Novel voltage clamp circuits for ultra low-voltage applications

Contributed Article from Advanced Linear Devices

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

Today's electronic systems often include many different protection technologies in order to ward off Electro Static Discharge (ESD), Electro-Magnetic Interference (EMI), voltage transients, and supply faults or fluctuations that can randomly occur on power supplies, analog signal lines, communications lines, and data busses.

Laptop computers for instance, include peripherals, open ports, busses, 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 utilize DC/DC switching regulators that generate both transients and noise.

This spells trouble for micro-controllers and other MOS-based ICs and devices that are susceptible to damage from over-voltage. 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 over-voltage protection and voltage clamps is even more important now than ever.

There is, however, a subtle difference between an over-voltage 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 over-voltage 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

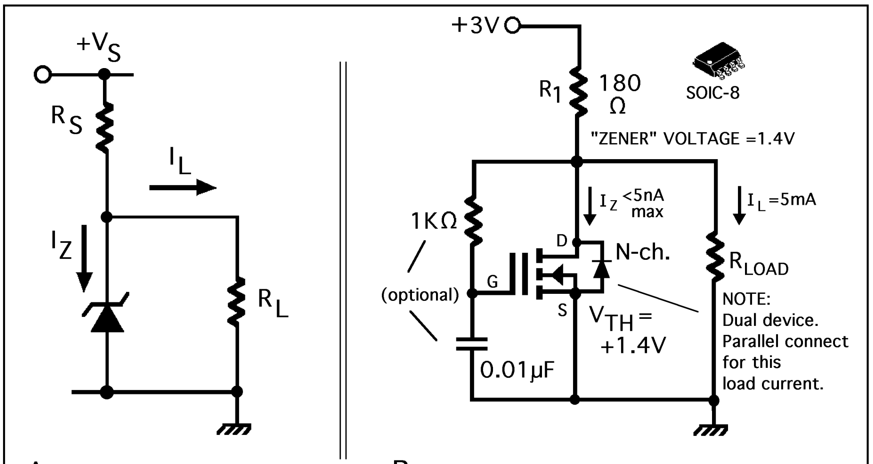
Very low voltage operation puts severe strain on the existing methods of over-voltage protection. Low voltage zeners used as clamps have high leakage currents, and their voltage ratings are not precise ($1.8V_Z \pm 5\% = \pm 90mV$; $2.7V_Z \pm 5\% = \pm 135mV$ etc.), while MOVs and most TVS products are mostly impractical due to their >5V 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 upon the clamping actions of zener diodes (**Figure 6A**). Figure 6B shows a circuit which is made to simulate a low-power zener shunt regulator, using two parallel-connected ALD EPAD® transistors (ALD110914). Under normal conditions the resistor R_1 will drop the voltage difference between the supply voltage (+3V), and the EPAD's precise gate threshold voltage (V_{TH} = +1.4V ±1.5%). The difference between each MOSFETs' gate threshold voltage is typically 10mV. One should always ensure that R_1 is small enough to supply the minimum I_Z (5nA max), even when the supply voltage is minimum (2.5V), and load current is at its maximum (6mA). The total current passing through the resistor is ($I_L + I_Z$). The value of the resistor will be:

$$R_1 = \frac{1.1V}{6mA} = 183\Omega \qquad \text{(Eq.2)}$$

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

Figure 6.



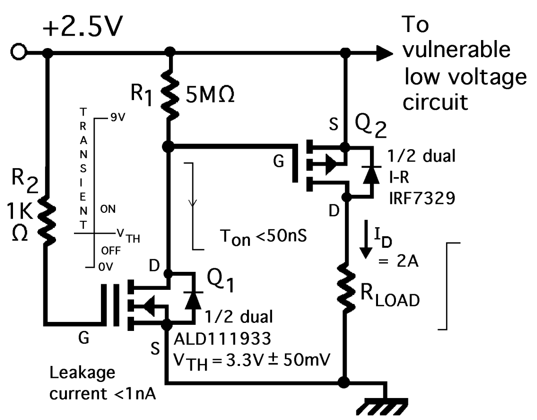
A. The typical low-voltage zener shunt regulator suffers from a high power dissipation.

B. ALD110914 EPAD® dual-matched enhancement-mode MOSFETs serve as a precision ultra low-power, low voltage zener shunt regulator.

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 <5nA max is involved), and at a voltage (1.4V), completely unavailable as a zener diode voltage (1.8V min). Additionally, the EPAD's ±1.5% tolerance on its threshold voltage is far better than the best zener voltage (±5%). Should the load become disconnected, the parallel EPADs still continue regulating, and this regulation spans three orders of magnitude - far beyond a zener diode's capabilities. Output impedance and noise levels are both far lower, and tempco is also improved.

Figure 7 shows a "Zero-Power, Precision Zener-Voltage Clamp" circuit. This voltage clamp circuit has very fast turn-on and turn-off characteristics (between 10nS to 100nS), and at a high current level (>1Amp). 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 (< 100nA) of the ALD111933 dual EPADs® and the dual P-channel power MOSFETs (International Rectifier IRF7329). The EPADs' precise threshold voltages $V_{GS(TH)}$ are utilized 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, so turning 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-Amps. The IRF7329 is a member of a family of similar devices. It is a -12V (DUAL) device, with each MOSFET having an $R_{DS(on)}$ of 30-mΩ @ V_{GS} = -1.8V, @ I_D = ±4.6A, and available in an SO-8 package.

Figure 7.



The precise, ultra-low gate threshold voltage of an ALD111933 EPAD® is used to control this sharp fast turn-on clamp circuit, with zero power dissipation when not activated.

The actual clamp voltage is adjustable within a certain range by varying the value of R_1 (i.e. 500KΩ to 20MΩ), 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 due to the EPAD's unique precision, and 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 (<100nA max), versus the low-voltage zener's unacceptably high leakage current. It also features a much sharper voltage vs. current (I-V) characteristic, along with more precise voltages (ALD111933 = 3.3V, or ALD111920 = 2.0V), due to the EPAD's ±1.5% tolerance on its threshold voltage vs. the best zener tolerance (±5%). Response time (<100nS) is also better than with the zener, as well as its surge current handling capability (>2-Amps). For higher voltages from 5V to 10V, it may be necessary to stack two or more EPAD® devices on top of each other. Care should be taken to ensure that neither MOSFET in Figure 7 are subjected to any voltages beyond the following: (ALD1119xx =+10.6V, 500mW; IRF7329 = -12V, 2W). As neither product is internally ESD-protected, inclusion of a 6V TVS device across the supply rails is recommended. For a good precision clamp circuit that operates at voltages between 1.5V and 3.5V, this circuit may be one of the best available, not to mention its simplicity.

In summary, the vast majority of existing protection devices were designed for +5-volt (and higher) systems. Very few products are available with clamping voltages below this. Suppression devices will always be necessary for protection against conducted transients, but at present other types of high-speed voltage clamps all require more power to operate, have significantly higher threshold voltages, or are much more complex. They cannot yet support very low-voltage operation, as demonstrated here using some very unique products from Advanced Linear Devices, Inc.

======================////// END \\\\\\===================