Controlling "Inrush" current for load switches in battery power applications

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Abstract

Battery powered systems make extensive use of load switches, turning the power to subsystems off, in order to extend battery life. Power Trench MOSFETs are used to accomplish this task due to the very low RDS(ON). In PDA's and Cell phones, these MOSFETs are usually low threshold P-Channel device. Since the loads typically include bypass capacitor components, a high inrush current can occur when the load is initially switched on. A driver to control the slew rate (dV/dt) of the P-Channel MOSFET allows for a smooth ramp up of the power to a given load without affecting the subsystem to be switched.

Introduction

Portable electronic equipment is increasingly dependent upon efficient usage of the limited battery supply. This can be found where use of load switches and power management units have evolved to meet the challenge of extracting more useful energy (time), for less battery volume and weight. Figure 1, is a simplified block diagram of a battery-powered application using load switches.

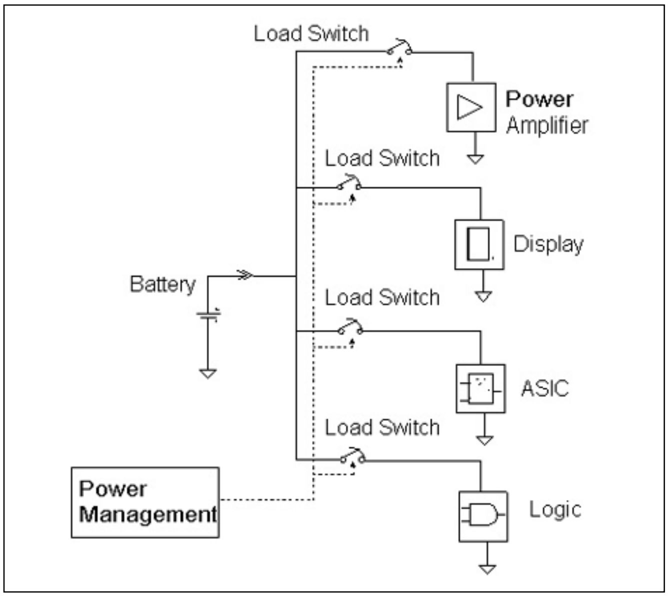

Figure 1. A simplified block diagram of a battery-powered application using load switches.

One of the challenges designers must take into consideration is how to intelligently manage the rapid rise/fall of voltages and current levels for load switch applications. With today's fast switching times and very low equivalent series resistance (ESR) filter capacitor; circuits appear to react similar to a perfect short circuit during initial turn on. The initial power applied to a load from a power supply can posses a very high dV/dt. This high dV/dt interacting with filter capacitors will introduce short duration of high-peak current, which can exceed far beyond the device rating, seriously damaging or destroying semiconductor components. This inrush current can cause transients on the main power supply disturbing other subsystems.

This paper will offer a solution to control the inrush current in load switch applications, and will also compare two approaches to controlling the slew rate.

The Load Switch Dilemma

There are typically two methods of switching power to a load using MOSFET switches, low- and high-side switching. A low-side switch is a circuit configuration in which the MOSFET switch is placed between ground and a positive power supply referenced load. A high-side switch is a circuit configuration in which the MOSFET switch is placed between the positive power supply, and a ground reference load. Here we will be discussing the high-side switch and how to control the MOSFET switch turn-on to eliminate inrush current.

Electrical subsystems in portable battery-powered equipment are typically bypassed with large filter capacitors to reduce supply transients and supply induced glitching. If not properly switched, these capacitors may themselves become the source of the unwanted transients.

For example, if a 100 ㎌ filter capacitor is powered through a p-channel MOSFET switch(as shown in Figure 2), and uses a typical value of 0.1V/㎲ for the slew rate, the inrush current is given by:

$$I_{inrush} = C_{LOAD}\left(\frac{dV}{dt}\right)$$

From the simple equation above, it is easy to see that slowing or controlling the slew rate (dV/dt) of the MOSFET switch can substantially reduce the inrush current. Traditionally, most of the inrush current limiting was done by the use of additional resistors and capacitors (see Figure 3). This approach can occupy significant PCB area, which will increase the weight, and the cost of the product.

$$= (100\text{x}10^{-6}) \times (1\text{x}10^{5})$$
$$= 10\text{A}$$

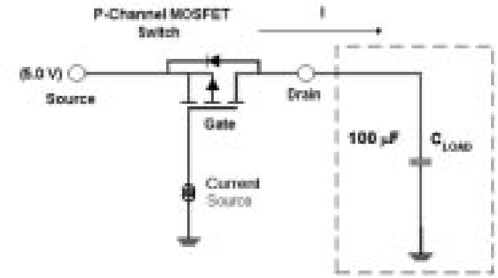

Figure 2. A simplified P-Channel MOSFET switch with a large capacitive load.

There are several load switch configurations that use MOSFETs (n- and p-channel). Following is a comparison of two specific configurations. A p-channel MOSFET with an n-channel driver will be compared with a specific slew rate driver to control the p-channel MOSFET for load switching. The focus will be comparing the drivers (n-channel and slew rate control driver) and not on a particular p-channel MOSFET.

N-Channel MOSFET Driver

A typical integrated p-channel MOSFET (Q2) load switch, with an n-channel MOSFET (Q1) gate driver, is depicted in Figure 3. This load switch has a simple external RC network, R1 and C1, which is used to substantially slow the slew rate of the p-channel MOSFET gate. The actual slew rate will depend on the values of R1, C1, and C_{RSS} of the p-channel MOSFET (Q2). The resistor R2 is required to turn the p-channel MOSFET off, and the ratio of R2/R1 should be 10 to 100 to ensure adequate turn off. The n-channel MOSFET interfaces with the 5V logic.

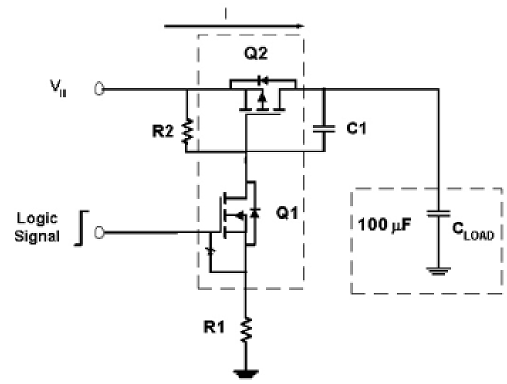

Figure 3. A typical integrated load switch using n-channel MOSFET driver.

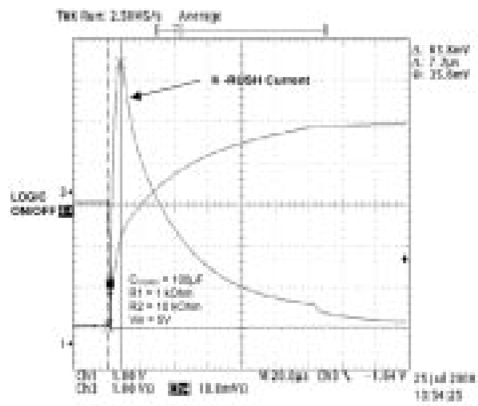

Figure 4. Inrush current at load switch turn-on.

The inrush current at turn-on of the p-channel MOSFET is shown in Figure 4. This peak inrush current can cause sever damage to semiconductor components in the particular load being switched. The external resistor and capacitor can slow the turn-on but does not change the non-linear behavior of the slew rate. Following is a description of the mechanisms observed behavior.

Slew Rate Control Driver

The ability to control the turn-on of a MOSFET lies in the ability to control the current-to-gate of the MOSFET. The slew rate control driver is designed to turn the MOSFET fully on or off. The slew rate drives the gate of a MOSFET by a constant current source to control the dV/dt. The slew rate controller interfaces with low voltage digital circuitry, which allows the power management unit to control the load switch.

The ability to regulate the current will allow complete control of the dVDS/dt of the MOSFET and be independent of load conditions. It is this ability to control dVDS/dt that eliminates inrush current to the capacitive load, or resistive load, as shown by Figure 5.

The slew rate control driver is designed to give a programmed choice of three steady dV/dt states. The three settings have a constant current value of approximately 80 mA, 1 mA, and 10 nA respectively. The slew rate control driver is an IC device in a small SC-70 package that can deliver a constant current to a variety of MOSFETS.

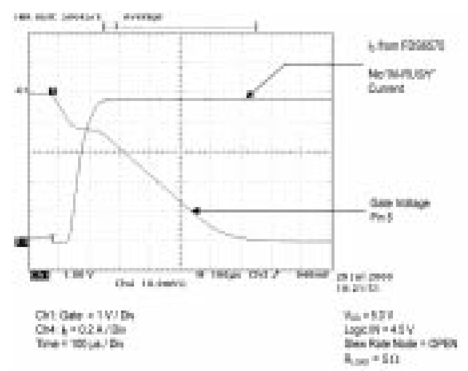

Figure 5. Slew Rate Control Driver with P-Channel MOSFET

The switching times for the p-channel MOSFET (depending of the gate-charge characteristics provided by the manufacture) can be calculated by using the simple equation:

$$t = \frac{Q_g}{I_G}$$

Where Q_g is the gate charge in nC for a given MOSFET, and I_G is the gate current controlled by the slew rate driver, the gate charge number will give the total gate charge necessary to switch the device from an off- to an on-state. How fast the capacitance is charged or discharged will determine how fast the device turn on or off. Using a typical MOSFET (FDS6575) characteristics of Q_g of 11 nC, and a gate current supplied by the slew rate control driver (I_g) of 80 mA, a switching time of 137 msec is calculatedæa value of 140 msec is obtained from Figure 5.

MOSFET Switching Characteristics

A simplified MOSFET model is given below where the associated gate-transfer curve describes the switching mechanism of a MOSFET.

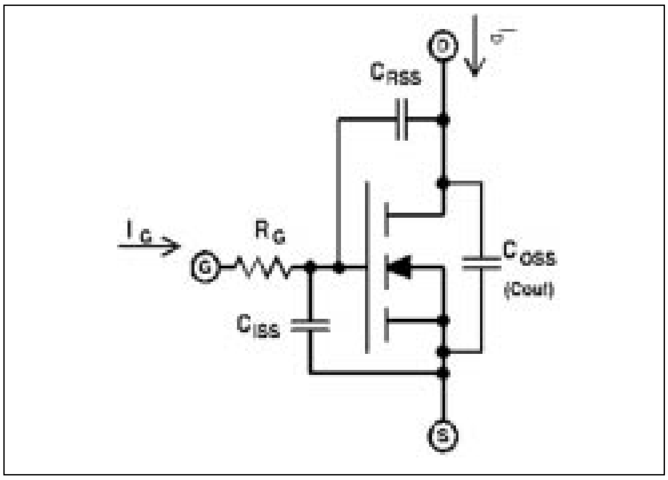

Figure 6. Equivalent Circuit for a N-Channel MOSFET

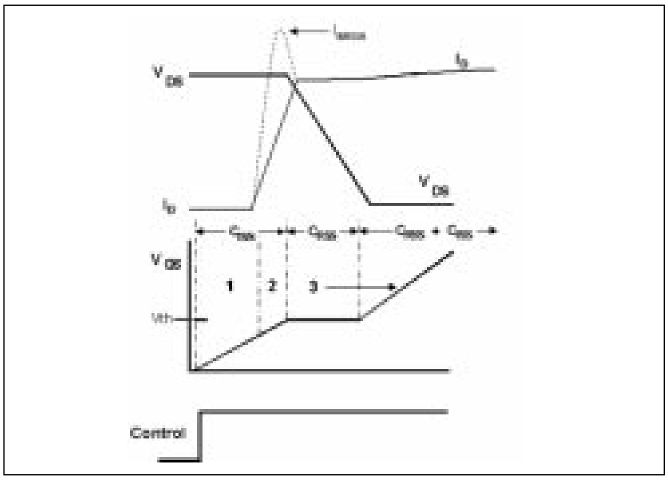

Figure 7. Gate charge transfer curve

Industry standard expressions are given for the common-source configuration of a MOSFET and can be found in any MOSFET data book or device physics book [2].

$C_{ISS} = C_{GS} + C_{GD}$ (Input Capacitance)
$C_{RSS} = C_{GD}$ (Reverse Transfer Capacitance)
$C_{OSS} = C_{DS} + C_{GD}$ (Output Capacitance)

Where R_G is the internal gate resistance of the MOSFET, C_{GS}, C_{GD}, and C_{DS} are the gate-to-source capacitance, the Miller capacitance, and the drain-to-source capacitance, respectively.

The gate-charge transfer curve of a typical MOSFET (Figure 7) contains all the necessary information to explain the switching behavior of a MOSFET. Region 1 is a pre-threshold region and the drive current is used to charge the input capacitance (C_{ISS}). The time-to-charge corresponds to the MOSFET's delay time. Then, at a voltage V_{th}, the threshold voltage of the MOSFET is crossed and the device begins to switch. In region 2 and 3, the drain voltage begins to fall and the Miller capacitance takes current from the gate drive and causes the plateau region. When the device is saturated and the drain voltage stops changing, this will allow the gate voltage to rise. At this time the drain-to-source resistance should be optimally low, and the gate fully enhanced. The gate-charge transfer curve will vary depending upon the drain supply voltage.

The V_{DS} transition is determined during the region 2 and 3 of the gate charge curve. The drain-to-source voltage transition is contained in region 3, and controlling this region means a constant rate of charge of the drain-to-source voltage dVDS/dt. This can be expressed as follows [2]:

$$\frac{dV_{DS}}{dt} = \frac{I_g}{C_{RSS}}$$

In the case described above using an n-channel MOSFET to control the p-channel MOSFET, the dVDS/dt is not a constant and the slew rate is dependent upon the nonlinear turn-on characteristics of the n-channel MOSFET. The slew rate control driver is essentially a constant current source, which gives a controlled response of the turn-on of the p-channel MOSFET. The slew rate control driver allows for a controlled ramp-up of the power to a given load by a steady dV/dt condition. It is this ability to control d_{VDS}/dt that controls the inrush current to the capacitive loads or resistive loads.

Conclusion

The slew rate control driver eliminates inrush current, reduces the cost by eliminating external RC components, and increases the reliability of the MOSFET device. All these advantages make the slew rate control driver an ideal alternative to the n-channel MOSFET driver. A controlled slew rate is beneficial for switching loads with a high value of capacitance, and where the use of a driver is desirable. Further applications can include laptop computers, mainframes, storage arrays, and telecom office equipment.

References

[1] Alan Li and John Bendel, Application Note AN1030 Design with MOSFET Load Switch, Fairchild Semiconductor Power MOSFET Databook, 1999.

[2] Ducan A. Grant and John Gowar, "Power MOSFETS Theory and Applications", John Wiley & Sons Publications, 1989.

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Outline

- Why load switches?
- The load switch dilemma.
- Load switch drivers.
- Understanding MOSFET switching.

What are load switches?

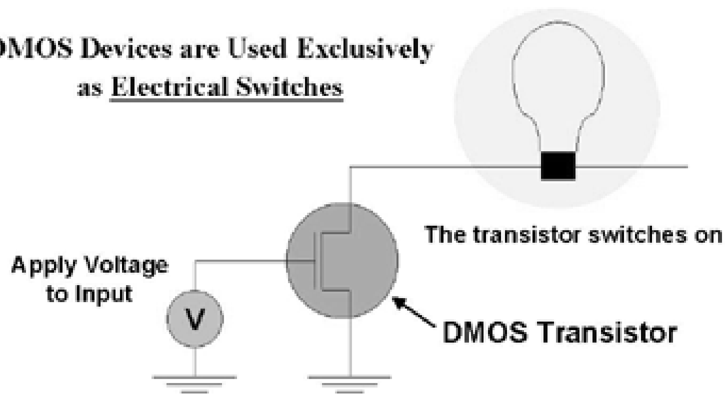
Devices that provide control of power loads.

- Switch loads from high side or low side
- Bi-directional load switch
- Unidirectional load switch

1.Why load switches?

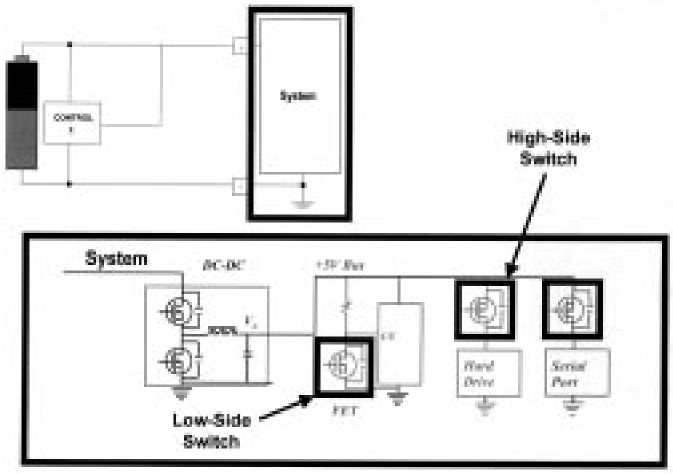
The Semiconductor Switch

DMOS Devices are Used Exclusively as Electrical Switches

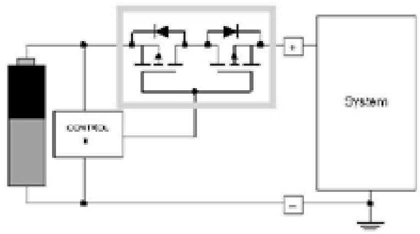


1.Why load switches?

High-Side and Low-Side Switch

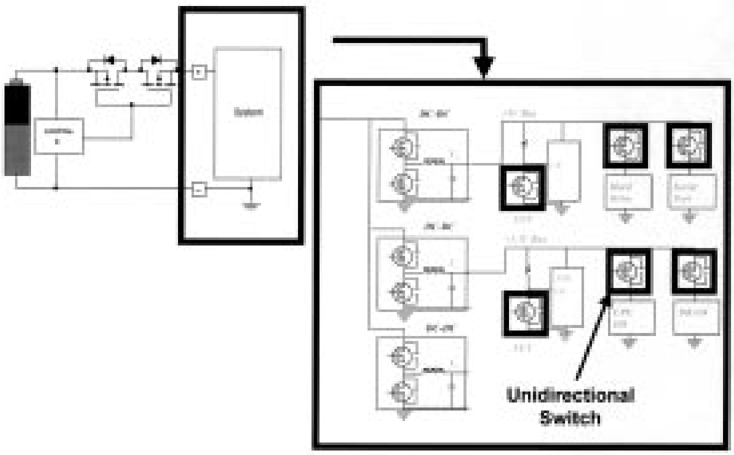


Bi-Directional Load Switch



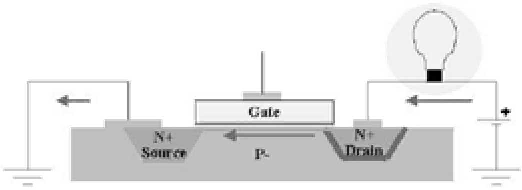
1.Why load switches?

Unidirectional Load Switch



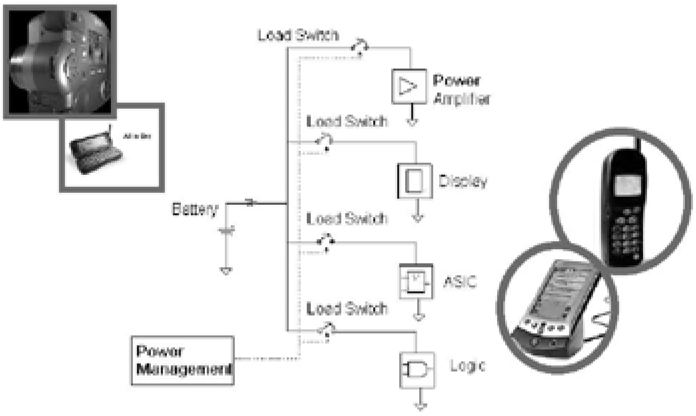
How does the switch work?

- Source and Drain are connected to circuit
- Reverse bias pin junction blocks current flow
- Applying voltage to Gate inverts p-type silicon
- Allows current to flow — completing circuit



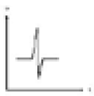
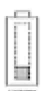
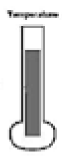
1.Why load switches?

Battery Power Architecture



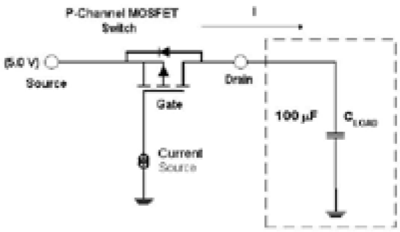
1.Why load switches?

Load Switch Dilemma

- High dV/dt or dI/dt at Turn On 
- Transients 
- Power Losses 
- Increased Peak Junction Temperature 

2. The load switch dilemma.

Simplified Inrush Calculation



Equation

$$I_{inrush} = C_{LOAD}\left(\frac{dV}{dt}\right)$$
$$= (100\times10^{-6})\times(1\times10^{5})$$
$$= 10\text{A}$$

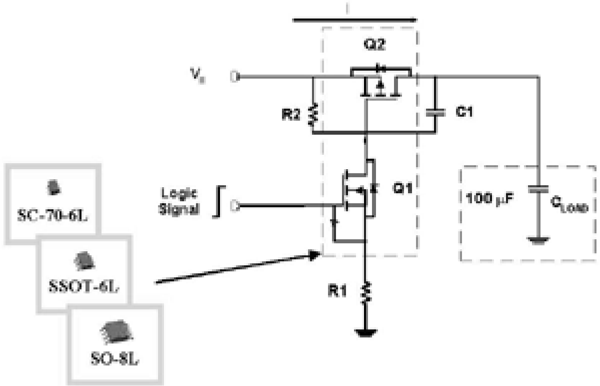
Using

C_{LOAD} = 100 µF

Slew Rate (dV/dt) = 0.1 V/µs

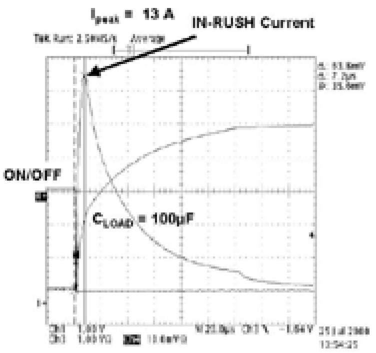
2. The load switch dilemma.

Typical Integrated Load Switch



3. Load switch drivers.

Typical Load Switch at Turn On

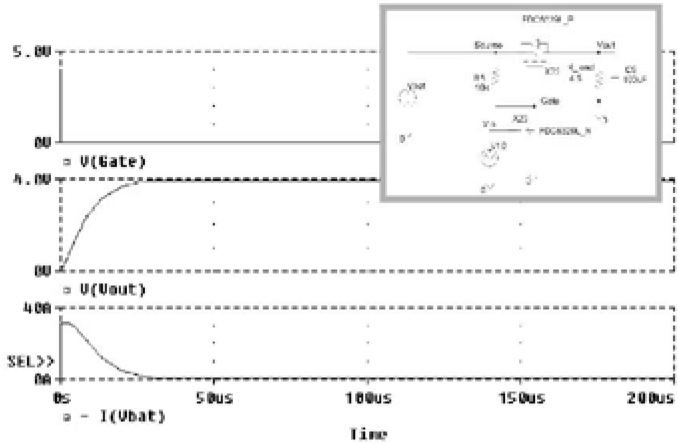


Inrush Current Causes

- ↑ Power Loss
- ↑ Device Stress
- Transients

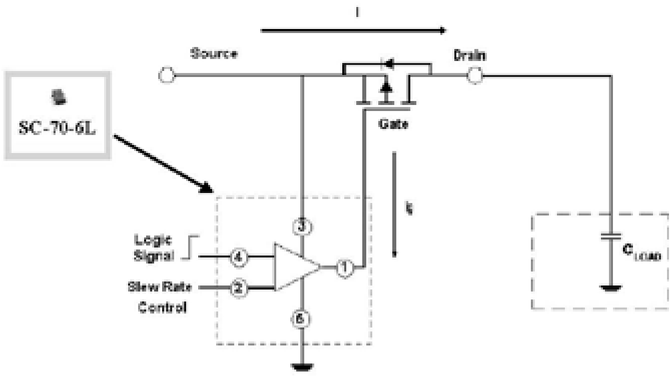
3. Load switch drivers.

SPICE Simulation



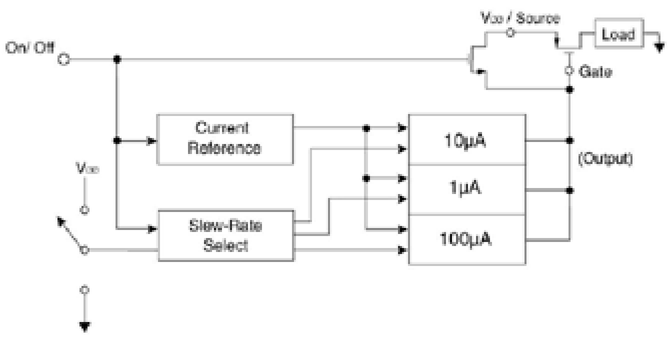
3. Load switch drivers.

Slew Rate Controlled Load Switch



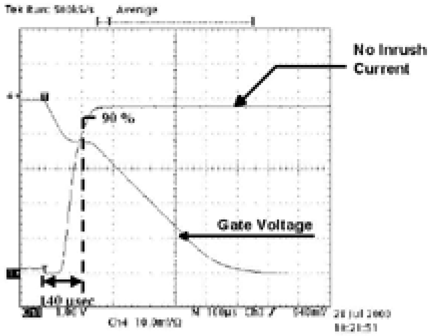
3. Load switch drivers.

Block Diagram of Slew Controller Driver



3. Load switch drivers.

Slew Rate Control Driver With P-Channel DMOS



Equation

$$t = \frac{Q_g}{I_G}$$

Where

Q_g is is the Gate charge in nC
I_G is the gate current

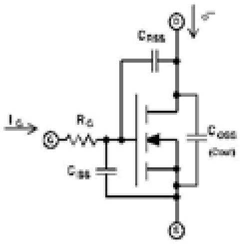
From FDS6575 Data sheet
Qg = 11 nC

Slew Rate Driver Current
I_G = 80 µA

$$t = 137 \quad \mu \text{ sec}$$

3. Load switch drivers.

Equivalent Circuit for a N-Channel MOSFET



Equations

$C_{ISS} = C_{GS} + C_{GD}$ (Input Capacitance)
$C_{RSS} = C_{GD}$ (Reverse Transfer Capacitance)
$C_{OSS} = C_{DS} + C_{GD}$ (Output Capacitance)

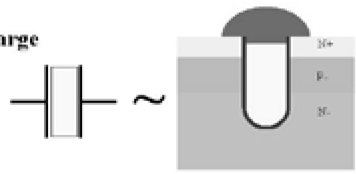
Where

R_G gate resistance of the MOSFET
C_{GS} gate-to-source capacitance
C_{GD} Miller capacitance
C_{DS} drain-to-source capacitance

4. Understanding MOSFET Switching.

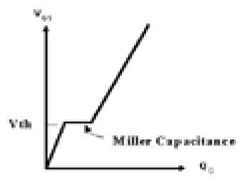
Gate-Charge for PowerTrench™ MOSFET

When you think - Gate Charge
↓
Think of a Capacitor →



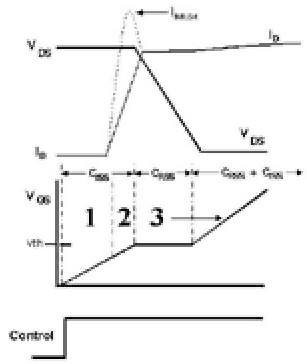
$i\,dt = C\,dV$

As C increases, so does $i\,dt$



4. Understanding MOSFET Switching.

Gate Charge Transfer Curve



Region 1

A pre-threshold region and the drive current is used to charge the input capacitance (C_{ISS})

Region 2

The threshold voltage (V_{th}) of the MOSFET is crossed and the device begins to switch

Region 3

The drain voltage begins to fall and the Miller capacitance takes current from the gate drive and causes the plateau region. When the device is saturated and the drain voltage stops changing, allowing the gate voltage to rise

4. Understanding MOSFET Switching.

Conclusion

Slew Rate Control Driver <u>will</u>

- Reduce the number of components
- Eliminate Inrush current
- Control the turn onto a load