by **Robert Regensburger** | Maxim Integrated Products, Germany

ACTIVE HIGH-VOLTAGE TRANSIENT PROTECTORS TRUMP CONVENTIONAL APPROACHES

Most vehicle electronic systems require overvoltage, reverse-battery, and transient protection. The use of active protectors for these purposes offers substantial advantages in terms of power dissipation, optimization of the operating voltage limits, part cost savings, and the reduction of quiescent current.

Various electric and electromagnetic disturbances generated inside and outside a car can be hazardous to vehicle electronic equipment. They can degrade performance, cause malfunctions, and even destroy electronic devices. The most severe disturbances—large positive and negative overvoltages and transients—can be generated in the vehicle electrical system itself.

In an automotive network, most electronic modules are powered by the car battery, either directly or through the ignition switch. Electrical disturbances and high-frequency effects can occur even during normal operation, and be distributed across the wiring harness to the onboard electronics by conduction, coupling or radiation. Sources of disturbance include the ignition system, the alternator, load switching, switch bounce, and "load dump" effects—i.e., voltages generated by dc motors that are disconnected from their supply while running.

The most aggressive of these surges is the so-called "load dump pulse" that occurs when the engine is running and the battery lead is disconnected while the alternator is charging the battery. That transient, potentially lethal to semiconductor circuits, can last several hundred milliseconds and reach levels of more than 100 V.

Another danger is the "double battery" voltage that can be applied during a jumpstart, in which two 12 V batteries in series are connected to the vehicle power harness. When you crank the engine, especially in cold weather and with a partly charged battery, activating the starter causes a brief dip in supply voltage that can depress it from a nominal 12 V to less than 5 V. This reduction can last for several tens of milliseconds, causing electronic systems to temporarily suspend operation. An additional hazard that vehicle electronics must withstand is battery-polarity reversal, which can occur when a battery is connected incorrectly.

IMPROPER POWER LEVELS

The aberrations mentioned above create a need for protection against improper voltages. Analysis shows that the "load dump pulse" is the most energy-rich type of disturbance. To protect electronic modules against destruction by this pulse, three protection methodologies are in use today:

- Clamp the voltage centrally for all modules at the vehicle alternator (central load-dump suppression).
- Provide a protection circuit on each electronic control unit (ECU).
- Combine the above techniques.

Other, lower-energy pulses are usually filtered at the board level only. Centralized load-dump suppression is usually achieved by clamping circuitry (diodes) internal to the alternator. Despite clamping, however, vehicle voltages can still reach as high as 36 V.

Vehicle electrical systems that do not feature central load-dump suppression must include local protection against disturbances, usually with a protection circuit internal to the ECU, just beyond the connector terminals. Such protection is needed at many locations within the car and, therefore, requires a large number of components with consequent effects on the

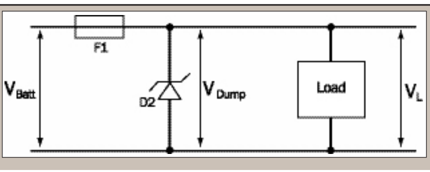

Figure 1. Overvoltage protection circuit.

total leakage current and overall cost. Onboard protection is usually achieved with components such as diodes, zener diodes, varistors, damping resistors, capacitors, and suppression filters, which should be connected to the terminals likely to receive transients.

The third technique for ensuring that ECU circuitry is not subjected to damaging voltages combines the use of central load-dump suppression with local clamping circuitry. Various sample circuits showing classical on-board protection are shown below.

STANDARD DEVICES

Several devices can clamp overvoltages at the board level:

1. Transient-voltage-suppression diodes.

Avalanche diodes (similar to zener diodes) are used as clamping devices to suppress all overvoltages above their breakdown voltage. Their especially high energy-absorption capability protects electronic circuits against overvoltage spikes. They feature very fast switch-on times, but slow switch-off times. In the vicinity of their breakdown voltage, avalanche suppression diodes exhibit significant leakage current. Often they are referred to as Transil (registered brand name, ST Microelectronics), Transzorb (registered brand name, Vishay), or simply TVS diodes.

2. Varistors.

Varistors are voltage-dependent resistors (VDR): symmetric, nonlinear resistive elements whose resistance decreases abruptly above a certain voltage. In clamping both positive and negative voltages, their behavior is similar to two back-to-back zener diodes. They handle high levels of current and energy for their small size, but they exhibit relatively high leakage current as the applied voltage approaches the clamping voltage. The clamping voltage also increases significantly with applied current.

CONSERVATIVE PROTECTION CIRCUITS

A simple and cost-effective way to protect sensitive circuitry is to parallel the load with a clamp such as a transient voltage suppressor (TVS) diode, preceded by a fuse (Figure 1). This circuit protects the electronic control unit against transient overvoltages above the breakdown voltage of the TVS diode (D2). When exposed to negative transients or steady-state reverse voltage, the TVS is biased in the forward direction—thus protecting downstream circuitry by limiting the negative voltage to its forward bias voltage (e.g., -1V). If either negative or positive overvoltages persist, the fuse will blow.

To avoid having to replace a fuse in an inaccessible ECU, or to ensure continuous ECU operation, other techniques must be employed, such as additional series protection. The circuit of Figure 2 protects the electronic control unit against reverse-battery conditions (D1) and impulse overvoltages greater than the breakdown voltage of the TVS diode (D2). Note that you must choose (for D1) a peak reverse voltage greater than the largest possible negative transient.

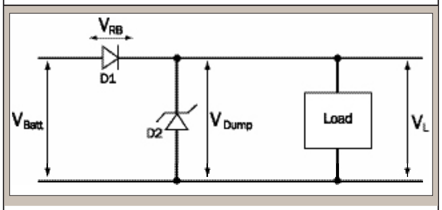

Figure 2. Overvoltage and reverse battery protection circuit.

Because of their small dimensions and high power-dissipation capability, varistors are often chosen for applications in which board space is critical and the downstream circuitry has some tolerance for positive and negative overvoltages. The circuit of Figure 3 protects the downstream circuitry from overvoltage pulses (positive and negative transients) greater than the breakdown voltage of the varistor.

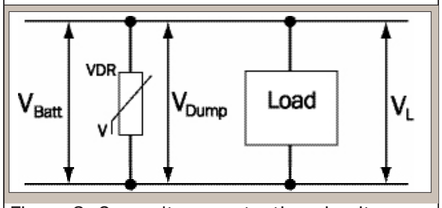

Figure 3. Overvoltage protection circuit.

ADVANTAGES AND DISADVANTAGES

All of the above circuits have advantages and disadvantages. In Figure 1, for instance, you must choose a TVS diode with breakdown voltage greater than the highest steady-state voltage present. This is usually the double battery voltage applied during jumpstart (often >26 V, for greater than 1 minute). Otherwise, the TVS starts conducting at a lower-level voltage, and is destroyed by the resulting power dissipation.

TVS diodes also exhibit a certain internal resistance above the breakdown voltage, which causes the clamping voltage to increase at high currents. For example, a 28 V TVS diode (SMBJ28) can allow exposure of the downstream circuitry to as much as 45 V during a load dump, thus mandating the use of circuitry tolerant to 45 V. Clearly, this

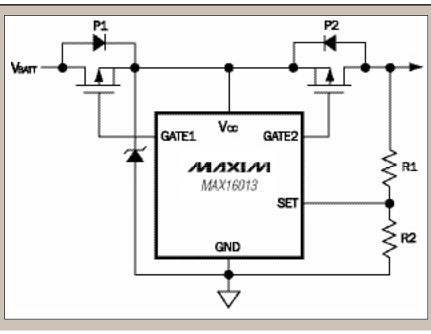

Figure 4. Typical application circuit, MAX16013.

complicates the selection of components for the downstream ECU circuitry, which generally needs to operate only to the upper end of the vehicle's normal operating voltage range (usually about 17 V). Higher-voltage semiconductors and other devices are more expensive, adding cost to the ECU.

To keep the maximum possible overvoltage as low as possible, you should choose a TVS with breakdown voltage as close to the highest occurring steady-state voltage as possible (the jump-start voltage, for instance). This, in turn, impacts the leakage current at voltages close to the breakdown voltage, and even at the vehicle's normal operating voltage (12 V). Such leakage current may make it more difficult for the ECU designer to meet the OEM requirements for low quiescent current when the vehicle engine is not running.

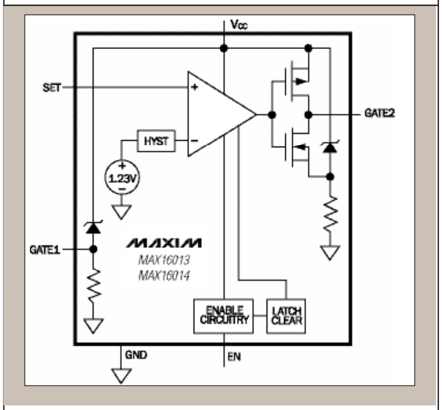

Figure 5.Block diagram, Max16013/16014.

During normal operation, the diode in Figure 2 (D1) exhibits an approximate voltage drop >0.7 V, which is a disadvantage in two ways:

- The voltage drop implies some power dissipation.
- Low-voltage operation of the ECU becomes more difficult.

For high-current applications such as a car's audio system, the current drawn can easily exceed 10 A. A diode voltage drop of 1 V in this system consumes 10 W, which is almost impossible to dissipate over the limited geometry of a circuit board. The use of a single or double Schottky diode can alleviate this problem in some applications. Assuming a voltage drop of 0.5 V, the power dissipation of a double Schottky diode would be 5 W at a 10 A load current. This value is still high, however, and may oblige the designer to use a big heatsink.

As mentioned above, the voltage loss of a diode drop can itself be a problem. In a 14.4 V audio system, for example, you maximize the output power by maximizing the voltage available for driving the speaker. Thus, a loss of 1 V in the power supply due to the reverse-battery diode corresponds to an output-power loss of approximately 8.4 dBW (for a 2 Ω bridge-tied speaker).

When an ECU must operate down to the low voltage levels that occur while cranking a vehicle at cold ambient temperatures, the loss of any voltage can be critical. During a cold crank, input voltages of 5.5 V and lower are common in OEM car manufacturer specifications. The voltage drop of a reverse-battery diode can eat up precious headroom. If, for example, the car battery voltage drops to 5.5 V at the ECU input connector, minus a 0.7 V diode drop for the reverse-battery diode, the remaining voltage for the rest of the circuitry is only 4.8 V.

If a 5 V microcontroller is supplied by a linear regulator with dropout voltage of 300 mV, then the microcontroller receives only 4.5 V, which might not be sufficient to keep the μC operating. It could go into reset, lose its memory, or cause the whole ECU to temporarily suspend operations. One illustration of this problem can be seen with a GPS navigation system: If you enter the coordinates of the destination before starting the car, it is imperative that data not be lost during a subsequent cold-crank.

For applications that include varistors as in Figure 3, the circuit board space is often critical. As with TVS diodes, the varistor breakdown voltage must be selected according to the highest steady-state dc voltage present. However, the V-I character-istic of a varistor above its break-down voltage rises much more slowly than that of a TVS diode. For that reason, a varistor passes on much higher voltages to the subsequent circuitry than does a TVS diode. The downstream circuitry should be designed accordingly, with a possible increase in the component cost.

Minimizing overvoltage by setting the breakdown voltage to relatively low levels worsens the quiescent current drawn in normal operating conditions. Quiescent current at the normal operating voltage is generally higher than that of a comparable TVS diode, but that effect depends on the application.

ACTIVE TRANSIENT-PROTECTION ALTERNATIVE

Given the aforementioned drawbacks of discrete protection circuits, active protection may be a good alternative. For applications that require low quiescent current, low voltage operation, reverse-battery and overvoltage protection, overvoltage protection/detection circuits such as the Max16013-160141 are good choices.

The operating principle is quite simple (see Figures 4,5). These ICs monitor input voltages on the supply rail, and isolate the load from the fault by controlling two external p-FET pass switches. The external MOSFETs are turned on between 5.5 V and the set upper rail, adjustable by a resistor divider on the SET pin to a value (usually) between 20 V and 28 V.

During fault conditions the FET P2 can behave in two different ways. In the first mode, P2 acts as an adjustable transient suppressor that regulates the output voltage to the maximum overvoltage allowed, thereby allowing continuous operation—even during a transient event—while providing overvoltage protection. In the second mode, P2 is simply a switch that turns off for as long as the overvoltage condition persists, thereby preventing high voltages from damaging any downstream devices.

You choose the operating mode by connecting the resistor divider on the SET pin either to the input or to the output. For example, you configure the MAX16013 as an overvoltage switch-off device by connecting the resistive divider to VCC instead of the load. MAX16014, on the other hand, keeps the MOSFET (P2) latched off until the input power is cycled or EN is toggled. Operating the MAX16013 in voltage-limiter mode for long durations elevates power dissipation in the external MOSFETs, due to the voltage drop across them.

The reverse-battery FET (P1, optional) replaces a series diode. It turns on under forward-bias conditions to minimize the forward voltage drop, and turns off at negative voltages. The EN pin provides shut-down control by turning off P2 and disconnecting the input from the output (Figure 5). Thus, quiescent current in the downstream circuitry is reduced to a minimum (<20 µA typical) while the circuit maintains reverse-battery protection (P1).

ADVANTAGE OF ACTIVE HIGH-VOLTAGE TRANSIENT PROTECTORS

Active overvoltage protectors offer several advantages:

A conservative transient suppressor (TVS diode or varistor) should have a breakdown voltage higher than the highest steady-state voltage in the vehicle (usually about 26 V). During a load dump event, the downstream circuitry temporarily sees a much higher voltage (an estimate is 45 V) due to the internal resistance and V-I rising characteristics of the TVS. You must, therefore, select downstream devices capable of tolerating higher voltages. An active transient protector limits output voltage to the level set by the resistor divider (e.g. 26 V), and has no rising characteristic. These features let you use lower-cost (lower-voltage) downstream components.

Some applications need operate only to the upper end of the normal operating-voltage range, and then switch off (an audio system, for instance, might operate only up to 17 V). Using an active protector in this case, and setting the threshold of the voltage limiter/switch to this level can reduce the downstream parts cost even more.

Replacing a standard reverse-battery diode with a FET can reduce the voltage drop in forward bias to millivolt levels. Especially in high-current applications, this substitution can reduce power dissipation, which in turn reduces the cooling effort and saves cost. Moreover, the power (voltage) that would otherwise be lost in a diode is delivered to the load (e.g., a speaker). Enhanced output power (performance) can be achieved in this way. Some applications must operate at low battery voltages (when cold-cranking an automobile, for instance) and still maintain reverse-battery protection. Minimizing the voltage drop with an active protector can be essential in keeping circuitry operating at low input voltages.

Varistors tend to exhibit relatively high quiescent or leakage current, but replacing a varistor with an active protector obviates that problem. Some applications have high quiescent current due to leakage currents in devices connected to the battery rail. In those cases, an active protector can serve as a main switch that disconnects (via the EN input) all subsequent loads in sleep mode.

ABOUT THE AUTHOR

Toni Versluijs is business development manager at NXP Semiconductors.