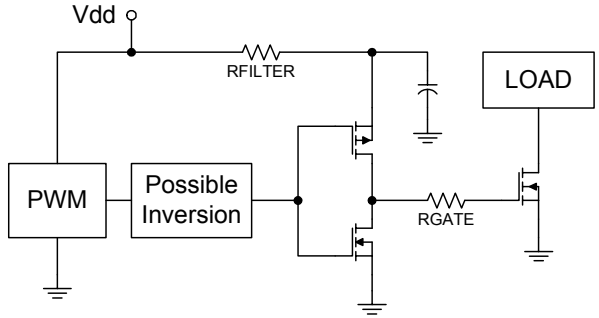


Candidate Circuits for Drivers

- Discrete designs built from bipolar or MOSFET devices
- Integrated circuit devices using bipolar, MOSFET, or compound (combined) device technologies
- All driver applications benefit from:
  - Local bypass capacitor
  - filtering from control circuit Vdd
  - location close to load
  - capability to dissipate power

Discrete Driver Configurations





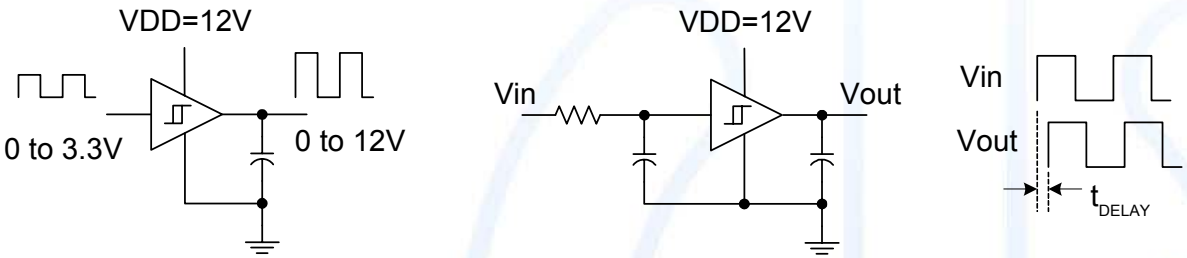
- NPN/PNP emitter follower
  - Non-inverting configuration works directly in phase with control chip
  - No shoot-thru, devices not on simultaneously
  - Output has no ohmic connection to rails
- PMOS/NMOS driver (inverter)
  - Natural inversion requires additional inversion to follow control
  - Overlap in V_{GS} conduction range leads to shoot-thru
  - Rail to rail operation

Discrete Driver Considerations

- More individual devices needed in circuit
  - assembly and test time grow
  - more reliability concerns
- Translation from logic level inputs to higher voltage drive levels adds complexity
- For fast switching, input driving signal needs fast edges (output not fully buffered from input)
- Difficult to introducing delay through drive stage while keeping fast edge rates
- MOS shoot-thru power loss increases with frequency

Integrated Circuit Driver Considerations

- Integrated features can reduce supporting circuitry
  - enable functions can simplify control in SR applications
  - UVLO can provide orderly startup in secondary side circuits
- Facilitates direct translation from TTL inputs to higher V_{GS}
- High impedance inputs with CMOS thresholds facilitate programming time delay in driver (HIGH = 2/3 V_{DD}, LOW = 1/3 V_{DD})
- Device input current usually negligible
- Small MLP packages enable highest density designs
  - dual 2 A, 4 A drivers in 3x3 mm ; single 2 A in 2x2 mm
  - thermal pads allow reduced thermal impedance
- Summary: Less component level design required from users

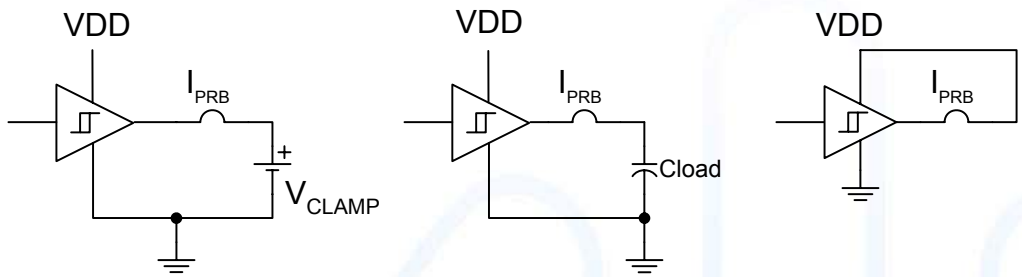


How Ideal are Real Drivers?

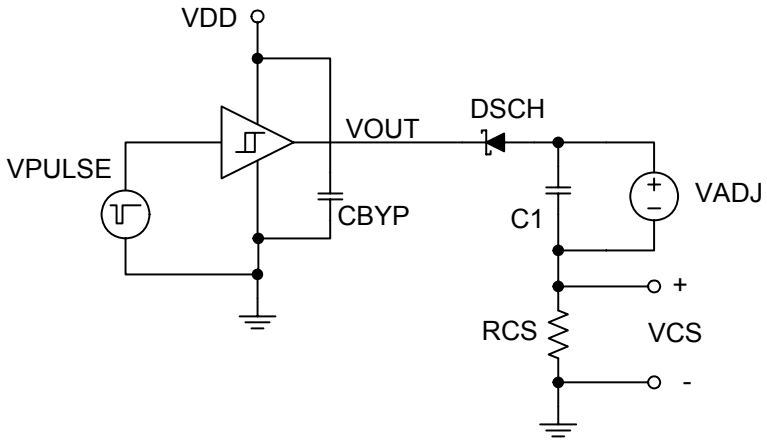
- Many users treat drivers as near-ideal signal amplifiers
- Some assumptions may not be justified:
  - Sink and source current defined by series resistances
  - Output slew rates are instantaneous
- Output current varies with V_{DD}, parasitic impedances, size of external load, temperature, other factors
- Output rise/fall specifications don't give much insight into instantaneous current capability

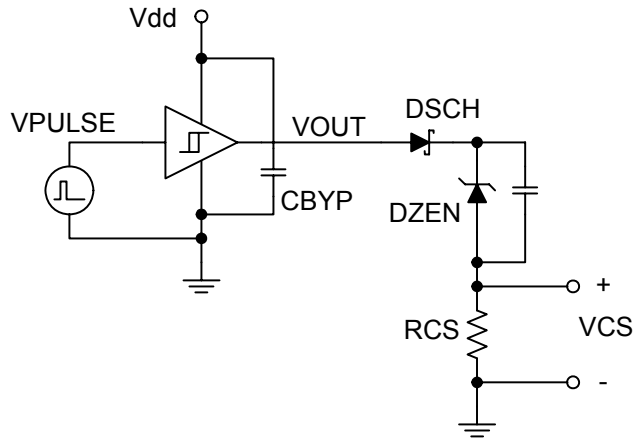
How do Driver Datasheets Rate Current?

- Current specified in one of several ways
  - Peak current available from driver
  - Current available with output at clamped voltage level
  - Current available through low value resistance (or short circuit)
  - Measure current with current probe – bandwidth, inductance concerns
- All driver measurements require attention to detail!



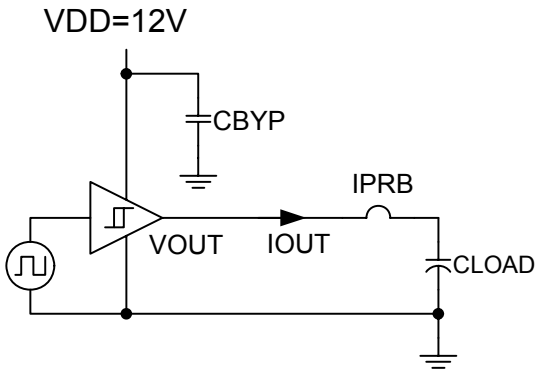
Clamped Circuits for Pulsed Testing





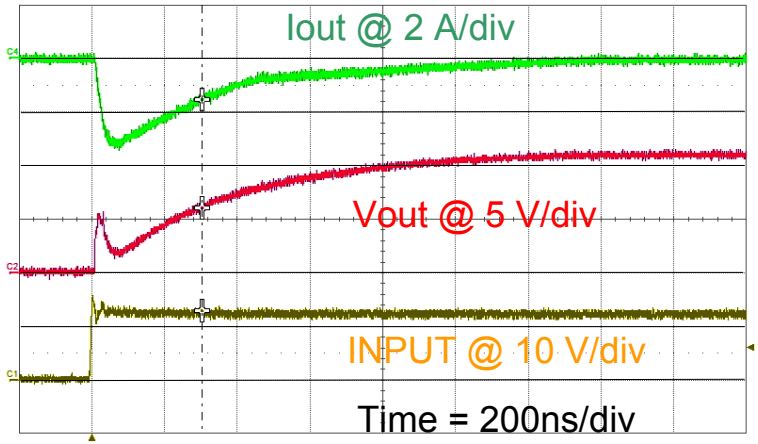
- These circuits test current capability for pulses of 200ns with **minimal** external resistance (R_{CS} is 0.05 Ω)
- With good layout, transient dies out < 100ns
- V_{PULSE} is 200ns pulse at low duty cycle, 2%
- At left – I_{SINK} is monitored as V_{CS} goes negative
- On right – I_{SOURCE} is monitored as V_{CS} is positive

Driver Testing Using Large Loads

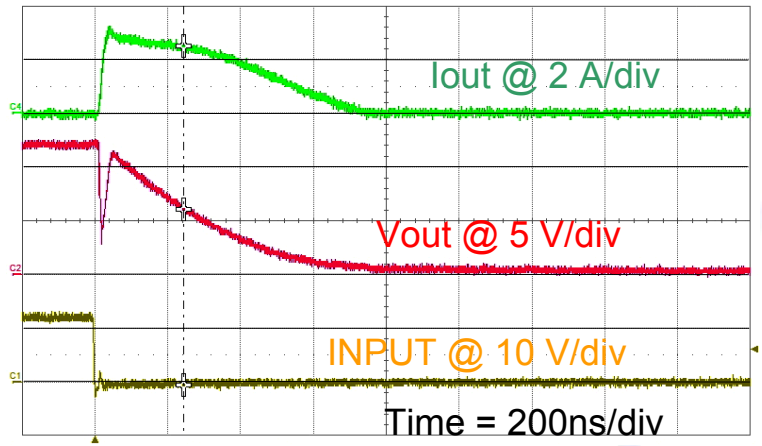


- I_{PRB} monitors I_{OUT} charging or discharging a large capacitor
- C_{LOAD} chosen as 100x capacitor used in rise/fall time specs
  - 2 Amp – 100 x 1nF = 0.1uF
  - 4 Amp – 100 x 2.2nF = 0.22uF
- This allows measurement of I_{OUT} at various values of V_{OUT}
- This is maximum current available from driver with **NO** external resistance
- This equates to the pulse current values obtained in clamped sink and source circuits

Look at 2 Amp Drivers with Large Load



- Top picture FAN3227C I_{SOURCE}
  - Approximately 3 Amps $I_{OUT,peak}$
  - I_{SOURCE} = 1.5 Amps @ $6V_{OUT}$

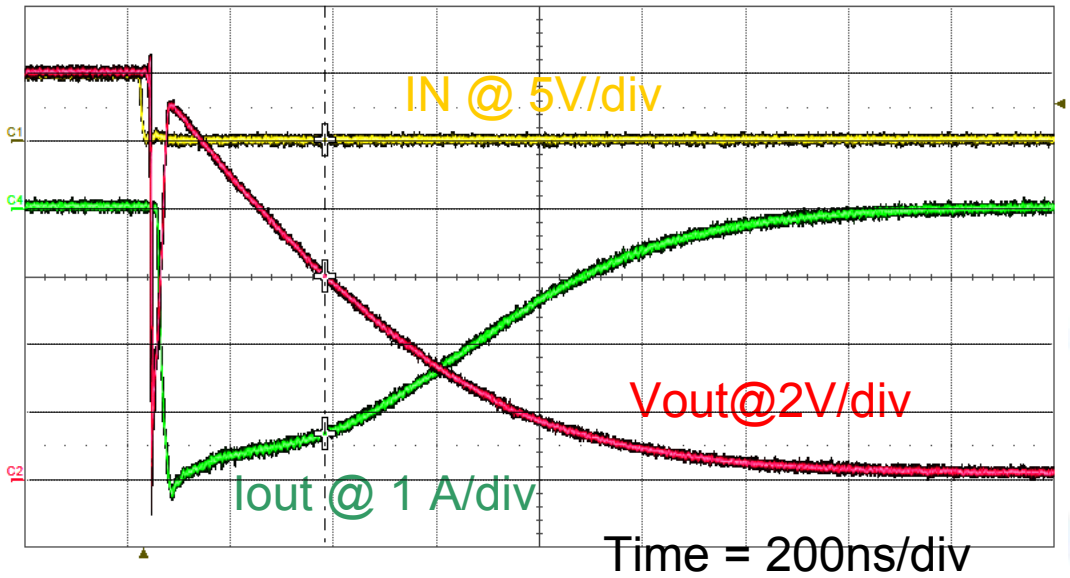


- Bottom picture FAN3227C I_{SINK}
  - Approximately 3 Amps $I_{OUT,peak}$
  - I_{SINK} = 2 Amps @ $6V_{OUT}$

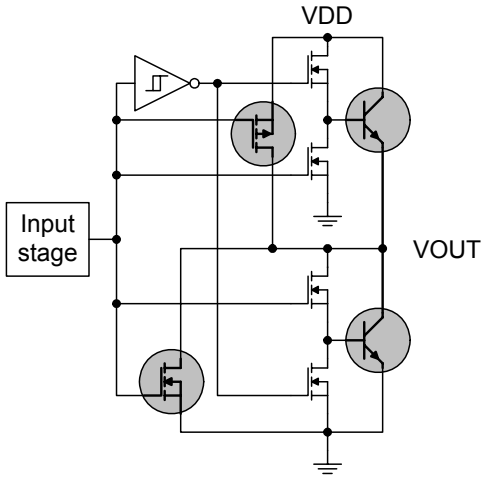
- Note initial transient due to current loop inductance (<100ns)

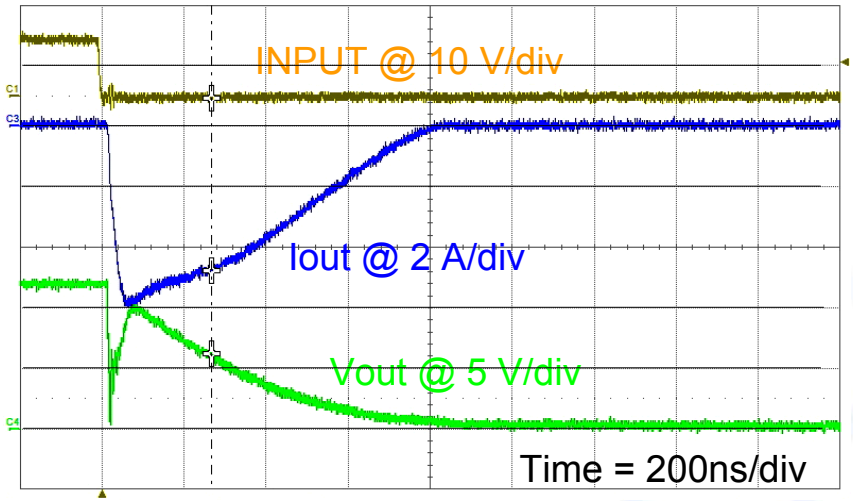
Integrated MOSFET Drivers with Large Load

- MOS-based drivers spec peak current and $R_{DS,high}$ or $R_{DS,low}$
- The $R_{DS,\ on}$ values not achieved during early stages of turn on
- Peak current is significantly less than $I=V_{DD}/R_{DS}$
- In examples tested, datasheet current rating is peak current available from device



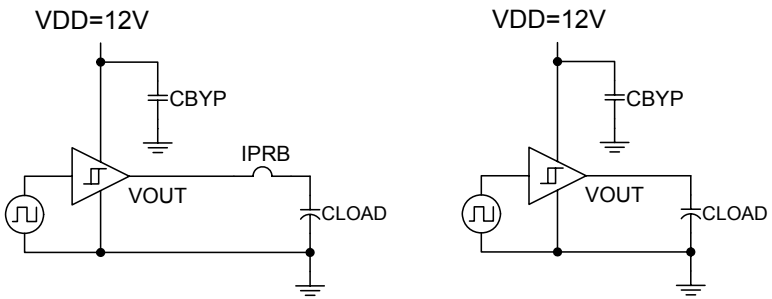
Integrated Driver with Compound Output Stage

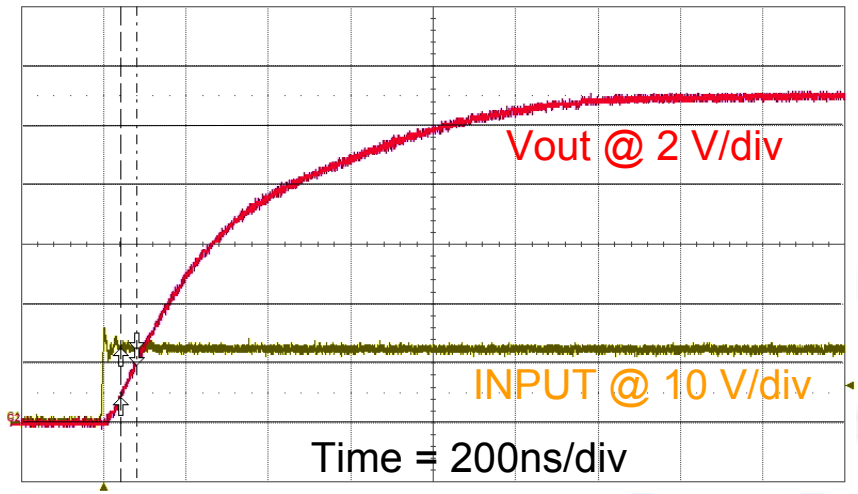




- Compound output stage combines bipolar and MOSFET
- Bipolars provide current during mid range of V_{OUT} and clamp V_{OUT} within 1 volt of rails
- MOSFETs pull V_{OUT} to rails and offers bi-directional current capability
- FAN3224C shows 6 Amp $I_{SINK,pk}$
- FAN3224C sinks 4.5 Amps at V_{OUT} = 6V (datasheet says 4 Amp driver)

Now Remove Current Probe





- I_{PRB} requires wire loop for current probe
- C_{LOAD} is surface mount 0.1uF, (0805) with minimal inductance
- Note lack of initial transient!
- Calculate current from familiar equation applied over short, approximately linear interval.

$$I = C_{LOAD} \cdot \left(\frac{dV_{OUT}}{dT} \right)$$

$$I = 0.1uF \cdot \left(\frac{1.131V}{40.6ns} \right) = 2.8A$$

Summary of Driver Presentation

- Key low-side driver applications include
  - ground referenced switches
  - SR applications
  - pulse and gate drive transformer applications
- Potential drivers include integrated and discrete
  - PMOS-NMOS drivers
  - bipolar drivers
  - compound drivers which combine bipolar and MOSFET
- Lab evaluation of drivers current capability
  - presented progression of pulse and “large load” circuits
  - correlated lab data provide confidence in results

References

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[3] Balogh, L. “Design and Application Guide for High Speed MOSFET Gate Drive Circuits,” Power Supply Design Seminar SEM-1400, Topic 2, Texas Instruments Literature No. SLUP169

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[5] 2006 Fairchild Power Seminar Topic, “Practical Power Application Issues for High Power Systems,” http://www.fairchildsemi.com/powerseminar/pdf/practical_power_high_power_systems.pdf

[6] Johnson, H. Dr, “High-Speed Digital Design On-Line Newsletter,” Vol. 3 Issue 8, www.sigcon.com/Pubs/news/3_8.htm