Automotive Power

PROFET™ Operating Modes (Normal, Inverse, Reverse)

Application Note

V1.0 2011-07-13

PROFET Operating Modes
Revision History: V1.0, 2011-07-13

Previous Version: none

Page	Subjects (major changes since last revision)

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1 Abstract

Smart, high-side power switches from Infineon® are designed to control all types of resistive, inductive, and capacitive loads within harsh automotive environments. The highly integrated PROFET™ (PROtected FET) family of high-side switches incorporates a broad range of smart features including sophisticated diagnostic and protection capabilities. The high-current PROFET power switches consist of a DMOS power MOSFET and CMOS logic circuitry. These switches offer protection against a wide range of conditions such as overload, overtemperature, and short circuit for all types of automotive and industrial applications.

In automotive applications, the **normal operating mode** is defined when the battery supply voltage is more positive than the output load voltage. In some cases, transient conditions may cause the battery voltage to become less positive than the output load voltage; this is known as the **inverse mode**. In other cases (such as replacing the battery or during jump-start conditions), the polarity of the battery might be applied in the reverse direction; this is known as the **reverse mode**. Some PROFET high-side switches have the ability to operate in inverse mode conditions and/or reverse mode conditions.

This application note first introduces some fundamental concepts. This is followed by a discussion of the normal, inverse, and reverse operating modes (OpModes) that may be encountered by high-side switches in automotive applications. The application note then considers the effects of inverse and reverse mode conditions on high-side switches (with and without inverse current and reverse battery capabilities); the electronic control units (ECUs) in which the switches reside, and the applications (loads) being controlled by the switches.

2 Introduction

2.1 Terms and Abbreviations

The terms and abbreviations used in this application note are summarized in Table 1.

Table 1 Terms and abbreviations

Abbreviation	Meaning
ECU	Electronic control unit
HSS	High-side switch
I_L	Load current (positive value indicates $V_{bb} > V_{OUT}$; negative value indicates $V_{bb} < V_{OUT}$)
$-I_{L(inv)}$	Maximum transient inverse load current
R_{ON}	Resistance of the power MOSFET when the switch is ON in **normal** mode
$R_{ON(inv)}$	Resistance of the power MOSFET when the switch is ON in **inverse** mode
$R_{ON(rev)}$	Resistance of the power MOSFET when the switch is ON in **reverse** mode
V_{bb}	Battery voltage (measured across the battery terminals)
$-V_{OFF}$	The voltage drop across the power MOSFET's intrinsic diode (also known as a body diode) when the switch is OFF in the inverse or reverse modes
V_{OUT}	Output voltage (measured across the load)

2.2 Alternative Automotive Switching Configurations

In a typical automotive system, a single electrical supply V_{bb} (also referred to as $V_{BATTERY}$ or V_{BAT}) is available. Five possible solutions exist to switch electrical loads ON and OFF as illustrated in Figure 1.

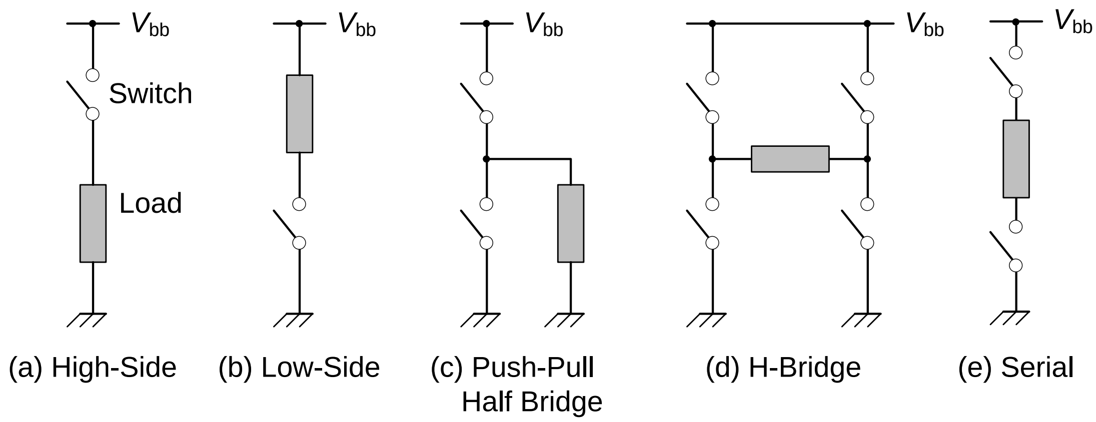

Figure 1 Alternative automotive switching configurations

This application note focuses on the use of the high-side switch (HSS) configuration. These switches are utilized in automotive applications around the world for multiple reasons: load driving, diagnosis performance, their ability to mitigate the system effects of short circuit faults, and their relatively low system cost. In particular, this application note focuses on Infineon's highly integrated PROFET family of high-side switches, which incorporate a broad range of smart features including sophisticated diagnostic and protection capabilities.

Note: Further information on PROFET high-side switches and their diagnostics and protection features can be found in the Application Note: [What the designer should know: Short introduction to PROFET™ +12V](#).

2.3 High-Side Switch Pin Names and Functions

Single-channel, high-side power switches of the general type considered in this paper have five pins (GND, IN, OUT, IS, and V_S) as illustrated in Figure 2.

Note: The operating mode behaviors presented in this application note cover all PROFET switches regardless of feature/function, number of channels, etc..

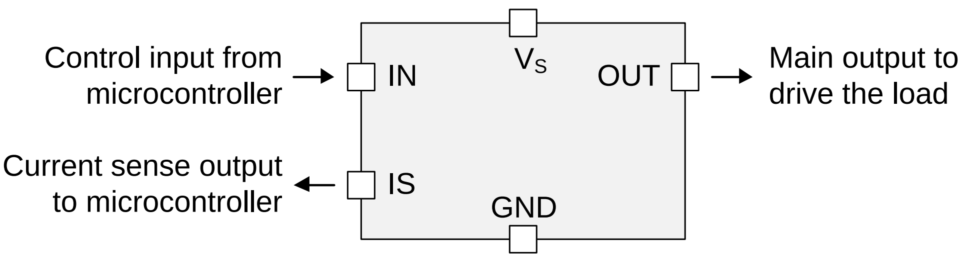

Figure 2 High-side switch pin names

The functions of these pins are detailed in Table 2.

Table 2 **High-side switch pin functions**

Pin Name	Pin Function
GND	**Ground:** Ground connection
IN	**Input:** Digital 3.3V or 5V compatible logic input; activates the power switch if set to HIGH level (definitions for HIGH and LOW can be found in the parameter tables of the respective device datasheet)
OUT	**Output:** Protected high-side power output
IS	**Sense:** Analog sense current signal for diagnostic purposes
V_S	**Supply Voltage:** Positive supply voltage for both the logic and power stages (this pin is connected to the battery supply voltage V_{bb} as illustrated in Figure 3).

2.4 Inside a PROFET high-side switch

A high-level visualization of the main elements of a PROFET high-side switch are presented in Figure 3.

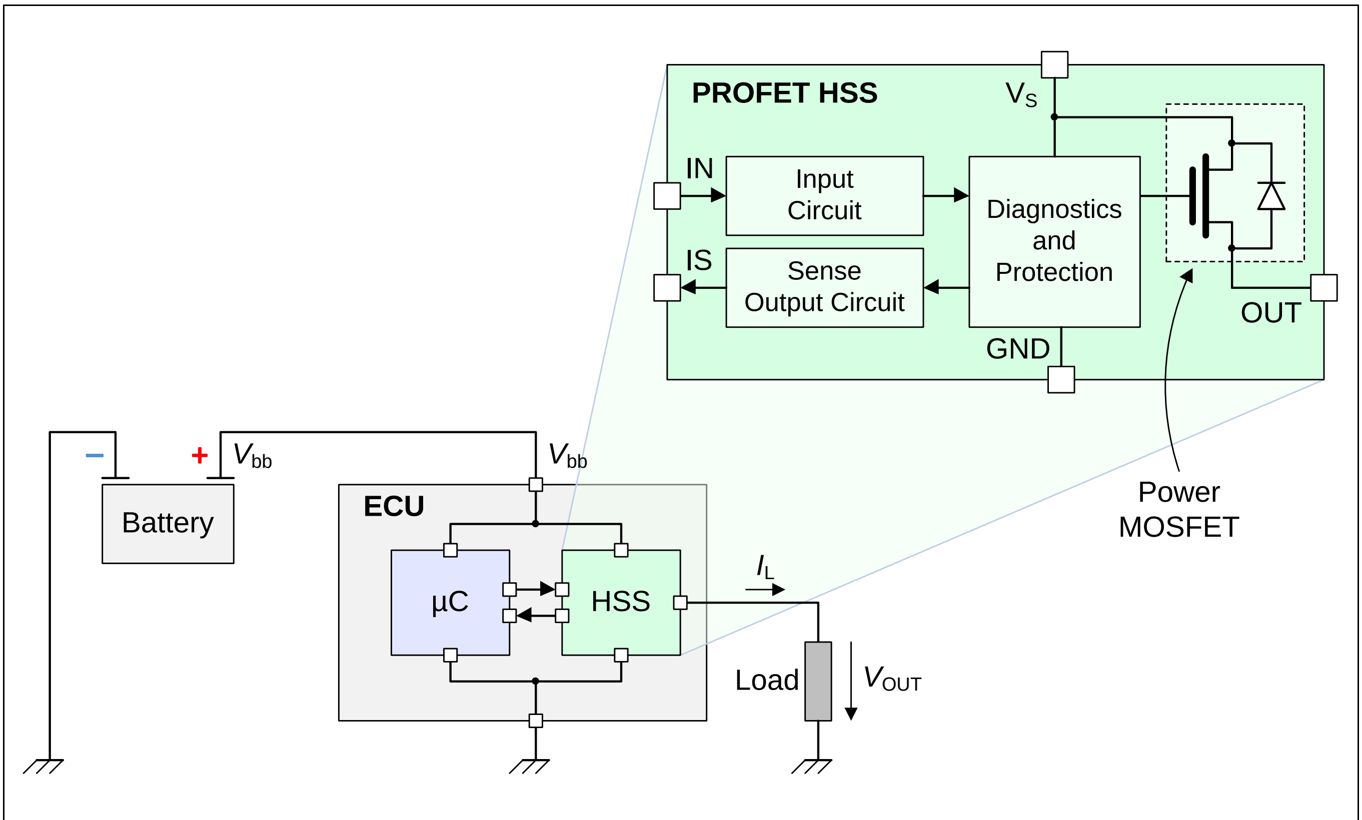

Figure 3 Inside a PROFET high-side switch (high-level visualization)

The IS pin on the high-side switch shown in Figure 3 is an analog current sense signal that can be monitored by the microcontroller in an electronic control unit (ECU). The value of the current sense signal is proportional to the load current I_L. Current sensing is implemented within high-side switches to diagnose and protect in the event of failures. High-side current sensing is used to protect both the load and the wiring harness, to diagnose the load to ensure proper operation, and to measure the output current for the purpose of controlling the output power.

Note: Additional information on current sensing in general, and Infineon's ADVANCED SENSE technology in particular, can be found in the Application Note: ADVANCED SENSE Calibration and Benefits Guide.

The power MOSFET inside the high-side switch shown in Figure 3 is used to supply and control the power from the battery to the load. The diode associated with this MOSFET is not a discrete component – instead it is an intrinsic part of the MOSFET that is associated with the construction and technology of the MOSFET and is often called the "body diode" or "intrinsic diode".

2.5 Introducing the Normal, Inverse, and Reverse Modes

In automotive applications, the **normal operating mode** is defined when the battery supply voltage V_{bb} is more positive than output load voltage V_{OUT}. In some cases, transient conditions may cause the battery voltage to become less positive than the output load voltage; this is known as the **inverse mode** or an **inverse current condition**. In other cases (such as replacing the battery or during jump-start conditions), the polarity of the battery might be applied in the reverse direction; this is known as the **reverse mode** or a **reverse battery polarity condition**. These three modes are summarized and illustrated in the graphical representation of Figure 4.

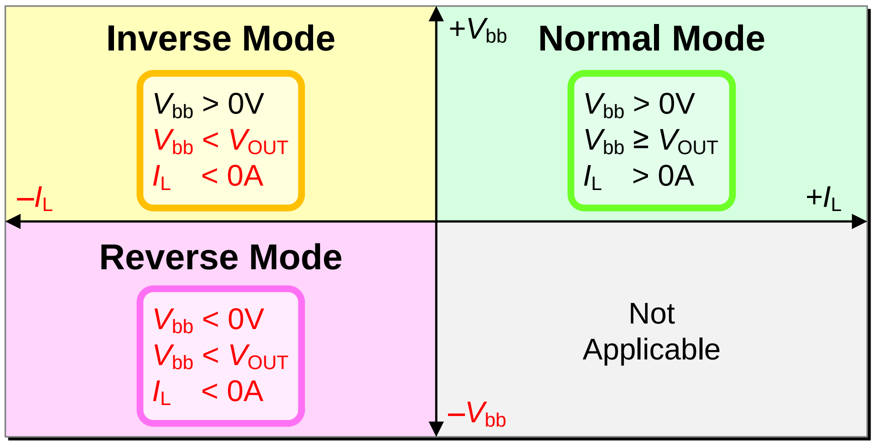

Figure 4 Graphical definitions of the normal, inverse, and reverse modes

As illustrated in Figure 5, some PROFET high-side switches have the ability to operate in inverse mode conditions; this is referred to as **inverse current capability**. Similarly, some PROFET high-side switches have the ability to detect and respond to reverse mode conditions; this is referred to as **reverse battery capability**, or **ReverSave™**. Additionally, some PROFET high-side switches even have both inverse current and reverse battery capabilities.

Different high-side switches offer different capabilities

Normal Operation	Inverse Current Capability	Reverse Battery Capability (ReverSave)
YES	NO	NO
YES	NO	YES
YES	YES	NO
YES	YES	YES

Figure 5 Different PROFET high-side switches offer different capabilities

Note: Reference the appropriate datasheets to select parts with the required capabilities.

3 Normal Mode

In the normal operating mode, the battery is connected with correct polarity and the battery voltage V_{bb} is greater than, or equal to, the output load voltage V_{OUT}. This mode is illustrated in Figure 6.

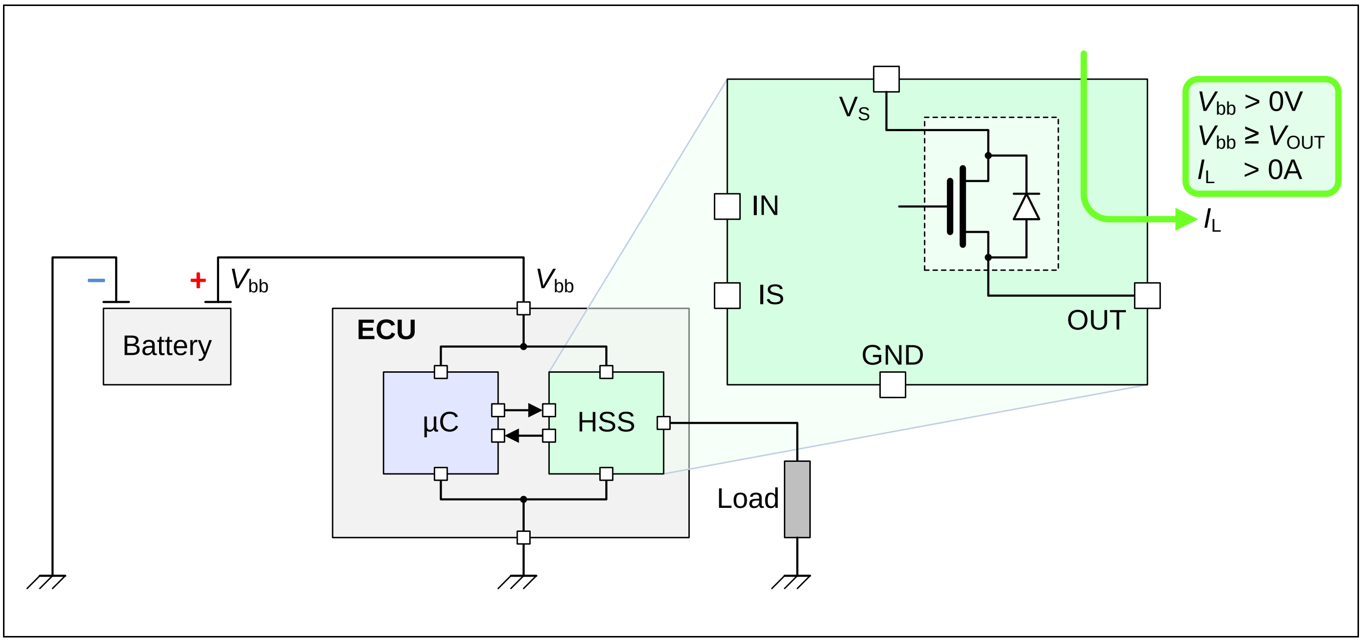

Figure 6 High-level representation of the normal operating mode

Since $V_{bb} \geq V_{OUT}$, the MOSFET's intrinsic diode is reverse-biased and therefore will not conduct. In this case, if the microcontroller has the high-side switch turned OFF, no current will flow through the MOSFET in either direction. If the microcontroller has the high-side switch turned ON, then current will flow (in the classical sense) from the battery, through the MOSFET, to the load. In this case, the power being dissipated by the MOSFET can be calculated using Equation (1).

Equation (1) $$P = I_L^2 \times \mathrm{R_{ON}}$$

In Equation (1), P is the power being dissipated, I_L is the load current, and R_{ON} is the resistance of the MOSFET. The actual value of R_{ON} should be determined from the appropriate high-side switch data sheet. For the purposes of this application note, a typical value of 10 mΩ will be used. Thus, assuming a load current of 10A, the MOSFET will be dissipating 10^2A × 10 mΩ = 1W. This level of power dissipation is normally manageable within automotive ECUs.

4 Inverse Mode

4.1 Introduction

In some cases, depending on the type of load being controlled and the specific application, transient conditions may cause the battery voltage V_{bb} to become less positive than the output load voltage V_{OUT}; this is known as the **inverse mode** or an **inverse current condition**. The characteristic of an inverse mode condition is a positive supply voltage $+V_{bb}$ that is lower than the output load voltage V_{OUT} resulting in a load current $-I_L$ that flows opposite to the normal load current direction. This mode is illustrated in Figure 7.

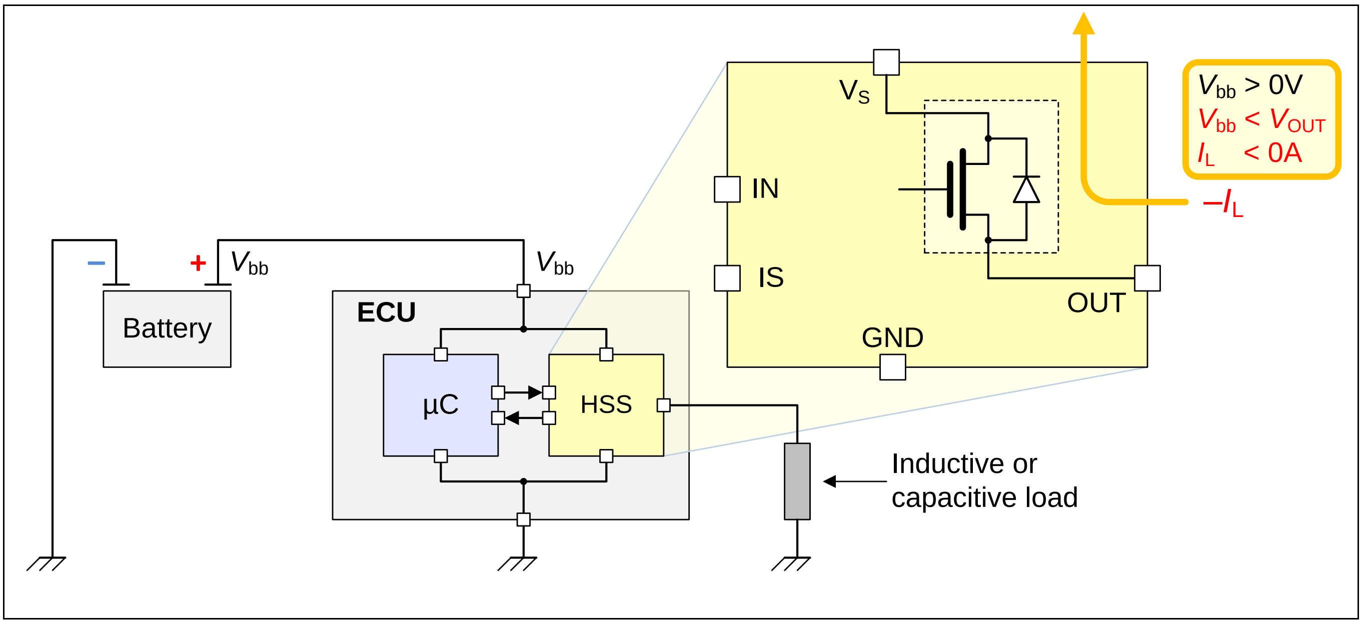

Figure 7 High-level representation of an inverse mode condition

Note that purely resistive loads cannot cause an inverse mode condition. Such a condition can only be caused by capacitive loads or inductive loads that can act in a generative mode. Also note that inverse mode conditions are transient in nature. Some examples that can cause inverse mode conditions are as follows:

- The high-side switch is controlling a load which can operate as a generator. A typical load of this type is an [inductive] motor. During transient dips in V_{bb}, the motor may act as a generator during the transient duration such that it supplies a voltage higher than the battery voltage.
- The high-side switch is controlling a load that can store energy, such as large capacitive loads (or large capacitors in parallel with the load). A possible condition is that the load is ON but the engine is OFF. Then, for example, engine cranking causes the battery voltage to temporarily drop (transient) but the capacitive load is now supplying a higher voltage than the battery voltage.
    - A real-world example of an inverse mode condition occurred when the HID headlights of an automobile were turned ON. Due to tolerances/small differences in the left and right HID ballasts, one headlight activated slightly before the other. Then, when the second headlight activated, its current draw pulled the battery voltage down, resulting in the charged HID ballast on the first headlight causing an inverse mode condition.

If the switch is ON and then an inverse mode condition occurs, the amount of power being dissipated by the MOSFET can be calculated using Equation (2) assuming an inverse current capable switch.

Equation (2) $$P = |-I_L^2| \times \mathrm{R}_{\mathrm{ON(inv)}}$$

In Equation (2), P is the power being dissipated, $-I_L$ is the load current (as defined in Table 1), and $R_{ON(inv)}$ is the MOSFET's resistance in inverse mode. The actual value of $R_{ON(inv)}$ should be determined from the appropriate high-side switch data sheet. This resistance value is similar to the resistance value, R_{ON}, in normal mode. For the purposes of this application note, a typical value of 10 mΩ is assumed. Thus, assuming a load current of 10A, the MOSFET will be dissipating 10^2A × 10 mΩ = 1.0W. This level of power dissipation is manageable.

If the switch is OFF when an inverse mode condition occurs, then the current will flow through the MOSFET's intrinsic diode. In this case, the amount of power being dissipated by the MOSFET can be calculated using Equation (3).

Equation (3) $$\mathrm{P} = |-V_{\mathrm{OFF}}| \times |-I_L|$$

In Equation (3), P is the power being dissipated, $-V_{OFF}$ is the voltage drop across the intrinsic diode, and $-I_L$ is the load current. The actual value of the intrinsic diode's voltage drop should be determined from the appropriate high-side switch data sheet. For the purposes of this application note, a typical value of 0.7V will be used. Thus, assuming a load current of 10A, the MOSFET will be dissipating 0.7V × 10A = 7W. This level of power dissipation is sufficient to damage the switch unless (a) it is a transient that only lasts for a short duration or (b) the high-side switch takes action to address the problem as discussed later in this application note.

Note: This application note is primarily concerned with high-current applications. There is less chance of an inverse mode condition damaging a switch in low-current applications.

4.2 Switch-, Module-, and Application-Level Considerations

The designer must consider what will occur at the switch (device) level, the module (ECU) level, and the application (automobile) level if an inverse mode condition occurs. These considerations are summarized in Table 3.

Table 3 Inverse mode: Switch, Module, and Application-level considerations

	Switches WITHOUT Inverse Current Capability	Switches WITH Inverse Current Capability
Switch-Level	The logic inside the switch will become non-functional and the MOSFET will be turned OFF.	If the switch is ON it will stay ON (unless this state is modified by the ECU's microcontroller), in which case the power being dissipated by the MOSFET can be calculated using Equation (2). This level of power dissipation is manageable. The inverse load current must remain below the inverse load current $-I_{L(inv)}$ as defined in the datasheet, or the intrinsic diode may start to conduct and the logic may be disturbed.
	With the switch turned OFF, the inverse load current will flow through the MOSFET's intrinsic diode. The power being dissipated by the MOSFET can be calculated using Equation (3). With the inverse current flowing through the intrinsic diode, there is potential for the switch to be damaged (see note below this table). The logic may be disturbed and any turn ON could be delayed by the inverse condition.	If the switch is OFF it will stay OFF. The inverse load current will flow through the MOSFET's intrinsic diode. The power being dissipated by the MOSFET can be calculated using Equation (3). With the inverse current flowing through the intrinsic diode, there is potential for the switch to be damaged (see note below this table). If the switch is commanded from OFF to ON during an existing inverse condition, refer to the appropriate datasheet to determine if the device will turn ON immediately or if the turn ON will be delayed by the inverse condition.
	The switch's analog sense current output will become non-functional.	
	In the case of multi-channel high-side switches, an inverse mode condition on one channel may also negatively affect the diagnostic and control logic associated with adjacent channels.	

	Switches WITHOUT Inverse Current Capability	Switches WITH Inverse Current Capability
Module-Level	The microcontroller in the ECU will no longer have access to an accurate current sense output from the high-side switch.	The microcontroller in the ECU will no longer have access to an accurate current sense output from the high-side switch.
	The microcontroller will not be able to control the high-side switch (the switch will not respond). In addition, there will be a turn-on delay after returning to normal mode which extends the duration that the load does not have V_{bb} supplied.	The microcontroller could monitor the values of V_{bb} and V_{OUT} if desired, which means it could detect when an inverse mode condition is present. Depending on the particular high-side switch, the controller may be able to turn the switch ON during the inverse mode condition (check the datasheet associated with the switch for more details).
Application-Level	There will be a turn-on delay after returning to normal mode which extends the duration that the load does not have V_{bb} supplied. If this is not permissible, then the designer should use a switch with inverse current capability.	Upon return to normal mode, the load is immediately supplied V_{bb}.

Note: With inverse current flowing through the MOSFET's intrinsic diode, there is a potential for the switch to be damaged. This will depend on the duration of the inverse mode condition, the amount of inverse current, and the corresponding power dissipation and temperature rise. Although inverse operation is a non-normal operation condition, its effects on the switch will not be critical if the applied conditions remain within the maximum ratings. The main life time relevant parameters during inverse operation conditions are the maximum inverse current, the resulting maximum power losses, the resulting junction temperature, and the maximum voltages (see the appropriate switch datasheet for more details).

5 Reverse Mode

5.1 Introduction

Replacing an automobile's battery or performing maintenance on an automobile's electronic system will require the battery to be disconnected and reconnected. During the reconnection, it is possible for the polarity of the battery to be applied in a reverse direction. This is known as the **reverse mode** or a **reverse battery polarity condition**.

While today's automotive battery terminals are marked and color-coded, the possibility for a reverse mode condition does still exist. Another possible cause of a reverse mode condition would be incorrect polarity of jumper cables while attempting to jump-start an automobile.

Applying a reverse battery condition can potentially lead to damage of the automobile's electronic systems. This means that the electronic control units (ECUs) have to be protected against a reverse mode condition. A typical industry requirement is for the ECU to withstand a reverse mode condition of -14V for one minute at 25°C.

Note: Refer to device datasheets for more detailed information on the techniques required to protect individual pins, such as series resistors.

A high-level representation of a reverse mode condition is illustrated in Figure 8.

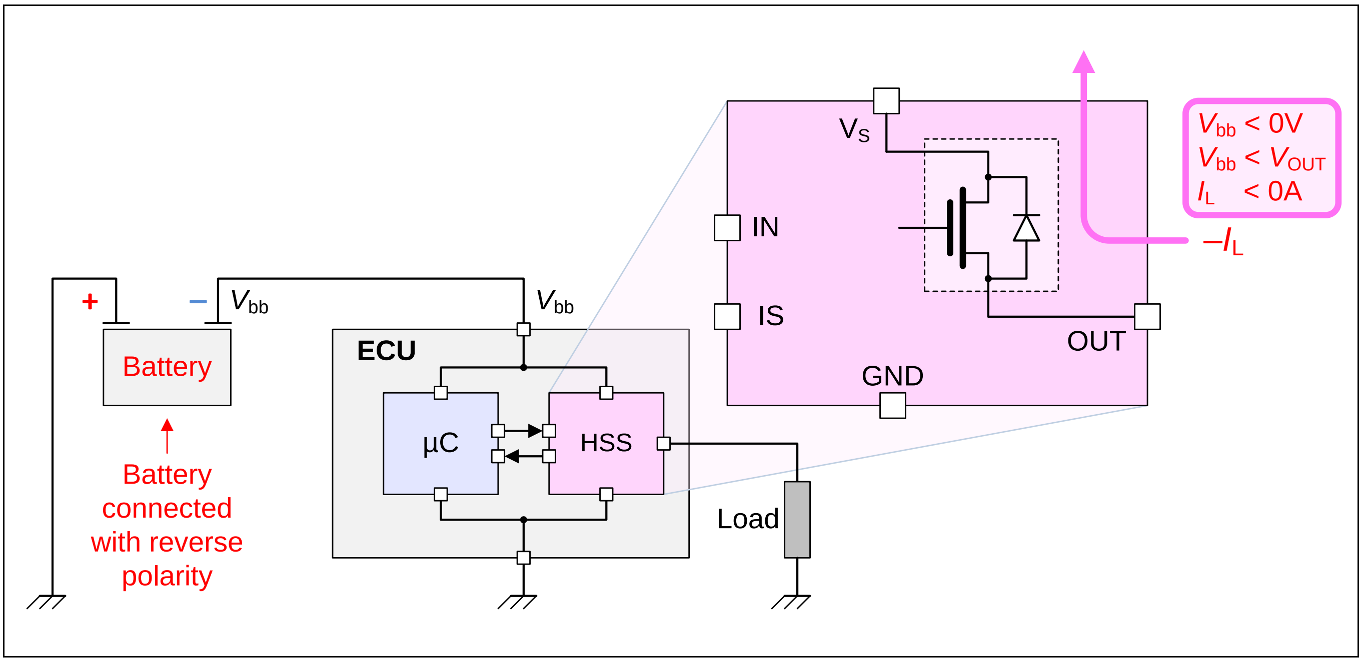

Figure 8 A high-level representation of a reverse mode condition

When a reverse mode condition occurs, the power being dissipated by the MOSFET can be calculated using Equation (4) assuming a reverse battery capable switch.

Equation (4) $$\mathrm{P} = |-I_L^2| \times \mathrm{R_{ON(rev)}}$$

In Equation (4), *P* is the power being dissipated, $-I_L$ is the load current (as defined in Table 1), and $R_{ON(rev)}$ is the MOSFET's resistance in reverse mode. The actual value of $R_{ON(rev)}$ should be determined from the appropriate high-side switch data sheet. This resistance value is usually 10-to-20% higher than the resistance value in normal mode. For the purposes of this application note, a typical value of 12 mΩ is assumed. Thus, assuming a load current of 10A, the MOSFET will be dissipating 10^2A × 12 mΩ = 1.2W. This level of power dissipation is manageable.

When a reverse mode condition occurs (and assuming the switch does not have reverse battery capability), then the current will flow through the MOSFET's intrinsic diode. In this case, the amount of power being dissipated by the MOSFET can be calculated using Equation (3).

The actual value of the intrinsic diode's voltage drop should be determined from the appropriate high-side switch data sheet. For the purposes of this application note, a typical value of 0.7V will be used. Thus, assuming a load current of 10A, the MOSFET will be dissipating 0.7V × 10A = 7W. This level of power dissipation is sufficient to damage a switch; therefore, (a) external [blocking] protection must be considered, or (b) the switch must take action to address the problem. For a low-current example, assuming a load current of 1A, the MOSFET will be dissipating 0.7V × 1A = 0.7W. This level of power dissipation is manageable.

Note: This application note is primarily concerned with high-current applications (usually 5A or more). There is less chance of a reverse mode condition damaging a switch in low-current applications.

5.2 Switch-, Module-, and Application-Level Considerations

The designer must consider what will occur at the switch (device) level, the module (ECU) level, and the application (automobile) level if a reverse mode condition occurs. These considerations are summarized in Table 4.

Note: Regarding the points in Table 4 describing what would occur if a high-side switch that does not have reverse battery capability, these discussions assume that the switch is not provided with any other form of [blocking] protection. In reality, any high-side switch that does not have reverse battery capability should be provided with some form of external [blocking] protection. See also Infineon's Application Note Automotive MOSFETs: Reverse Battery Protection.

Table 4 Reverse mode: Switch, Module, and Application-level considerations

	Switches WITHOUT Reverse Battery Capability	**Switches WITH Reverse Battery Capability (ReverSave)**
Switch-Level	The logic inside the switch will become non-functional and the MOSFET will be turned OFF. With the switch turned OFF, the reverse load current will flow through the MOSFET's intrinsic diode. The power being dissipated by the MOSFET can be calculated using Equation (3). With the reverse load current flowing through the intrinsic diode, there is potential for the switch to be damaged (see note below this table).	The switch will automatically turn ON, at which time the power being dissipated by the MOSFET can be calculated using Equation (4). This level of power dissipation is manageable.
	The switch's analog sense current output will become non-functional (this is *not* an issue because the ECU's microcontroller will also be non-functional during a reverse mode condition).	
Module-Level	The ECU's microcontroller will be non-functional.	
	The ECU's microcontroller will not be able to control the high-side switch during reverse battery conditions.	
Application-Level	Current will be flowing through the application load. If this is not permissible, then the designer should use some form of external [blocking] protection as discussed at the beginning of this section.	

Note: With reverse battery load current flowing through the MOSFET's intrinsic diode, there is a potential for switch damage if the applied conditions exceed the maximum ratings. The main life time relevant parameters during reverse mode conditions are the maximum reverse current, the resulting maximum power losses, the resulting junction temperature, and the maximum voltages (see the appropriate switch datasheet for more details).

6 Conclusion

Automotive applications have many demanding requirements due to their harsh operating environment. The Infineon PROFET family of high-side switches have been designed with features to increase robustness within these harsh environments.

ECU and system designers must consider what is required of the system for inverse and reverse mode conditions (should the load be turned ON, or OFF, or "don't care"), then select the appropriate PROFET high-side switch, and then determine if any necessary external protection components are required.

Inverse current capability and **ReverSave™** are just two of the many PROFET features that allow ECU and system designers to meet their system requirements with a higher level of robustness, simpler designs, reduced external components and lower system costs.

Figure 9 summarizes the definitions and illustrates in a graphical representation the normal, inverse, and reverse modes. This summary is useful for considering the modes, techniques and options discussed in this application note.

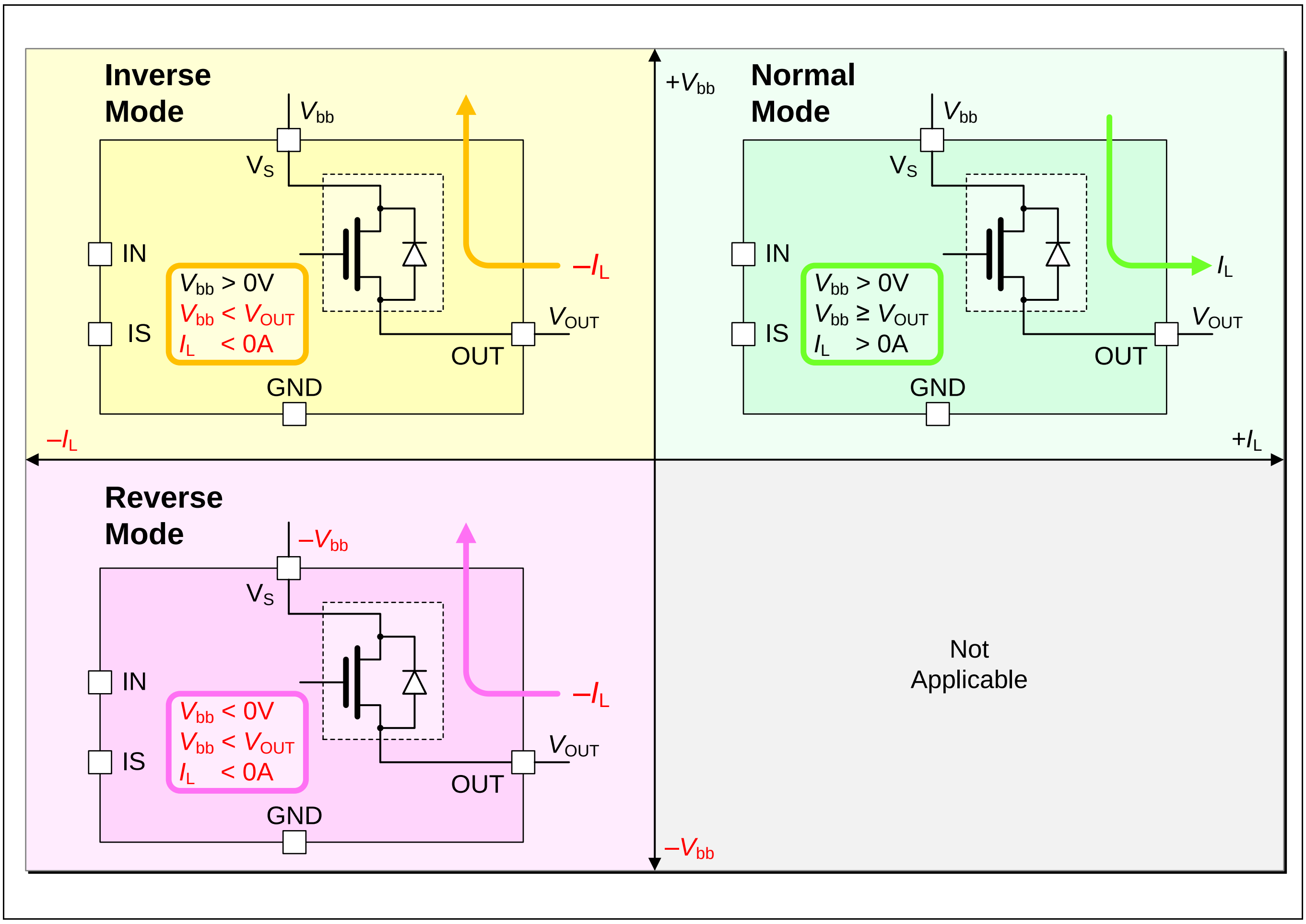

Figure 9 Graphical summary of the normal, inverse, and reverse modes

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Edition 2011-07-13

Published by
Infineon Technologies AG
81726 Munich, Germany

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