Application Report
SLVA714 – June 2015

Understanding IDRIVE and TDRIVE in TI Motor Gate Drivers

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ABSTRACT

The motor gate driver is an integrated circuit (IC) that primarily deals with enhancing external power MOSFETs in order to drive an electric motor. The gate driver acts as an intermediate stage between the logic level control inputs and the power MOSFETs. The gate driver must be flexible enough to accommodate a wide variety of external MOSFETs and external system conditions.

Texas Instrument's IDRIVE and TDRIVE features provide an intelligent solution for driving the external power MOSFETs. These features allow system designer's to adjust the MOSFET slew rate, optimize switching and EMI performance, reduce BOM count, and provide additional protection for the motor system design.

This report will describe the theory and methods behind enhancing a power MOSFET, how the IDRIVE and TDRIVE features are implemented in TI motor gate drivers, and detail the system level benefits.

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1 Power MOSFET Theory and Operation

1.1 Basics

The **metal-oxide-semiconductor field-effect transistor** or **MOSFET** is the most common transistor utilized in electronic circuit design today. It has many properties that make it useful in a variety of applications. These properties include its scalability, low turn ON current, high switching speeds, and high OFF state impedance. The MOSFET has found homes in integrated circuit design (analog and digital), switching power applications, motor control, load switches and numerous others.

The MOSFET consists of four terminals; the drain (D), source (S), gate (G), and body (B). Often, the body terminal is short-circuited to the source terminal making it a three-terminal device.

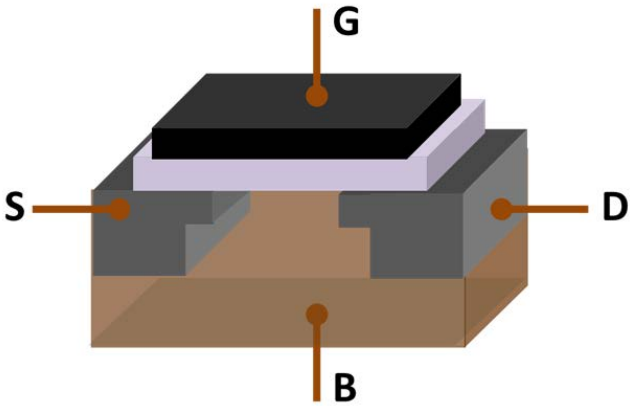

Figure 1. MOSFET Model

The MOSFET has three basic regions of operation that can be defined with a few simple equations.

Cutoff	$V_{GS} \leq V_{th}$
Linear	$V_{GS} > V_{th}$, $V_{DS} \leq V_{GS} - V_{th}$
Saturation	$V_{GS} > V_{th}$, $V_{DS} > V_{GS} - V_{th}$

V_{GS} = Voltage between the MOSFET's gate and source terminals.

V_{DS} = Voltage between the MOSFET's drain and source terminals.

V_{th} = MOSFET threshold voltage

The **cutoff** region is where the MOSFET is "OFF" and there is no conduction between the drain and the source. In the **linear** region the MOSFET is "ON" and the MOSFET behaves similar to a resistor controlled by the gate voltage with respect to both the source and drain voltages. Lastly, in the **saturation** region, the MOSFET is "ON" and behaves similar to a current source controlled by the drain and gate-to-source voltages.

1.2 Parameters

Figure 2 is a common MOSFET model highlighting the terminal-to-terminal capacitances and gate resistance.

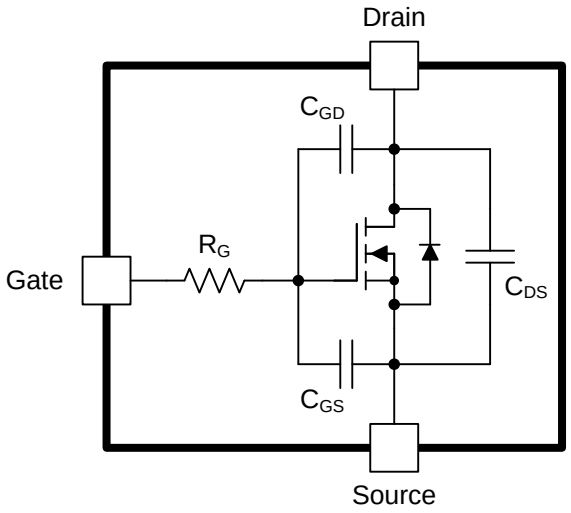

Figure 2. MOSFET Circuit Model

While C_{GS} is fairly constant, C_{GD} and C_{DS} vary heavily with the gate-to-drain voltage, drain-to-source voltage, and applied frequency. Looking at some typical power MOSFET datasheet parameters we can begin to understand some of these values and how they affect the switching performance of the MOSFET.

Table 1. MOSFET Datasheet Parameters

DYNAMIC CHARACTERISTICS					
C_{iss}	Input Capacitance	V_{GS} = 0 V, V_{DS} = 30 V, f = 1 MHz	3250	4230	pF
C_{oss}	Output Capacitance		622	808	pF
C_{rss}	Reverse Transfer Capacitance		15	20	pF
R_G	Series Gate Resistance		0.8	1.6	Ω
Q_g	Gate Charge Total (4.5 V)	V_{DS} = 30 V, I_D = 28 A	20	26	nC
Q_g	Gate Charge Total (10 V)		41	53	nC
Q_{gd}	Gate Charge Gate-to-Drain		6.7		nC
Q_{gs}	Gate Charge Gate-to-Source		8.8		nC
$Q_{g(th)}$	Gate Charge at V_{th}		6.3		nC
Q_{oss}	Output Charge	V_{DS} = 30 V, V_{GS} = 0 V	83		nC
$t_{d(on)}$	Turn On Delay Time	V_{DS} = 30 V, V_{GS} = 10 V, I_{DS} = 28 A, R_G = 0 Ω	6		ns
t_r	Rise Time		9		ns
$t_{d(off)}$	Turn Off Delay Time		20		ns
t_f	Fall Time		3		ns

C_{ISS} = A measure of the input capacitance between the gate and source terminals with the drain and source shorted ($C_{ISS} = C_{GS} + C_{GD}$).

C_{OSS} = A measure of the output capacitance between the drain and source terminals with the gate and source shorted ($C_{OSS} = C_{DS} + C_{GD}$).

C_{RSS} = The reverse transfer capacitance measured between the drain and gate terminals with the source connected to ground ($C_{RSS} = C_{GD}$).

R_G = The series resistance in line with the gate terminal.

To account for variation in the capacitance value with respect to voltage a gate charge curve is typically used to provide more meaningful information. Gate charge values relate to the charge stored within the inter-terminal capacitances. Gate charge is more useful for system designers since it takes into account the changes in capacitance with respect to voltage during a switching transient.

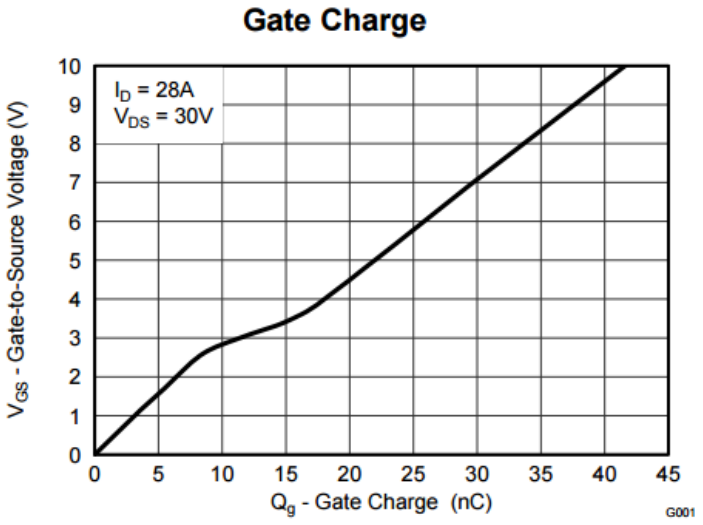

Figure 3. MOSFET Gate Charge Curve

Q_G = The total gate charge required to raise the gate-to-source voltage to the specified value (4.5 V and 10 V are commonly used voltages).

$Q_{G(th)}$ = The charge required from 0 V to the threshold voltage of the MOSFET. Current will begin to flow from the drain to the source at the threshold voltage.

Q_{GS} = The charge required from 0 V to the Miller plateau voltage. At the plateau voltage the drain-to-source voltage will begin to slew.

Q_{GD} = The charge required to move through the Miller region. The Miller region derives its name from the fact that the gate-to-source voltage remains relatively constant during this period as the reverse transfer capacitance is charged. You will see the MOSFET V_{DS} slew during this period as the MOSFET becomes enhanced.

1.3 Turn On Behavior

The information in section 1.2 tells us that a specific amount of charge is required to bias the gate to a certain voltage. Using these parameters we can begin to understand how the MOSFET will behave when certain voltages and currents are applied to it. Figure 4 shows the typical turn on response of a MOSFET.

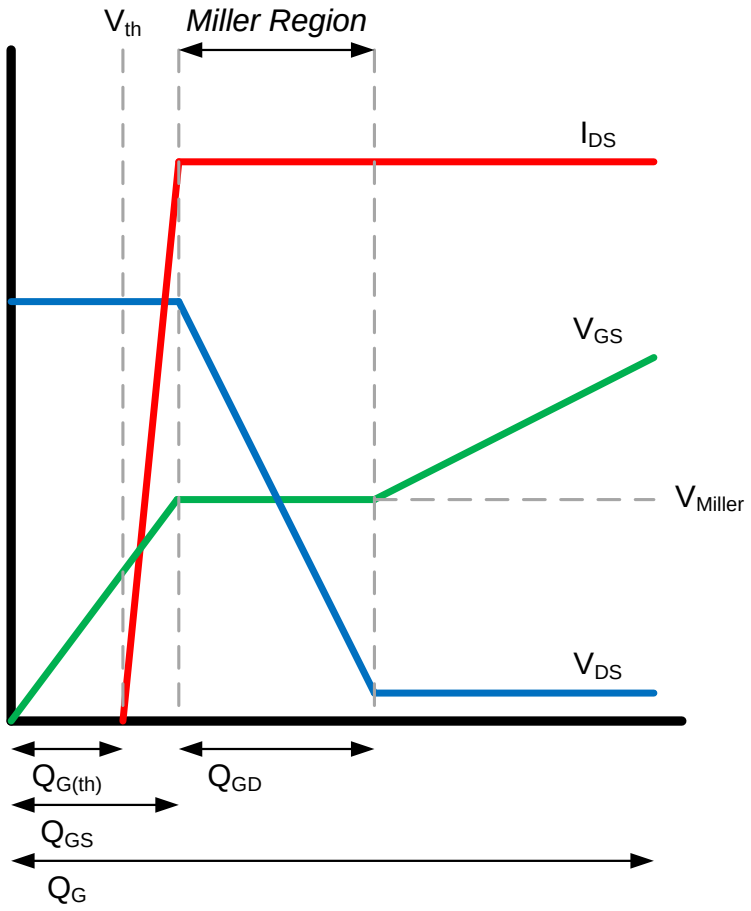

Figure 4. MOSFET Turn On Response

The curve begins with the gate-to-source voltage increasing as charge is supplied to the gate. Once the gate-to-source voltage reaches the MOSFET threshold voltage, current begins to flow from the drain to the source. The gate-to-source voltage will then remain fairly steady as the MOSFET moves through the Miller region. During the Miller region the drain-to-source voltage will drop. After the Miller region the gate will continue to charge until it reaches the final drive voltage.

1.4 Simple Slew Rate Calculation

Unfortunately, calculating precise MOSFET V_{DS} slew rates from parameters and equations requires specific knowledge of the MOSFET, the board and package parasitics, and detailed information on the gate drive circuit. These calculations go beyond the scope of this paper. This paper will just focus on simple first order approximations that are compared to lab data.

Since the MOSFET V_{DS} slew occurs during the Miller region, we can take the Miller charge (Q_{GD}) and gate drive strength to approximate the slew rate. The first assumption that will be made is that we are utilizing an ideal or close to ideal constant current source for the MOSFET gate drive.

Example:

The waveform in Figure 5 shows a DRV8701 driving a CSD18532Q5B at 24 V. The DRV8701 is configured for its 25-mA source current setting. The purple signal is V_{DS} and the yellow signal is V_{GS}. The waveform shows an approximately **312 ns** slew rate which matches closely with our first-order approximation calculated below.

Q_{GD} = 6.9 nC

I_{SOURCE} = 25 mA

$t_{SLEW} = Q_{GD} / I_{SOURCE}$

t_{SLEW} = 6.9 nC / 25 mA = **276 ns**

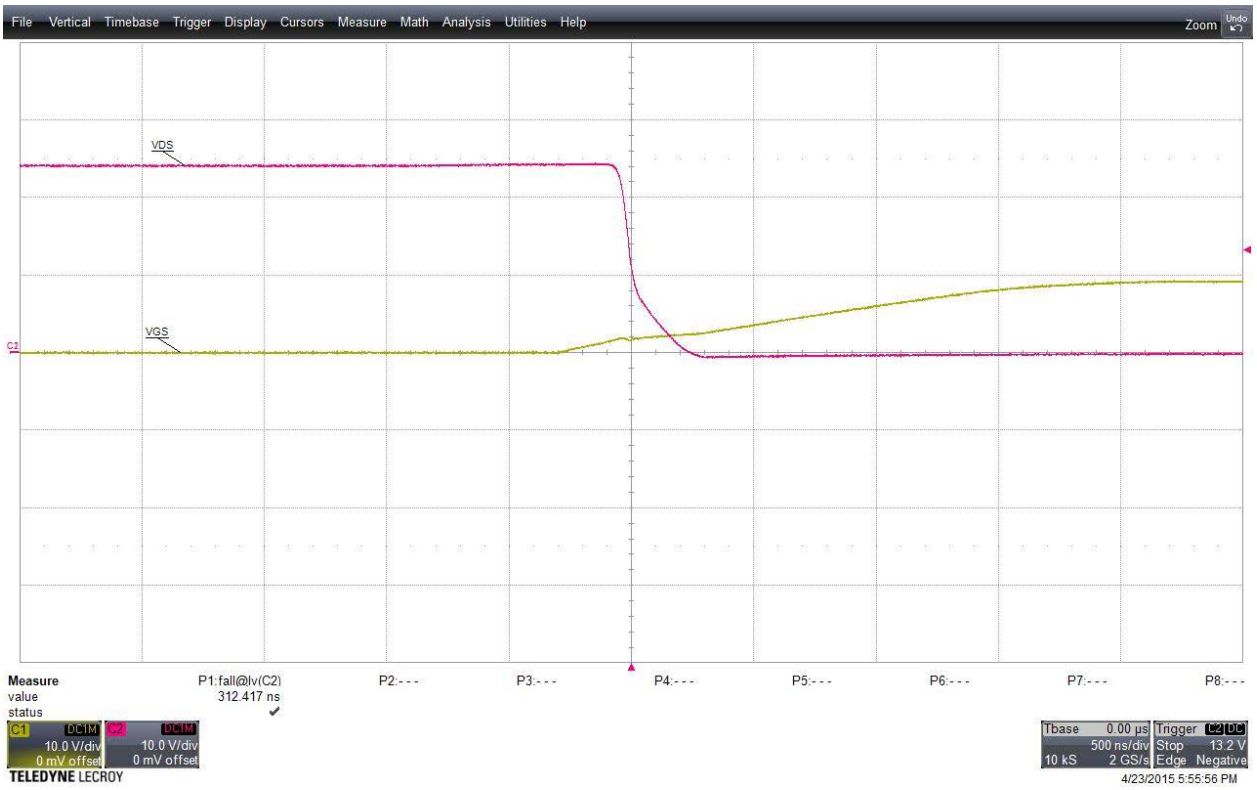

Figure 5. Measured MOSFET Slew Rate

1.5 Gate Drive Current

There are two key current parameters that should be examined when designing a switching power MOSFET system such as a motor driver.

1.5.1 Peak Gate Drive Current

This is the peak current that the gate driver can source or sink to the power MOSFET gate during the turn ON and turn OFF periods. This value will be primarily responsible for how fast the MOSFET can slew.

Example:

The DRV8701 supports a peak source current of 150 mA and a peak sink current of 300 mA. Using the example from section 1.4, a rise and fall time can be calculated.

Rise Time:

Q_{GD} = 6.9 nC

I_{SOURCE} = 150 mA

$t_{RISE} = Q_{GD} / I_{SOURCE}$

t_{RISE} = 6.9 nC / 150 mA = **46 ns**

Fall Time:

Q_{GD} = 6.9 nC

I_{SINK} = 300 mA

$t_{FALL} = Q_{GD} / I_{SINK}$

t_{FALL} = 6.9 nC / 300 mA = **23 ns**

1.5.2 Average Gate Drive Current

This is average current required from the gate driver when switching the power MOSFETs constantly. As shown above, the amount of charge to switch a power MOSFET is small (6.9 nC), but when switching the MOSFET in the kHz range this charge will average into a constant current draw from the gate driver supply.

The average gate drive current can be approximated with a simple equation.

$I_{AVG} = Q_G$ x # MOSFETs Switching x Switching Frequency

Example:

I_{AVG} = 6.9 nC x 6 x 45 kHz = **1.863 mA**

2 IDRIVE and TDRIVE

2.1 IDRIVE Implementation

As seen in the previous section, precisely controlling the current applied to the MOSFET gate allows one to make a reasonable calculation for and adjust the MOSFET V_{DS} slew rate. This is a valuable feature in power stage design and several system level benefits will be expanded on later in this paper.

Texas Instruments incorporates an adjustable gate drive current scheme in many of its motor gate drivers in order to easily control the MOSFET slew rate. This feature goes under the name IDRIVE. This section will detail how IDRIVE is commonly setup and implemented.

The most commonly implemented method is shown in Figure 6. In this method a MOSFET pre-driver switch is enabled between the gate and the voltage supply to manage the current directed to the external power MOSFET gate.

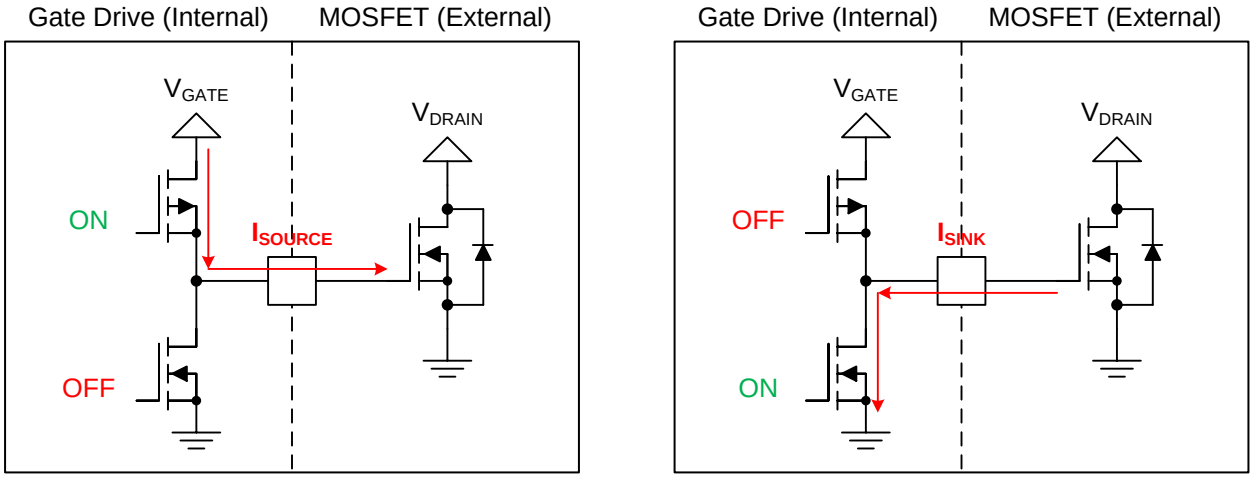

Figure 6. Switch IDRIVE Method

In order to control the current to the gate of the external MOSFET during the V_{DS} slew, the gate driver takes advantage of several MOSFET properties.

1. If the switch (pre-driver MOSFET) can be operated in the saturation region (Section 1.1) the current to the external MOSFET will be limited to a fixed value.
2. As the external MOSFET moves through the Miller region the gate-to-source voltage will plateau and remain relatively constant (Section 1.3).

Using these two properties, the gate driver can ensure the proper voltage bias is applied to the gate of the pre-driver switch and the switch is in the saturation region for the duration of the Miller charging period. Since the gate of the external MOSFET appears as a short (AC voltage applied to a capacitance) the source or sink current will be limited to the saturation current of the switch.

By utilizing multiple switches (shown in Figure 7), the gate driver can alternate between different current levels during normal operation.

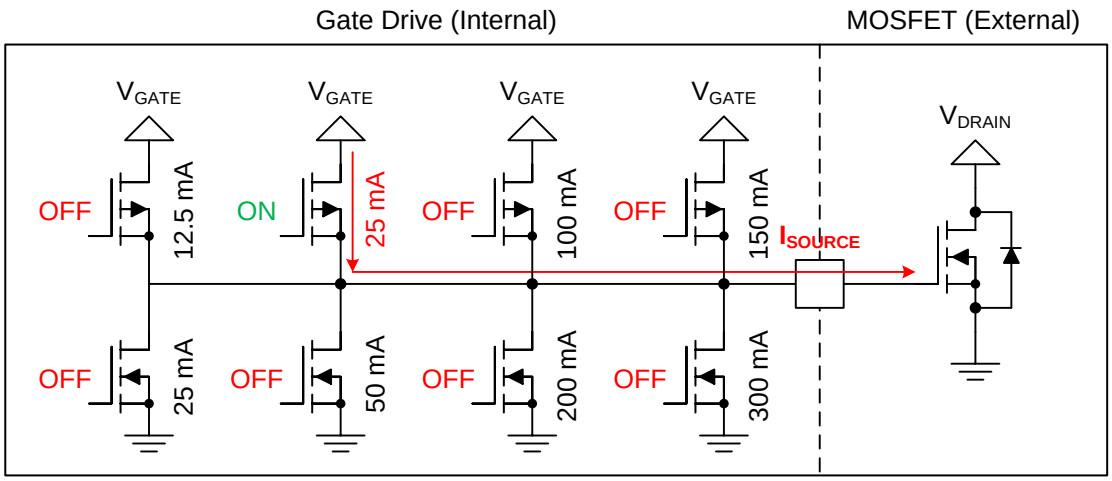

Figure 7. Multiple IDRIVE Settings

The second method to implement the IDRIVE feature utilizes current sources instead of switches. This is done in applications that require very precise and consistent control of the external MOSFET V_{DS} slew rate across device, voltage, and temperature. While a switch in saturation can be sized appropriately to act as a simple current source, there will still be variation across the factors mentioned before. To remove this variation a current source is used in place of the switch (see Figure 8). This architecture is especially important in applications that are EMI sensitive and depend on characterizing the system at a specific slew rate.

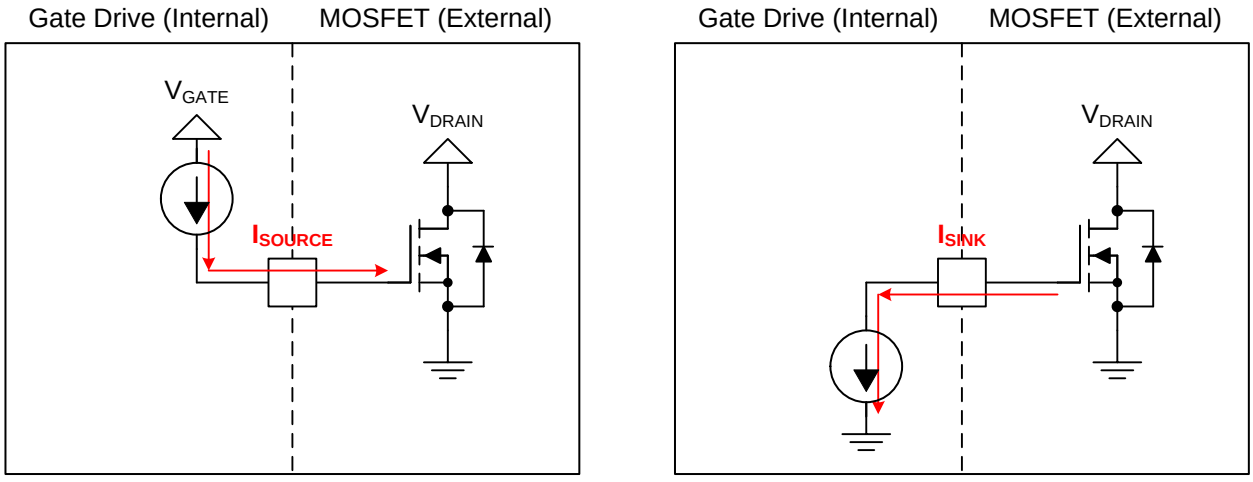

Figure 8. Current Source IDRIVE Method

Similar to the switch method (Figure 7), multiple current sources can be used to provide adjustable gate drive levels.

2.2 TDRIVE Implementation

In addition to the IDRIVE slew rate control, TI motor gate drivers also implement the TDRIVE feature. TDRIVE consists of an internal gate drive state machine that optimizes the dead time between high-side and low-side switching, protects against dV/dt turn on, and monitors for excessive current to the MOSFET gate. The state machine allows for the design of a robust, protected, and efficient motor drive system with minimal external overhead.

This section will explain the various components of the TDRIVE state machine and how they are implemented.

2.2.1 MOSFET Handshaking

The IDRIVE state machine incorporates internal handshaking when switching from the low to high-side external MOSFET or vice-versa. The handshaking is designed to prevent the external MOSFETs from entering a period of cross conduction, also known as shoot-through.

Cross conduction (shown in Figure 9) occurs when both the high-side and low-side MOSFET are enabled at the same time. A low impedance path is introduced between the power supply and ground. The path will allow large current to flow, potentially damaging the external MOSFETs or power supply.

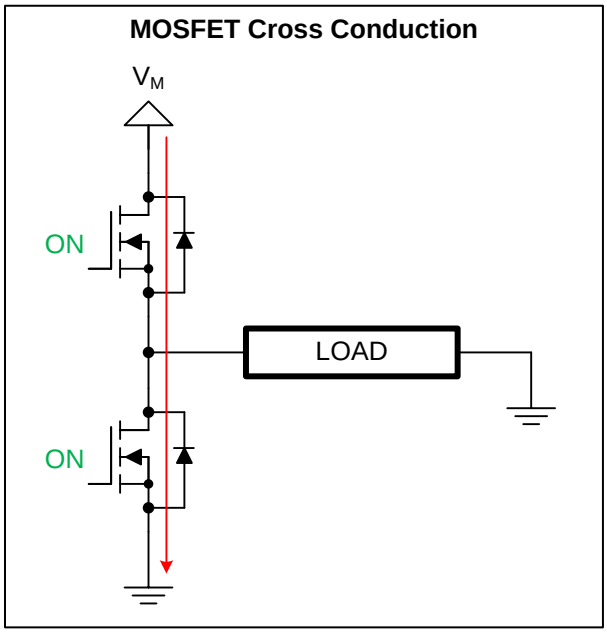

Figure 9. Cross Conduction Example

Cross conduction, or shoot through, most commonly occurs when switching from the low to high-side MOSFET or vice-versa. There is a delay from when the input signal is received to when the external MOSFET is off related to the internal propagation delay and slew rate of the MOSFET. If the opposite MOSFET is enabled before this delay period expires, cross conduction can occur. A simple method to prevent this issue is to add a period of timing before enabling the opposite MOSFET (shown in Figure 10). This period of time is called dead time. Increased dead time reduces the efficiency of the motor driver due to diode conduction losses.

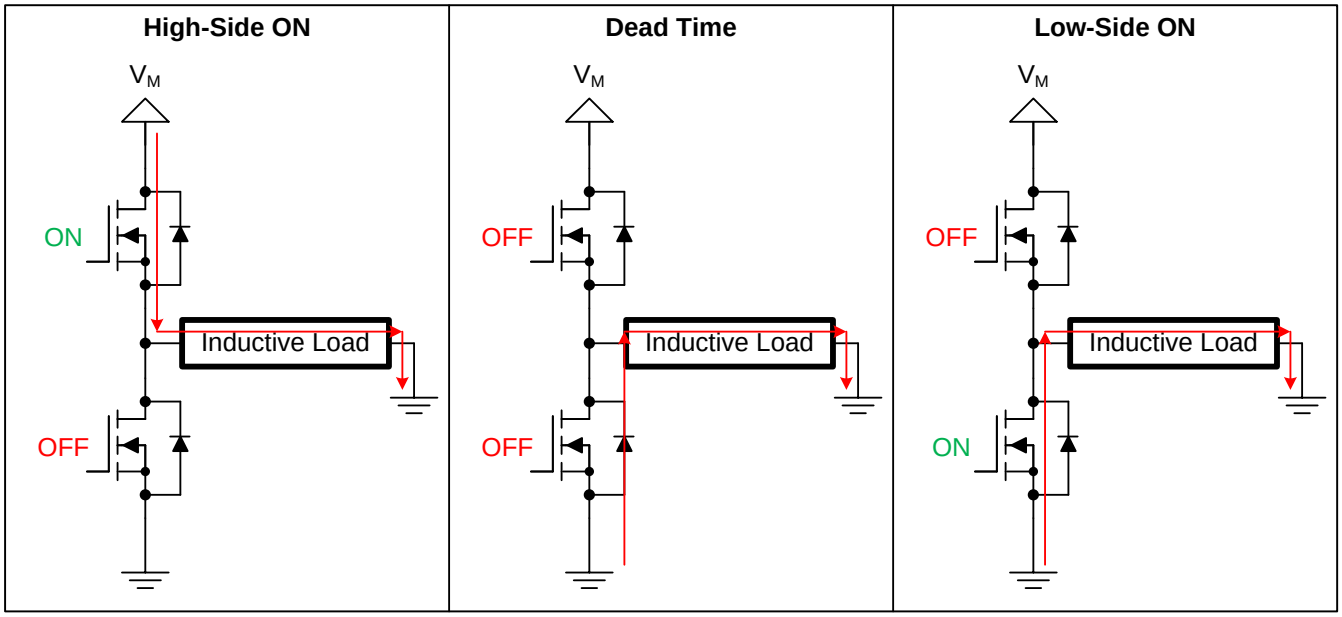

Figure 10. Dead Time Example

The internal handshaking utilizes V_{GS} monitors of the external MOSFETs (Figure 11) to determine when one MOSFET has been disabled and the other can be enabled. This allows the system to insert an optimized dead time into the system without the risk of cross conduction.

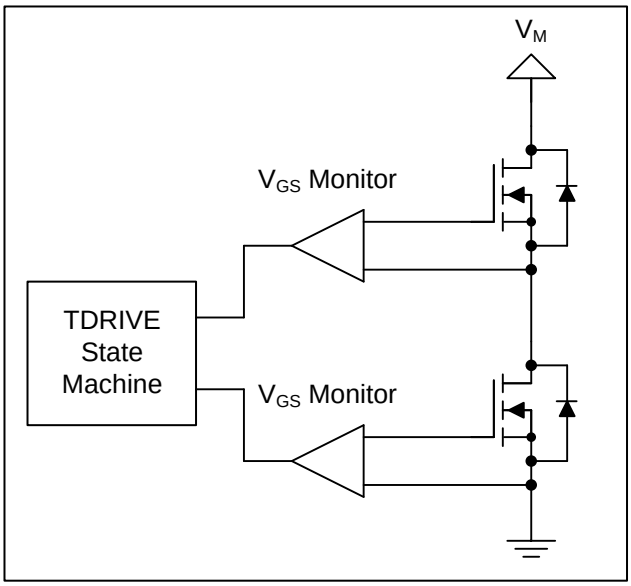

Figure 11. V_{GS} Monitor Example

2.2.2 Gate Drive Timer

The TDRIVE gate drive timer ensures that under abnormal circumstances such as a short on the MOSFET gate or the inadvertent turning on of a MOSFET V_{GS} clamp, the high peak current through the gate driver and MOSFET gate is limited to a fixed duration. This concept is visualized in Figure 13.

1. The gate driver receives a command to enable the MOSFET gate.
2. A strong current source is then applied to the external MOSFET gate and the gate voltage begins to rise.
3. If the gate voltage has not increased after the t_{DRIVE} period (indicating a short circuit or overcurrent condition on the MOSFET gate), the gate driver signals a gate drive fault and the gate drive is disabled to protect the external MOSFET and gate driver.
4. If a gate drive fault does not occur, the gate driver enables a small current source after the t_{DRIVE} period to maintain the proper gate voltage and reduce internal current consumption.

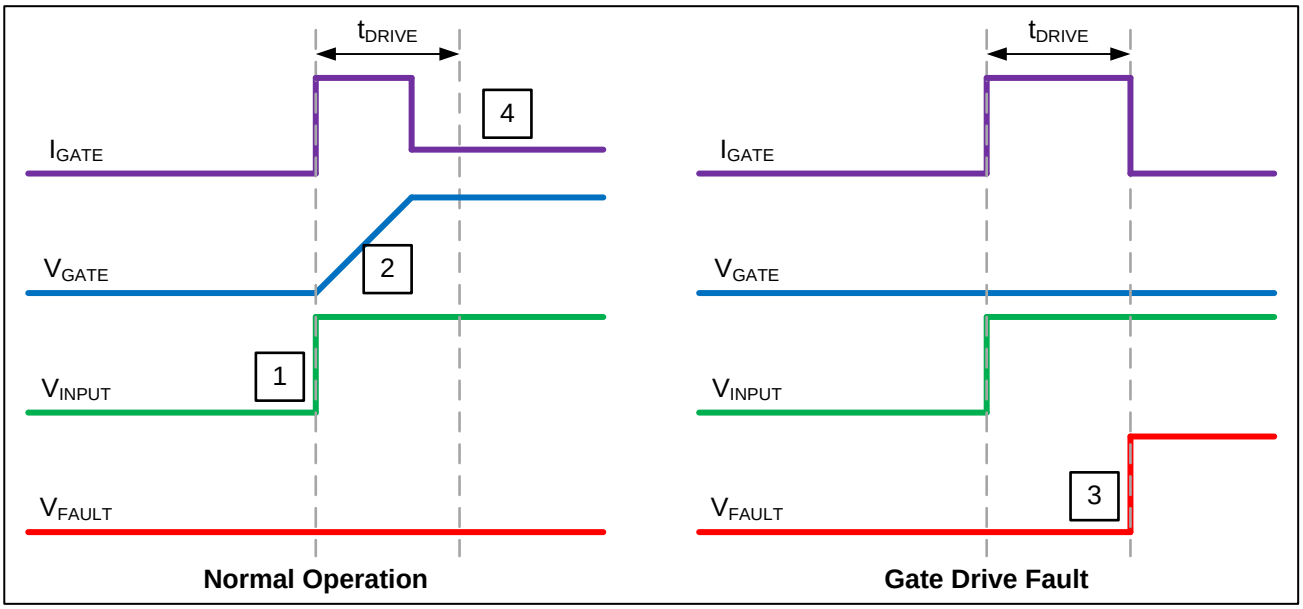

Figure 12. TDRIVE Example

2.2.3 Strong Gate Pull Down

In addition to the cross conduction and gate overcurrent protection features, the internal TDRIVE state machine also provides a mechanism for preventing dV/dt turn on.

A dV/dt turn on is a system issue that can occur when rapidly slewing the high-side MOSFET. When the switch node rapidly slews from low to high (Figure 13), it can couple into the gate of the low-side MOSFET through the parasitic gate to drain capacitance (C_{GD}). The coupling can raise the gate-to-source voltage of the low-side MOSFET and enable the MOSFET if the voltage crosses the MOSFET threshold voltage (V_{th}). If the low-side MOSFET enables while the high-side MOSFET is on, cross conduction will occur.

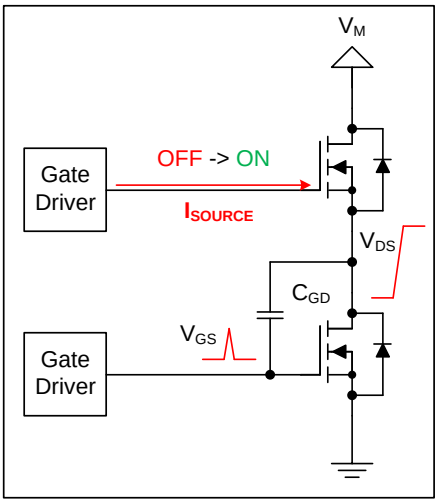

Figure 13. dV/dt Example

To protect against this scenario, the TDRIVE state machine enables a strong gate pull down on the low-side MOSFET while the high-side MOSFET is slewing (Figure 15). The pulldown provides a path for the charge that couples into the MOSFET gate.

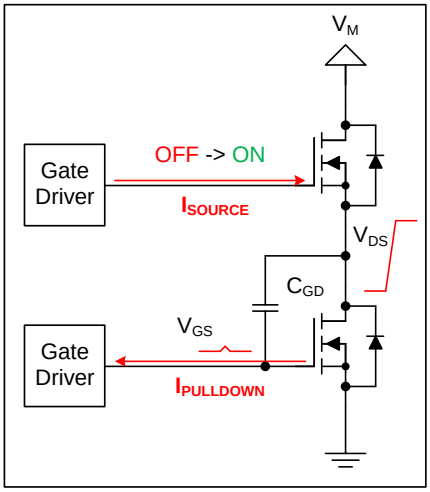

Figure 14. TDRIVE Pulldown

3 System Benefits

The IDRIVE and TDRIVE features provide a more efficient, flexible, and robust motor gate driver solution. This section will focus specifically on key system benefits that these features deliver.

3.1 Slew Rate Control

The IDRIVE feature allows the V_{DS} slew rate to be adjusted on the fly without adding or removing external components to the system. This allows a system designer to fine tune the MOSFET's switching performance with regards to efficiency, radiated emissions performance, diode recovery inductive spikes, and dV/dt turn on.

The persistence plot below (Figure 15) shows the effect on the V_{DS} slew rate from adjusting the IDRIVE setting on a TI motor gate driver. The MOSFET V_{DS} is slewing from 24 V to 0 V and the slew rate reduces as IDRIVE is adjusted across seven levels (10 mA, 20 mA, 30 mA, 40 mA, 50 mA, 60 mA, and 70 mA) of gate source current.

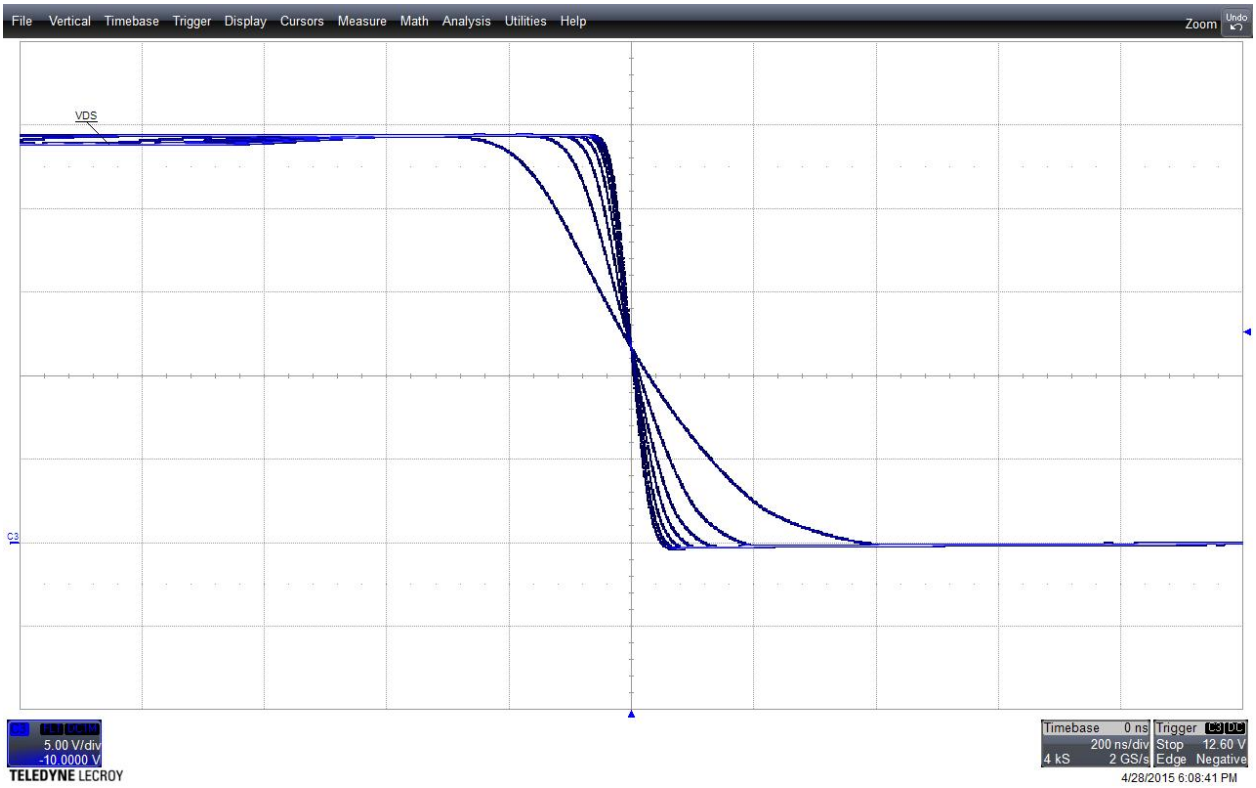

Figure 15. V_{DS} Persistence Plot Across IDRIVE Settings

Figure 16 and Figure 17 show additional signals of the MOSFET while it is being enhanced. You can clearly see the current from the gate driver and the Miller region of the external MOSFET when the V_{DS} slews.

Blue: V_{DS}, Green: I_{GATE}, Purple: V_{GS}

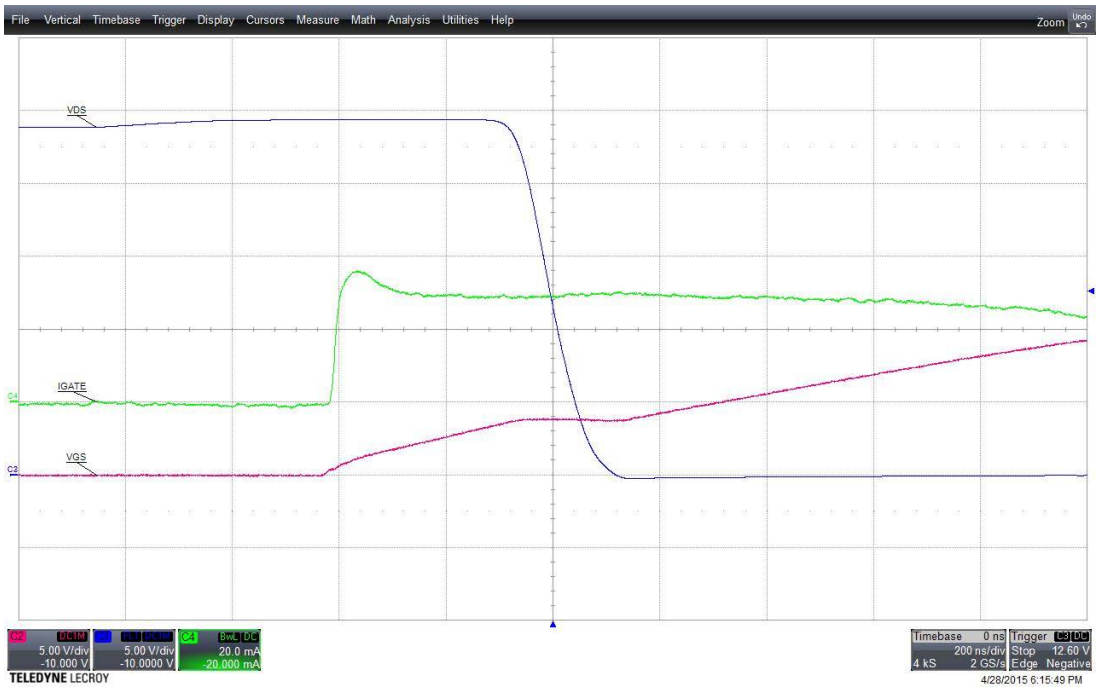

Figure 16. IDRIVE 30-mA Setting

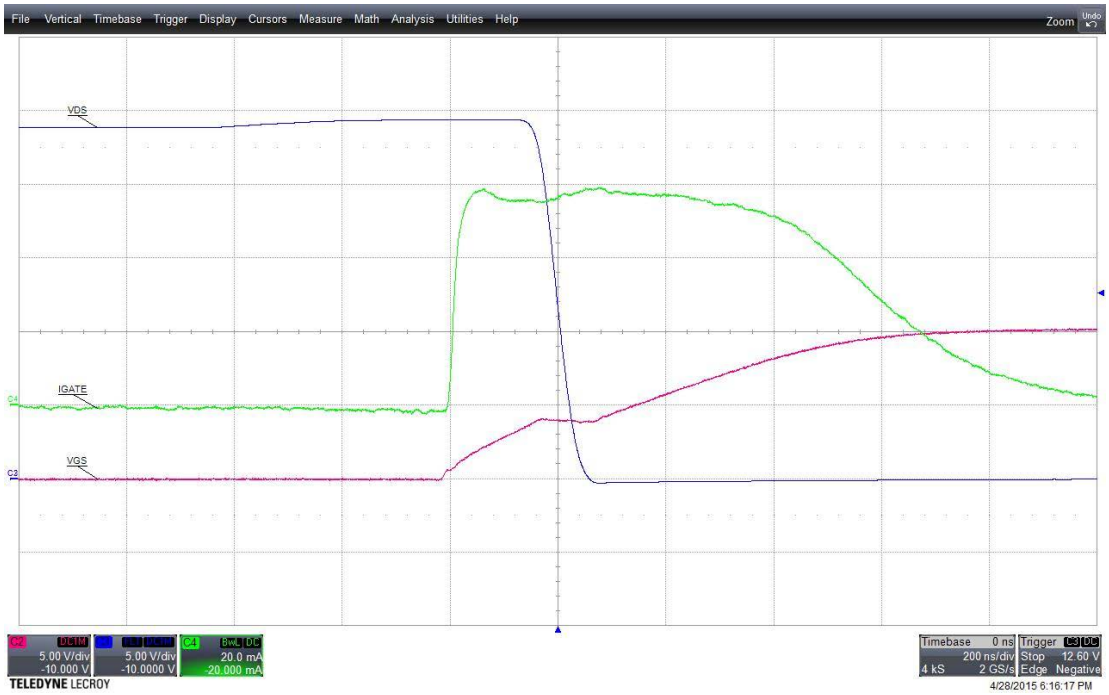

Figure 17. IDRIVE 60-mA Setting

As mentioned in Section 1.4, if we have a close to ideal current source and an accurate MOSFET Q_{GD} parameter you can make an approximate calculation for the V_{DS} slew rate. In Table 2 we compare the calculated vs. measured V_{DS} slew rates for several IDRIVE settings. In these calculations we assume that the effects of the series gate resistance and additional non-idealities are minimal.

$t_{SLEW} = Q_{GD} / I_{SOURCE}$

Table 2. IDRIVE Slew Rate Correlation

MOSFET Q_{GD} TYP (nC)	IDRIVE Setting (mA)	Calculated Slew Rate (ns)	Measured Slew Rate (ns)	Approximate Error (%)
8	10	800	617	23
8	20	400	305	24
8	30	267	206	23
8	40	200	158	21
8	50	160	128	20
8	60	133	109	18
8	70	114	97	15

Although there is some error from the ideal calculation, these values allow a system designer to design for an approximate slew rate and then finely tune the system during prototyping. The accuracy of the MOSFET Q_{GD} will play a large part in the accuracy of the calculation.

Scope plots for the measurements in Table 2 are provided in Figure 18- Figure 24.

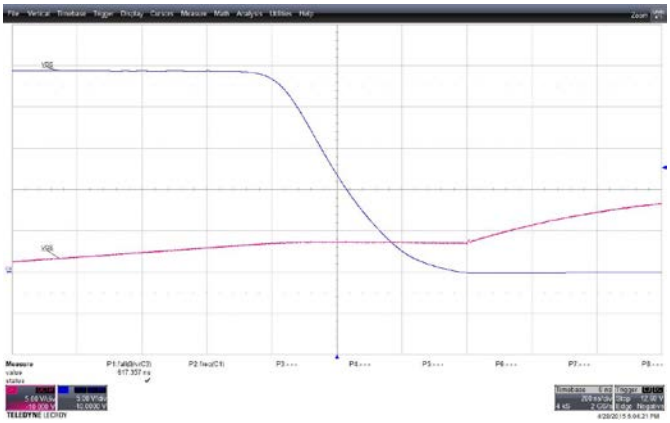

Figure 18. 10-mA IDRIVE

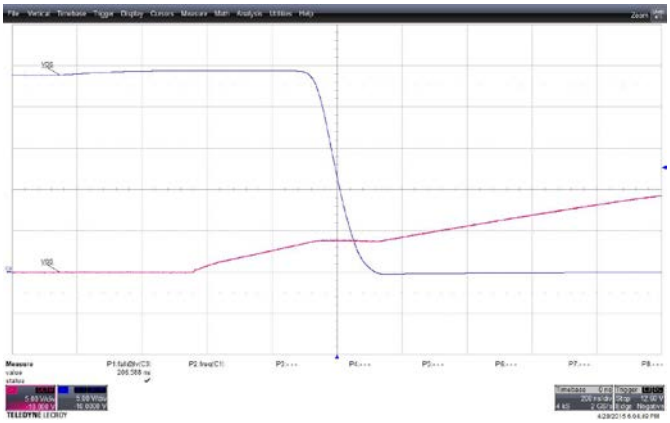

Figure 21. 40-mA IDRIVE

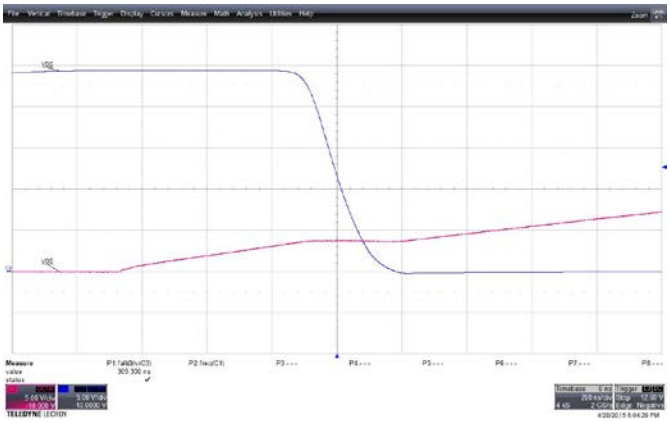

Figure 19. 20-mA IDRIVE

Figure 22. 50-mA IDRIVE

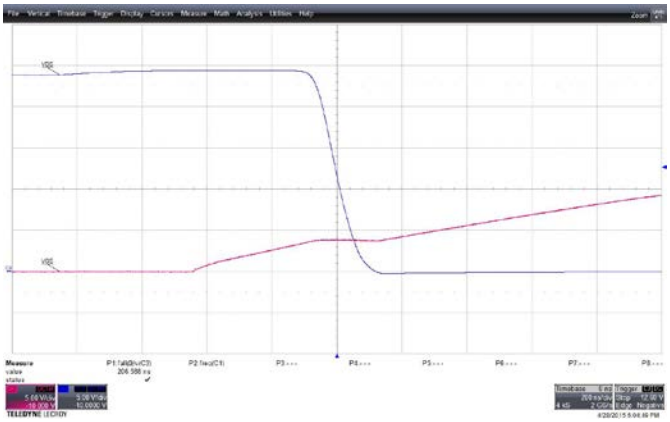

Figure 20. 30-mA IDRIVE

Figure 23. 60-mA IDRIVE

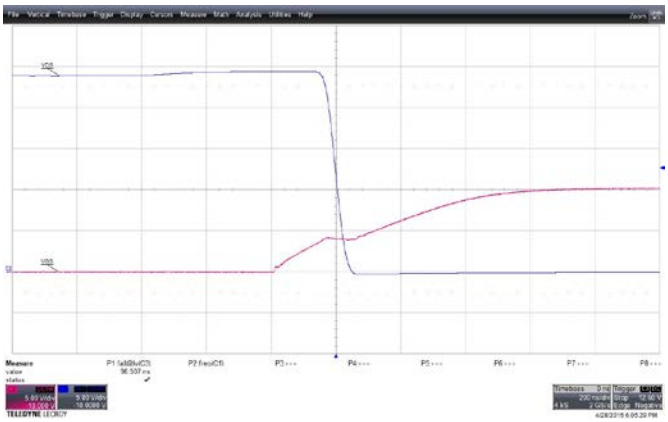

Figure 24. 70-mA IDRIVE

3.2 BOM Reduction

In addition to system flexibility, the IDRIVE slew rate control and TDRIVE state machine provides the ability to reduce the system BOM (bill of materials) and required board area. A typical configuration for driving a power MOSFET is shown in Figure 18.

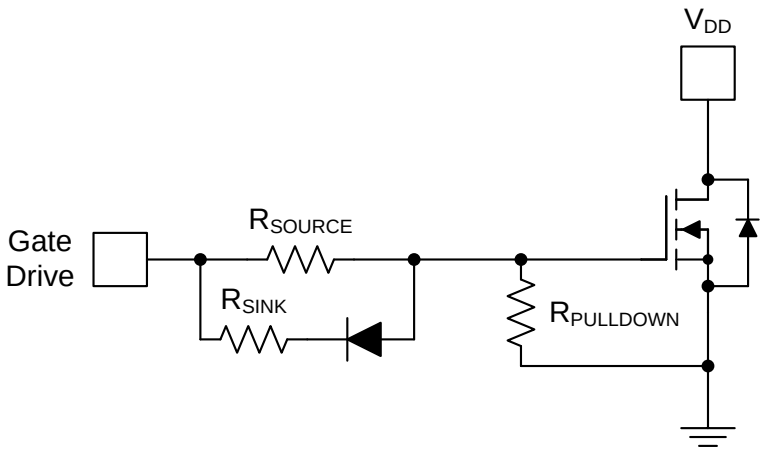

Figure 25. Typical Gate Driver Configuration

R_{SOURCE} and R_{SINK} manually adjust the impedance between the gate driver and MOSFET gate. The diode allows for the rise and fall V_{DS} slew rates to be individually adjusted. $R_{PULLDOWN}$ ensures that the MOSFET remains disabled even when the gate driver is inactive.

The IDRIVE and TDRIVE features remove the need for up to 24 passive components for controlling slew rate and gate pulldown in a triple half-bridge design.

3.3 System Protection

Lastly, the TDRIVE state machine provides additional system protection through intelligently driving the external power MOSFETs.

3.3.1 Switching Protection and Dead Time Optimization

As outlined in section 2.2, by monitoring the MOSFET V_{GS} voltage, the gate driver can provide an optimized amount of dead time for the switching MOSFET system. The V_{GS} monitors ensure the opposite MOSFET in the half-bridge is disabled before enabling the commanded MOSFET.

In addition to cross-conduction protection (shoot through), this method can provide system performance benefits by reducing the period of diode conduction. Conduction losses of the MOSFET internal body diode are typically worse than standard MOSFET conduction losses and will reduce the overall system efficiency.

3.3.2 dV/dt Turn On Prevention

The TDRIVE state machine works to prevent dV/dt turn on which can lead to cross conduction in the external half-bridge. By enabling a strong pulldown, on the low-side MOSFET, during high-side V_{DS} slew, the gate driver can provide a low-impedance path for parasitic charge that couples through the parasitic capacitance of the low-side MOSFET gate to drain capacitance (C_{GD}). This will prevent a rise in the gate-to-source voltage of the low-side MOFET, which could potentially enable the MOSFET while it is supposed to be off.

The TDRIVE state machine disables the strong pulldown after the switching period and moves to a weak pull down to reduce the chance of damage to the gate driver or system in the scenario of a gate to drain short of the external low-side MOSFET. By limiting the period of high current, the gate driver can prevent damage to itself and limit further damage to the system.

3.3.3 MOSFET Gate Fault Detection

In addition to the slew rate flexibility provided with IDRIVE, the TDRIVE state machine allows the gate driver to detect fault conditions on the gate of the external MOSFET.

By monitoring the voltage and managing the current to the external power MOSFET, the gate can driver can detect and report when an abnormal event (partial short, short circuit) has occurred on the MOSFET gate. Additional information is provided in Section 2.2.

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