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APPLICATION NOTE

Application Note AN-1083

Features of the Low-Side Family IPS10xx

By Fabio Necco, International Rectifier

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Introduction

The new IPS10XX family of protected power MOSFETs consists of three terminal low side devices based upon the latest IR proprietary vertical technology P^3 (Power Product Platform). IR protected MOSFETs are vertical power MOSFETs integrated with protection circuitry. The new IPS10XX family features logic level inputs, over-temperature shut down protection, over-current shut down protection, active clamp and diagnosis through the input pin.

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Diagnosis

Diagnostic features are used to communicate the condition of the IPS to the microcontroller. The IPS protects itself against different fault conditions. Fault conditions can be either over current or over temperature. Once the fault condition is detected by the IPS, the diagnostic information is made available through the input pin. The low side family can detect different kind of faults but only provide two statuses: fault or normal condition. Fault conditions can be over current, over temperature or open load. No distinction on the kind of fault is made. The diagnostic is implemented through the input current. When the input is turned ON (to V_{IN} = 5V) the current at the input terminal (In) will change depending on the condition of the IPS. The current in case of a fault condition is about 8 times higher than that in normal conditions. A resistor in series with the input allows current variations to be translated to voltage variations. A typical connection of the IPS is shown in figure 1. Diagnostic voltage can be detected at the input pin, after the input resistor (R_{DIAG}).

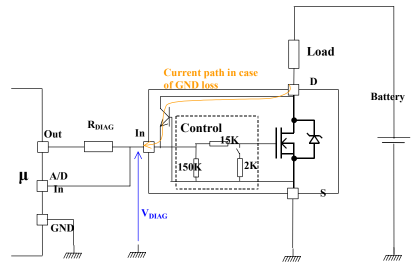


Figure 1. Diagnostic voltage reading on LS

Typical diagnostic voltages for a 1.2KΩ R_{DIAG} resistor are shown in table 1.

Condition	I_in	Vdiag	Rdiag
Normal	32uA	4.96V	1.2KΩ
Fault	230uA	4.72V	

Table 1. Low side diagnosis levels

Input current vs. temperature

The value of the input current changes with the junction temperature. Curves similar to the one showed in Figure 2 are provided in the device datasheet.

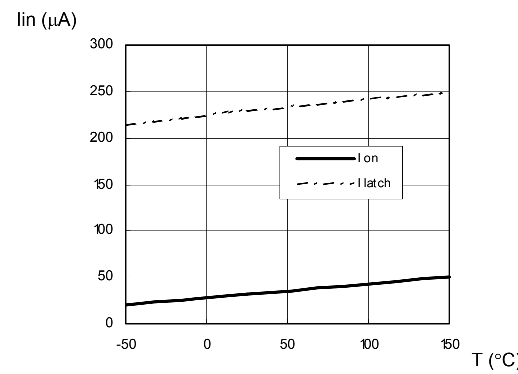


Figure 2 Input current variation with temperature

Selection of the resistor Rdiag

The resistor R_{DIAG} serves two purposes. First of all, it provides protection for the microcontroller in case of ground disconnection. Under this condition a current flows between V_{BAT} and the input pin (In) as shown in figure 1. Secondly, since the current through the input pin changes when a fault is detected, the value of this resistor determines the diagnostic voltage levels. R_{DIAG} must be selected according to the characteristics of the input stage that is used to read the diagnostic. The higher R_{DIAG} the bigger the voltage difference between fault and no-fault condition. There is a limit to the maximum value for this resistor and it is due to the minimum high-level input voltage (VIH min). In order to keep the device ON the input voltage must be above the V_{IHmin} = 4.5V. R_{DIAG} can be selected as follows:

$$R_{DIAG} = \frac{V_{OHmin} - V_{IHmin}}{I_{INmax}}$$

$V_{IHmin} = 4.5V$ and $I_{INmax} = 250\mu A$ from the datasheet.

Assuming $V_{OHmin} = 4.8V$ (min. microprocessor V_{OH})

$$R_{DIAG} = 1.2K\Omega$$

The diagnostic levels, corresponding to a 1.2 Kohm resistor, are shown in Table 1. Due to the input current level, an analog input is required to read the diagnostic voltage.

Protections

The previous section describes the diagnosis features that can be used to inform the logic stage (micro controller) about the IPS status. The following section explains how the device protects itself when a fault condition is detected. Over current and over temperature could damage the IPS if no protection is implemented.

Over-temperature protection

The IPS shuts down when the junction temperature exceeds the over temperature limit of 165°C. The IPS10XX latches after the shut down takes place. In order to restart in latch mode (after OT shutdown), the input needs to be kept "low" for a time longer than T_{RESET}. This time is set by design to allow the temperature to go below a defined level and is defined based on the thermal characteristics of the package. Shut down waveforms are shown in figure 3.

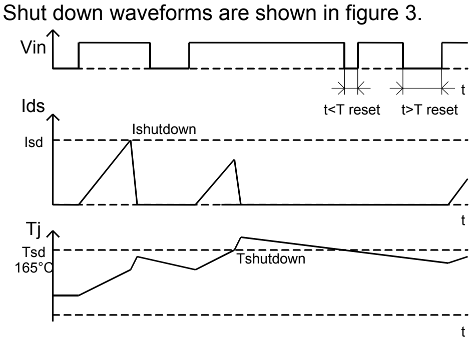


Figure 3. Shut down and re-start feature

Thermal run-away prevention

The response time of the over temperature protection circuit has been significantly improved from the previous family. A faster response time protects from thermal run-away.

If, after a thermal shut down, the device is turned ON before T_{RESET}, the over temperature protection circuit will react before the device can be activated, preventing thermal run away.

OT protection response time

The over temperature protection response time varies depending on the output current. The system will react faster to higher currents, due to the fact that the junction temperature will reach the over temperature shut down threshold quicker. The behavior of the Over temperature protection for the IPS1011 is shown in figure 4. Figures like this are provided in the data sheet of each device. When the IPS is used in series with a fuse, the fuse characteristic must be above the Over temperature protection response time characteristic of the IPS, as shown in figure 4.

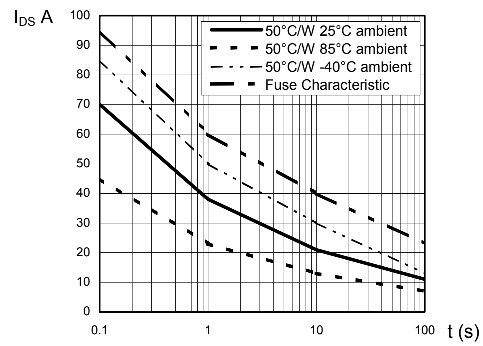
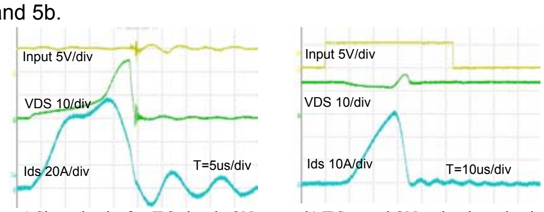


Figure 4. Over temperature response time

Over-current protection

The IPS10XX family features an over-current shut down protection.

When the drain current reaches the preset shut down limit, the device will be turned OFF. The response time of the current shut down feature is a function of the peak current, the inner delay and the di/dt slope. The behavior of the IPS10XX depends on whether the over current happens when the device is already ON or the device is turned ON under an over-current condition. A typical behavior of an IPS1031 under these two conditions is shown in figure 5a and 5b.



a) Short circuit after IPS already ON   b) IPS turned ON under short circuit

Figure 5. Over current shut down behavior

Operation at V_{IN} > 5.5V

Continuous operations at input voltage higher than 5.5V are not recommended since the behavior of the protections changes with the input voltage, as shown in figures 6 and 7. In particular, increased over temperature may reduce the long-term reliability of the device. Operating continuously with V_{IN} > 5.5V is therefore not recommended.

Operation at V_{IN} < 4.5

In the IPS10XX the protection features are supplied through the input pin and therefore depend on V_{IN}.

The behavior of the over temperature shut down versus the input voltage is shown in Figure 6. The over temperature threshold is low at low V_{IN} causing the device to fail to turn ON at high temperatures. This does not affect the life of the device.

Figure 7 shows the behavior of the over current protection as a function of the input voltage. In normal operation, the gate voltage is equal to the input voltage. When V_{IN} is around 2.5V, the power MOSFET will not be fully 'ON' and the current will be limited by the trans-conductance of the power MOSFET. In this mode the current is limited below over current shut down threshold and the MOSFET will not latch.

The power dissipation under this condition can be very high, causing the junction temperature to rise.
Repeated turn on and off under this condition may reduce the reliability due to the high thermal excursion of the junction temperature (thermal cycling).
Operating continuously with Vin < 4.5V is therefore not recommended.

In conclusion continuous operations are recommended only for input voltages between 4.5V and 5.5V.

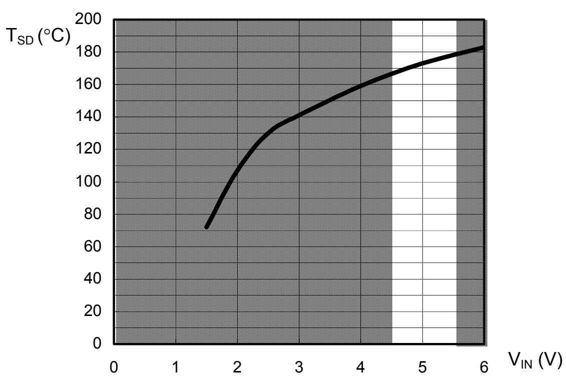


Figure 6. Over temperature protection vs. input voltage

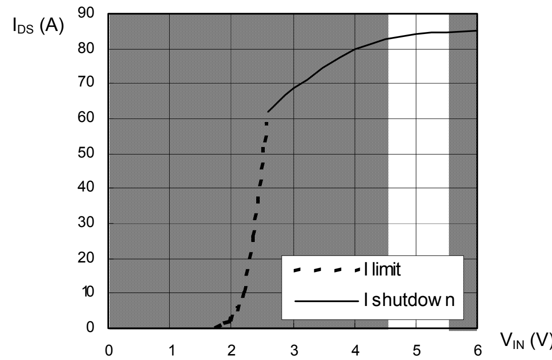


Figure 7. Over current protection vs. input voltage

Active clamp

Purpose of the active clamp

When switched OFF, an inductive load generates a voltage across its terminal whose amplitude depends on the current slope and the inductance value. In a low side configuration the over voltage across the inductance will cause the drain-to-source voltage to rise above battery. This causes the body diode to go into avalanche if no external zener clamps or freewheeling diodes are used, as shown in figure 8.
The purpose of the active clamp is to limit the voltage across the MOSFET to a value below the body diode break down voltage to reduce the amount of stress on the device during switching.

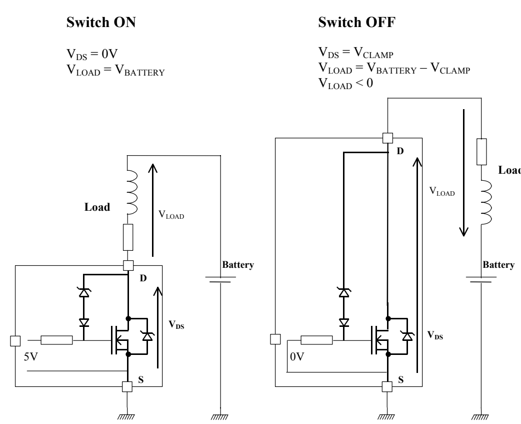


Figure 8. Active clamp circuitry

Active clamp methodology

One way to control the V_{DS} of a MOSFET is by driving it in linear region. A feedback loop inside the IPS, regulates the V_{DS} to the targeted active clamp voltage by adjusting the output MOSFET gate voltage independently from the load current. The internal circuitry consists of a zener diode connected between drain and gate and a resistor from gate to ground. Please note that during active clamp, the output MOSFET is driven in linear region and the power dissipation does not depend on the R_{DSON}.

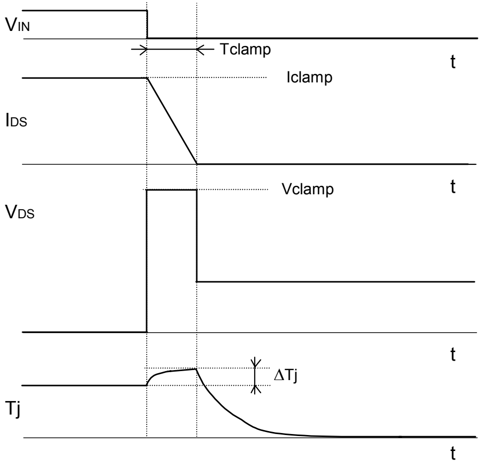


Fig 9. Active clamp waveforms

Energy consideration when using active clamp

An active clamp allows faster recirculation compared to free wheeling techniques, and does not require the use of external devices.
However the drawback of the active clamp technique is that the energy is dissipated by the IPS and is potentially damaging. Energy dissipation calculations are shown in the following section:

Energy dissipated by the IPS:

$$E_{IPS} = \frac{1}{2} \cdot L \cdot I^2 \cdot \frac{V_{CLAMP}}{V_{CLAMP} - V_{BATT}}$$

Energy dissipated by the load:

$$\frac{1}{2} \cdot L \cdot I^2$$

Since V_{CLAMP} must be higher than V_{BATT}, the IPS dissipates more energy than the load. This is due to the fact that during active clamp some energy is taken from the battery.

The energy dissipated by the IPS is proportional to the load inductance and the load current.
Curves similar to figure 10 are given in the data sheet and can be used to estimate the maximum load inductance versus load current. These curves are based upon the amount of energy that can be dissipated by the IPS during an active clamp. The section "maximum inductive load" explains how to calculate the maximum value of inductance.

Please note that the load 'parasitic resistance' provides a limitation to the load current. Maximum load current must be calculated in the worst possible supply conditions.
For example for a 100uH load, the curves shows a maximum Iloadmax = 23A. If the worst-case $V_{BATTERY}$ is 37V, the inductor minimum series resistance must be 37V/23A= 1.6 Ohm, according to figure 10.

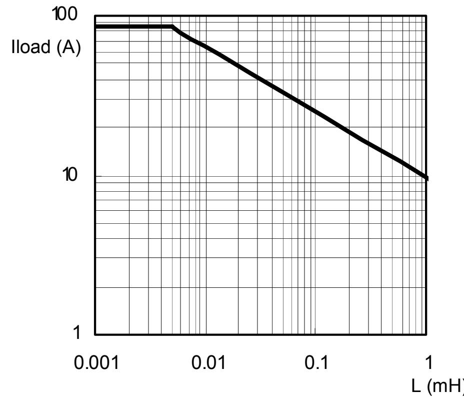


Figure 10. Output current vs. maximum inductive load

Temperature increase during active clamp

The energy dissipation during active clamp will cause the junction temperature to increase as shown in figure 9.

The temperature increase during active clamp can be estimated as follows:

$$\Delta_{Tj} = P_{CL} \cdot Z_{TH}(t_{CLAMP})$$

Where: $Z_{TH}(t_{CLAMP})$ is the thermal impedance @t = t_{CLAMP} which be read from the thermal impedance curves given in the data sheets and in figure 12.

$P_{CL} = V_{CL} \cdot I_{CLavg}$: Power dissipation during active clamp

$V_{CL} = 39V$: Typical V_{CLAMP} value for the IPS10XX

$I_{CLavg} = \frac{I_{CL}}{2}$: Average current during active clamp

$t_{CL} = \frac{I_{CL}}{\left|\frac{di}{dt}\right|}$: Active clamp duration

$\frac{di}{dt} = \frac{V_{Battery} - V_{CL}}{L}$: Demagnetization current

The temperature increase during active clamp must be limited by design to avoid damaging the IPS.

Switching performances

The input of the IPS10xx is internally connected to the gate of the MOSFET through a 15Kohm resistor. This limits the speed of the IPS, reduces electrical noise and improves EMC performances compared to the previous families.
Typical switching waveforms are showed in Figure 11.
Switching times are provided in the data sheet.

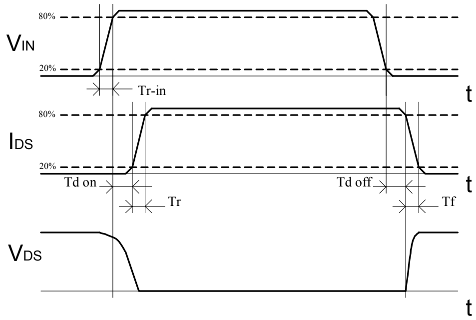


Figure 11. Typical switching waveforms

Maximum frequency

The data sheet indicates a maximum recommended frequency which is calculated to have conduction losses equal to switching losses. Operating at higher frequency is possible, but the contribution due to the switching losses will be higher than that of the conduction losses. The maximum switching frequency is therefore only limited by the turn ON and turn OFF times and by the power dissipation.

Input voltage maximum rise time

The over temperature (OT) protection block is supplied via the input. The OT response time will decrease with input voltage for V_{IN} below 4.5V.
If the input rise time is longer than the over temperature protection response time, the over temperature can be triggered before the device can turn ON, even if the temperature is lower than 150°C.
Table 2 shows typical over temperature shut down thresholds for different input rise times.

Tr-in (0.5V - 4.5V).	< 1us	3us	6us	20us
Typical max start temperature °C	165	145	100	80

Table 2. OT reaction time vs. Tr-in

The data sheet suggests 1us as the maximum input voltage raise time.

Maximum inductive load

As explained in the active clamp section, inductive loads contribute to the junction temperature increase due to the active clamp feature. The value of inductance affects the duration of the active clamp and therefore the maximum junction temperature of the device. The worst condition is when the device shuts down due to over temperature (Tj=165C) and the load current is just below the over current shut down threshold. Due to the inductive load, the active clamp will be triggered at shut down and the junction temperature will increase.
The maximum load inductance indicated in the datasheet is the value of inductance that causes an increase of 35 °C in the junction temperature in case of over temperature shut down (worst case OT=165C) at the maximum load current (typical Isd =85A for the IPS1011). The data sheet also shows that, if the load current is limited, higher inductances can be driven.
The formula below show how to calculate the maximum load inductance with the available data from the IPS10XX data sheet. ($I_{SHUTDOWN}$ typ = 85A V_{CLAMP} typ =39V @ V_{BATT} = 14V)

Power dissipation during a single active clamp can be calculated as follows: $P_{CL} = \frac{V_{CL} \cdot I_{CL}}{2} = 1657W$

If $T_{Jclamp} = 200°C$ (max Tj allowed during active clamp)

$\Delta_{Tj} = T_{Jclamp} - 165°C = 35°C$

Since $\Delta_{Tj} = P_{CL} \cdot Z_{TH}(t_{CL})$

We can calculate the maximum Z_{TH}(tcl) as follows:

$$Z_{TH}(tcl) = \frac{\Delta_{Tj} \cdot}{P_{CL}} = \frac{35}{1657} = 0.02\ °C/W$$

From the Z_{TH}(tcl) curve we can read t_{CL}.

$t_{CL} = 22\mu s$: active clamp phase duration

and $L = t_{CL} \cdot \frac{V_{Batt} - V_{CL}}{I_{LOAD}} = 6.5\mu H$

The formula above shows that the maximum inductance depends on the load current.
The calculations above are based upon 85A worst-case load current. However, the parasitic series resistance of the load limits the maximum load current. A load with a series resistance of 0.5 Ohm will limit the maximum current to 28A @V_{BATT} =14V and the maximum inductive load will be 100µH. Parasitic resistance must therefore be considered when calculating the maximum inductive load. Please note that the junction temperature will rise above 165°C if an OT shut down occurs while driving an inductive load. Repetitive operation during this condition may impact the reliability of the device (i.e. thermal cycling) and must be avoided.

Maximum capacitive load

There are two effects to consider when driving capacitive loads. First is the behavior of the current shut down threshold which decreases with the input voltage when Vin<4.5. For input below 3V the trans-conductance of the MOSFET limits the current. The second is the dynamic response of the over current shut down in relation to the slope of the output peak current caused by the capacitor.

A capacitive load generates a peak current which depends on the slew rate of the V_{DS} and on the capacitance value. For this reason when driving capacitive loads, the over current protection can be triggered at turn on, causing a protection feature to act during normal operations.

The maximum capacitive load can be estimated assuming the maximum peak current (at turn on) to be half of the shut down current threshold, given in the datasheet.

For the IPS1011, with a typical current shut down of 85A, the peak current during turn on should be limited to about 42A

The maximum capacitive load that the IPS can drive may be calculated as follows:

$$i_{Cload} = C \cdot \frac{dV_C}{dt}$$

Assuming $V_C = V_{BATT} - V_{DS}$, and a constant V_{BATT}

$$i_{Cload} = C \cdot \frac{dV_{DS}}{dt}$$

The minimum dV_{DS}/dt is given by the minimum Rise time (20uS) needed to go from 20% to 80% of V_{BAT} = 14V

$$\frac{dV_{DS}}{dt} = \frac{14 - 2.8 - 2.8}{20 \cdot 10^{-6}} = \frac{8.4}{20 \cdot 10^{-6}} = 420 \cdot 10^3$$

which gives:

$$C = \frac{i_{Cload}}{\frac{dV_{DS}}{dt}} = \frac{42}{420 \cdot 10^3} = 100\mu F$$

Please note that DC motors often use capacitors connected in parallel with the winding for EMC purposes. This capacitive load must be taken into account when selecting the IPS.

Maximum battery voltage

The 10XX families are designed and qualified to operate continuously at battery voltages up to 28V, as indicated in the datasheet. The drain-to-source voltage can exceed 28V but will be clamped at 36V by the active clamp. Energy dissipation calculations must be performed for voltages above 36V, such as in the case of inductive loads, or automotive pulses. The device can handle voltages between 28V and 36V as long as they are not permanently applied.

Loss of ground

In case of loss of the ground connection, a parasitic structure in the IPS will create a current path from the battery to the input pin, through the load. This current will flow into the output of the micro and can cause damage to the output stage of the micro if not limited. The connection of the diagnostic resistor (R_{DIAG}) in series with the input pin, as described previously in this document, provides a limitation for the current in case of GND loss.

Thermal impedance curve

Thermal impedance curves (similar to the one showed in Figure 12) are given in the data sheet and can be used to determine the maximum load inductance and the thermal performances of the device.

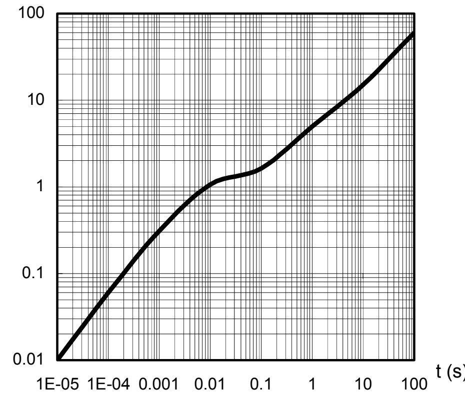


Figure 12. Thermal impedance

Summary

This application note explains the behavior of the IPS10XX and gives suggestions on how to design the circuitry around the IPS10XX for automotive applications. This document also explains how the protection features behave outside the recommended conditions of the data sheet.

Protection features, such as over-current shut down and over-temperature, are designed to protect the IPS against extreme conditions but are not intended to be used repeatedly under normal operations since they can shorten the life of the device.

Please contact the IR Technical Assistance Center with any questions regarding the IPS10XX family.