Voltage clamp circuits for ultra-low-voltage apps

Very-low-voltage enhancement-mode MOSFETs can play a significant role in low-voltage designs

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Voltage clamps for protecting low-voltage dc circuits require a new approach to circuit design. Many commonly used voltage clamps were built for systems of 5 V or higher, but lower-voltage systems require distinctive clamping abilities. The use of very-low-voltage precision enhancement-mode MOSFETs play a pivotal role in designing voltage clamps in low-voltage applications.

Today's electronic systems often include many different protection technologies in order to ward off ESD, EMI, voltage transients, and supply faults or fluctuations that can randomly occur on power supplies, analog signal lines, communication lines, and data buses.

Laptop computers, for instance, include peripherals, open ports, buses, connecting signal cables, and power cables that are all vulnerable. Electromechanical disk drives can generate sudden load changes, and inductive switching often generates high levels of transient energy that is radiated around the system.

Transient voltages often result from the sudden release of stored energy. In many systems, circuits share the same supply bus and power and data lines are often bundled together. Parasitic cable capacitances and inductances can create a path for transient voltages produced on the power lines and transferred to data lines. Connecting a USB cable into a socket, or hot-swapping a card or cable, can invisibly generate dangerous transients. Additionally, portable systems use dc/dc switching regulators that generate both transients and noise.

This spells trouble for microcontrollers and other MOS-based ICs and devices that are susceptible to damage from overvoltage. Transient voltages on low voltage power lines often attain amplitudes many times the nominal voltage level, thereby putting vulnerable components constantly at risk. As a result, the need for reliable overvoltage protection and voltage clamps is even more important now than ever.

There is, however, a subtle difference between an overvoltage protection circuit and a voltage clamp. Both types of circuits monitor the input voltage and control the gate of an external transistor switch without interfering with normal operation of the load circuit.

If the incoming voltage exceeds a preset threshold, the overvoltage protection circuit will disconnect the load during the event. In contrast the clamp circuit will continue to power the load during the transient event, but limit the voltage being applied to it. In both cases the protection circuit must be fast enough to prevent any transient from damaging the load.

Alternative protection methods

Very-low-voltage operation puts severe strain on the existing methods of overvoltage protection. Low-voltage Zeners used as voltage clamps have high leakage currents, and their voltage ratings are not precise (1.8 V_Z ±5% = ±90 mV; 2.7 V_Z ±5% = ±135 mV, etc.), while MOVs and most TVS products are mostly impractical due to their >5-V breakdown voltages. Simple diodes have limited forward voltages and power-handling capability.

A novel approach uses very low-voltage precision enhancement-mode MOSFETs to improve on the clamping actions of Zener diodes (see *Fig. 1a*). *Figure 1b* shows a circuit made to simulate a low-power Zener shunt regulator, using two parallel-connected EPAD transistors.

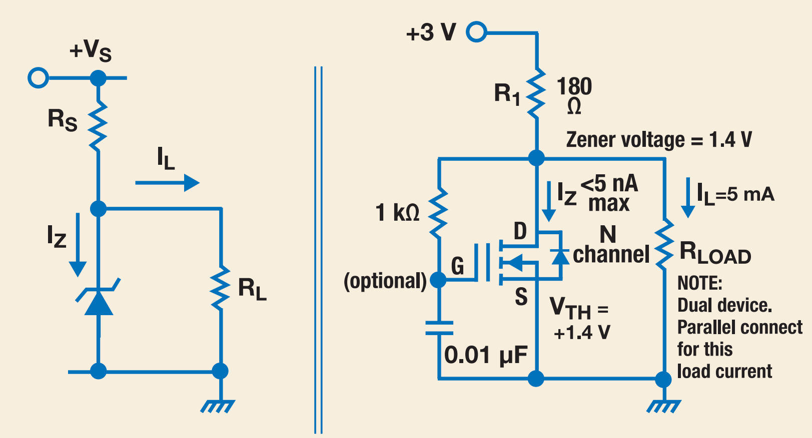

Fig. 1. The typical low-voltage Zener shunt regulator (a) suffers from a high power-dissipation.

Under normal conditions the resistor R_1 will drop the voltage difference between the supply voltage (3 V), and the gate threshold voltage (V_{TH} = +1.4 V ±1.5%). The difference between each MOSFET's gate threshold voltage is typically 10 mV.

You should always ensure that R_1 is small enough to supply the minimum I_Z (5 nA max), even when the supply voltage is at its minimum (2.5 V) and load current is at its maximum (6 mA). The total current passing through the resistor is (I_L + I_Z). The value of the resistor will be

$$R_1 = 1.1\ \text{V}/6\ \text{mA} = 183\ \Omega$$

Although the gate normally connects directly to the drain, the 1-kΩ protective resistor R_2 and the 0.01-µF capacitor C_1, may be required for improved stability.

Dual-matched enhancement-mode MOSFETs (b) serve as low-power low-voltage Zener shunt regulators.

Compared with a real Zener diode, this circuit illustrates that a much lower Zener current can be used to establish the Zener voltage (only the EPAD's leakage current of <5 nA max is involved), and a lower voltage of 1.4 V compared to 1.8 V for a Zener diode. Additionally, the circuit's tolerance on the threshold voltage is ±1.5%, which is better than the best Zener voltage of ±5%.

Should the load become disconnected, the parallel EPADs still continue regulating, and this regulation spans three orders of magnitude, which is better than a Zener diode's capabilities. Output impedance and noise levels are both far lower, and temperature compensation is also improved.

Figure 2 shows a zero-power, precision Zener-voltage clamp circuit.

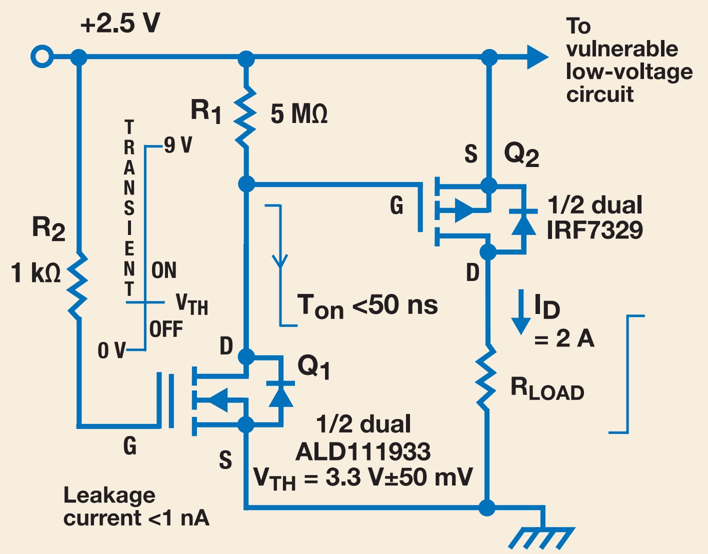

Fig. 2. The precise, ultra-low gate threshold voltage is used to control the sharp, fast turn-on clamp circuit with zero power-dissipation, when not activated.

This voltage clamp circuit has very fast turn-on and turn-off characteristics (between 10 to 100 ns), and at a high current level (>1 A).

Under normal operating conditions, when the clamp is not activated, it draws virtually zero power because the circuit's quiescent power dissipation consists essentially of the combined leakage currents (<100 nA) of the ALD111933 dual EPADs and the dual p-channel power MOSFETs (International Rectifier IRF7329). The EPAD's precise threshold voltages $V_{GS(TH)}$ are used to control the turn-on voltage of the clamp circuit.

At voltages below $V_{GS(TH)}$, both the power MOSFETs and the EPADs are turned OFF. Resistor R_2 is for protective purposes only. When an EPAD's gate-to-source voltage reaches its $V_{GS(TH)}$, it switches on and turns on the power MOSFET. The current supplied to R_{load} is limited by the $R_{DS(on)}$ of the power MOSFET, which in this example is 2 A. The IRF7329 is a member of a family of similar devices. Available in an SO-8 package, it is a -12-V (dual) device, with each MOSFET having an $R_{DS(on)}$ of 30 mΩ at V_{GS} = -1.8 V, at I_D = ±4.6 A.

The actual clamp voltage is adjustable within a certain range by varying the value of R_1 (that is, 500 kΩ to 20 MΩ), which allows a limited adjustment of precisely when the circuit turns on. This ability to turn on at slightly higher/lower gate-to-source voltages is enables the user to set the turn-on clamp voltage at a very precise level, which could be very close to the normal operating point of the circuit.

Compared with a real Zener diode clamp this circuit has a much lower quiescent current (<100 nA max), versus the low-voltage Zener's unacceptably high leakage current. It also features a much sharper voltage-versus-current (I-V) characteristic, along with more precise voltages). Response time (<100 ns) is also better than with the Zener, as well as its surge current handling capability (>2 A). For higher voltages from 5 to 10 V, it may be necessary to stack two or more EPAD devices on top of each other. Care should be taken to ensure that neither MOSFETs in Figure 2 are subjected to voltages beyond the following: (ALD1119xx = 10.6 V, 500 mW; IRF7329 = -12 V, 2 W). As neither product is internally ESD protected, including a 6-V TVS device across the supply rails is recommended. This is a good clamp circuit that operates at voltages between 1 and 3.5 V.

The low-voltage operating limit is determined by the higher of the threshold voltages of either the EPAD device or the p-channel power MOSFET plus an overdrive voltage to attain a preselected current clamp level. For example, using an ALD110814 and IRF7329 combination has an operating voltage limit of about 1.4 V and can achieve a current clamp of greater than 1 A while maintaining quiescent currents of just a few tenths of a nA in normal operation. Various EPAD devices can also be stacked to obtain different combinations of clamp voltages.

For more on voltage clamp circuits, visit http://www.electronicproducts.com/linear.asp.