Designing the front-end DC/DC conversion stage to withstand automotive transients

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Introduction

With rapidly expanding electronic content in the latest generation of cars, there is an ever increasing need for power conversion from the car's battery rail. The 12-V battery rail is subject to a variety of transients. This presents a unique challenge in terms of the power architecture for off-battery systems.

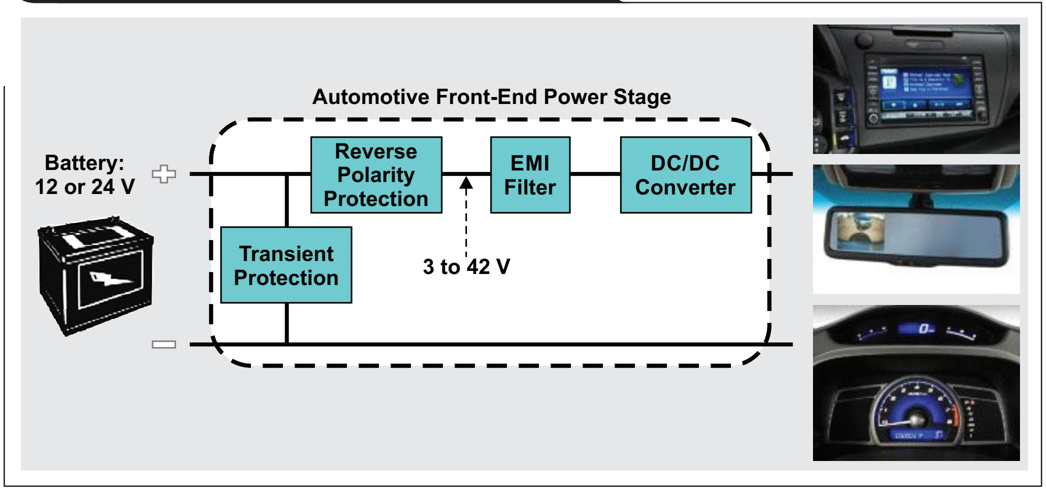
This article introduces the types of transients that occur in automotive battery rails, the causes of those transients, and the standards and specifications defining the test conditions for those transients. Different power architectures are covered for power-conversion and protection circuits to ride out the transients and minimize power interruption to the loads. Included are the advantages and trade-offs associated with buck-boost, boost, and pre-boost approaches for surviving cold-cranks and load dumps. Also presented are different approaches for reverse-polarity protection, which includes a comparison of smart diodes to alternate methods. This information can equip the designer with a deeper understanding of automotive transients and the approaches to tackle these transients when designing the power conversion stage.

Introduction to automotive transients

A variety of factors are responsible for the battery-rail transients in automotive systems . The purpose of the front-end power stage is to insulate the sensitive electrical and electronic loads from these wide variations and to power the loads with a conditioned voltage rail. Because of a large number of different vehicles, and the varied conditions of operation, it may be difficult for the designer to foresee every potential transient that will occur on the battery rail to a module. This means that a variety of testing standards must be used to determine the requirements for power conditioning.

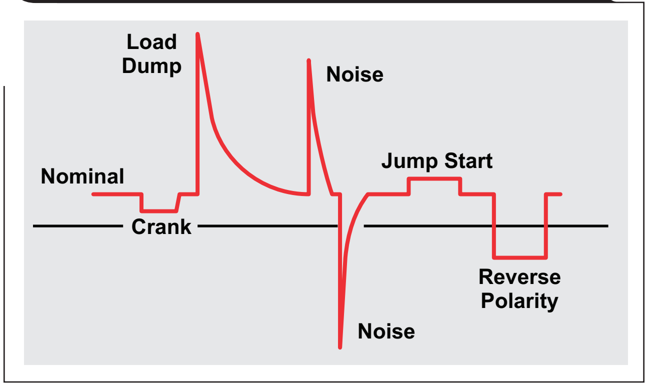
To address this concern, many original equipment manufacturers (OEMs) and organizations describe the immunity tests and the standardized test conditions for off-battery loads. A number of these tests are summarized in ISO 16750-2 and ISO 7637-2 standards.[1, 2] However, many of the extreme transients are taken care of using the transient protection shown in Figure 1. Subsets of these stresses that are often tackled in the power-stage design,

Figure 1. Front-end power conditioning circuit



in addition to their physical origins, are summarized in Figure 2 and Table 1. The ISO standards and a few OEM-specific documents describing these tests are referenced in Table 1.

Figure 2. Stresses on automotive battery rail



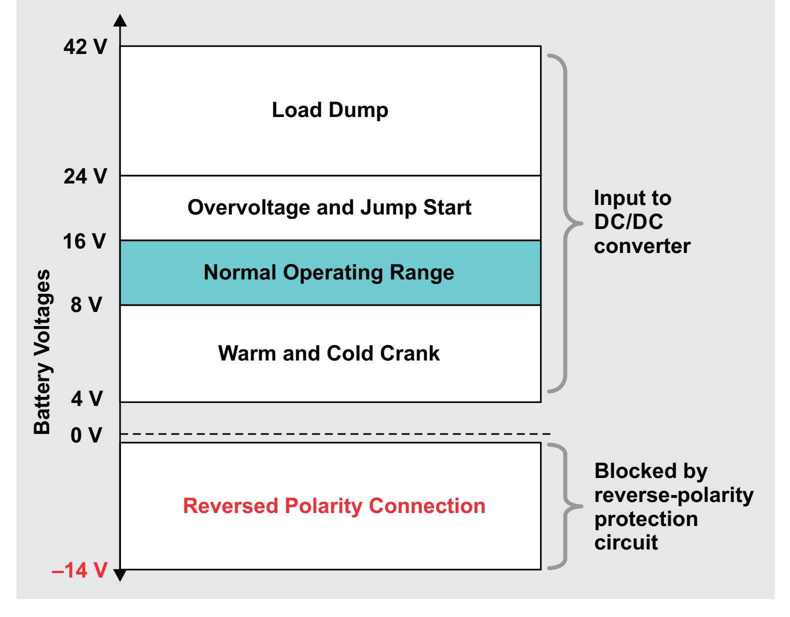
Designing the power conversion stage

The DC/DC conversion stage must be able to withstand voltages of up to ~42 V (for 12 V battery) during load dumps and must be able to supply power to the load during cold-crank, which can be lower than 4 V (Figure 3). The DC/DC converter that needs to regulate the output voltage within this range must be able to step down under high-rail conditions and step up under low-rail condition. Additionally, the designer must design the reverse-polarity protection circuit to prevent or limit the damage in case of an accidental reverse-polarity connection.

Table 1. Electrical stresses and their origins[1-3]

Test	What it Simulates	Reference Document
Load dump	Battery disconnection with alternator running with the other load remaining on the alternator rails.	ISO 16750-2 (sec 4.6.4), FMC1278 CI 222
Starting profile	Simulates the disturbances during and after cranking.	ISO 16750-2 (sec 4.6.3), FMC1278 CI 230-231
Superimposed AC	Residual voltage ripple due to rectified sinusoid from a generator.	ISO 16750-2 (sec 4.4)
	Superimposed pulses simulate sudden high-current loads switching on the battery rail.	FMC1278 CI 210, 220, GMW3172, BMW E-06
Reversed voltage	Reversed battery connection when using an auxiliary starting source.	ISO 16750-2 (sec 4.7)
Jump start	DC voltage overstress due to a generator failure or jump start using a 24-V battery.	ISO 16750-2 (sec 4.3), FMC1278 CI270

Figure 3. Voltage requirements for automotive power-conversion stage



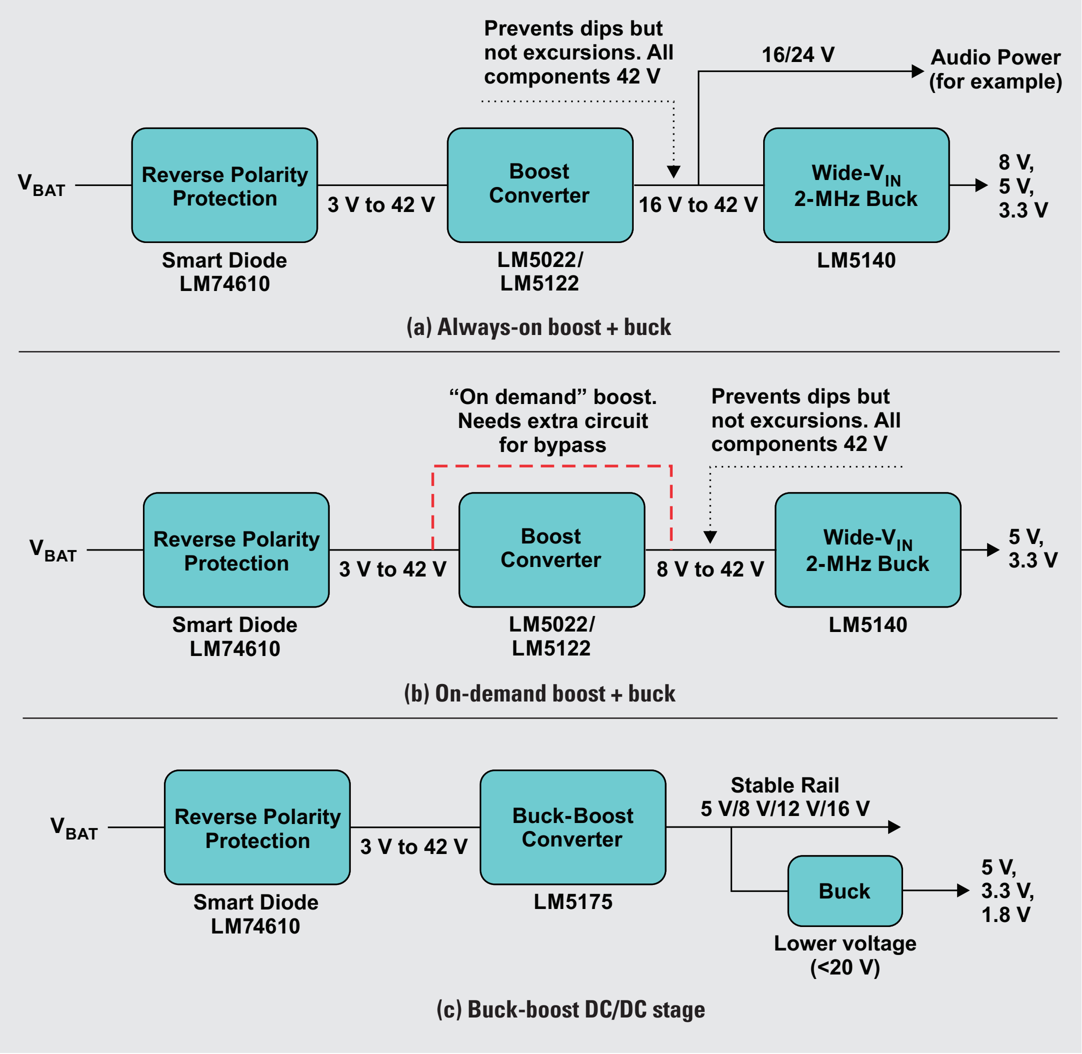
Boost + buck power stage

Figure 4 includes advantages and limitations for a few approaches to implement off-battery DC/DC conversion. One approach is to use a boost converter as the first DC/DC stage to create a higher voltage rail (Figure 4a). This is followed by a second DC/DC stage, which is a wide-V_{IN} buck converter. The boost action facilitates disruption-free operation when the battery-rail voltage drops too low, for example during cranking. The buck stage then steps down the voltage to the appropriate level. An important advantage of this approach is that the boost-input inductor current has relatively small ripple and it provides significant reduction in the ripple current going back to the battery rail. This reduces the attenuation required in the electromagnetic interference (EMI) filter, which means the size and cost of the EMI filter are lower.

A limitation of the boost front stage is that while it levels the dips in the battery rail voltage, it has no capability to limit the spikes, for example, during a load-dump or jump-start conditions. The following buck stage must be rated for the full load-dump voltage, which is usually around 42 V in most practical designs. This results in the size and cost of two stages that are both rated for wide-input voltage and full-load currents.

An additional cost of having two stages is the inherent double conversion in this architecture where both stages incur switching as well as conduction losses. This double conversion happens all the time, even when the battery voltage is within operating range and only step-down conversion would have been otherwise sufficient. To avoid this extra power loss due to the always-on boost stage in Figure 4a, a smarter approach is shown in Figure 4b that uses an on-demand boost stage. The on-demand boost is normally in a bypass-mode as shown by the red dashed line in Figure 4b, and only starts switching when the battery voltage falls below a pre-determined value based on the drop-out characteristic of the following buck stage. Since the boost converter is off most of the time, this

Figure 4. Approaches to off-battery DC/DC conversion



(a) Always-on boost + buck

(b) On-demand boost + buck

(c) Buck-boost DC/DC stage

saves the switching losses in the boost stage. The boost converter must respond quickly enough to prevent the load input voltage from dropping too low. Additional circuitry may be needed to sense the battery drop and switch over from bypass to boost-on mode.

Since the on-demand boost is only expected to switch when battery voltage drops, this architecture is suitable only for relatively lower-voltage rails, such as 5 V, 3.3 V, in other words, well below the normal range of battery voltage.

Buck-boost power stage

Buck-boost converters facilitate single-stage conversion to handle the wide-range battery voltage (Figure 3) on the input and provide a regulated rail at the output. A number of different topologies are used for buck-boost conversion.[4] The example in Figure 4c shows the LM5175 four-switch buck-boost converter because of its higher efficiency and power-handling capabilities.

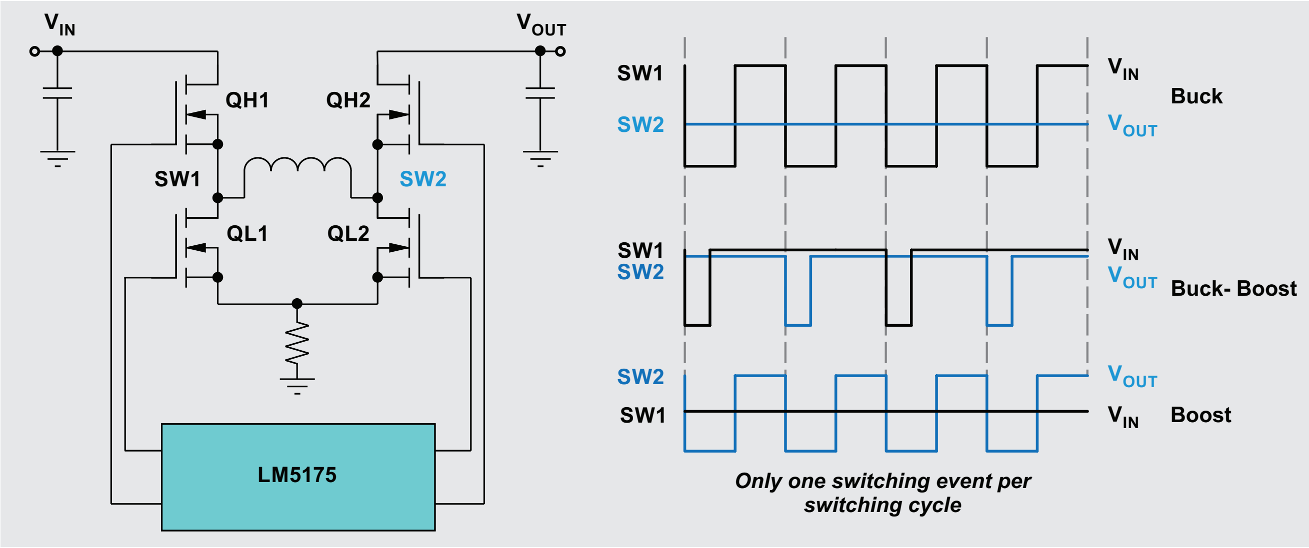
A wide-V_{IN} four-switch DC/DC converter can both step up and step down the input voltage and is able to regulate the output, even when the input voltage is equal to the output voltage. The simplified diagram and switching waveforms are shown in Figure 5. When the input voltage is higher than the target output, it operates in buck-mode with the output stage in the pass-through mode. When the input voltage is lower than the target output, it operates in boost mode with the input stage is in the pass-through mode. When V_{IN} is close to V_{OUT}, it interleaves buck and boost cycles to maintain smooth operation. Since only one leg (buck or boost) is switching in a cycle, it avoids the higher losses associated with a two-stage conversion.

Unlike a boost pre-regulator, which only lifts the output voltage for low V_{IN} but cannot clamp the output voltage below V_{IN}, the buck-boost provides immunity against both dips and excursions in input voltage. For automotive applications with the output voltage above the nominal battery range (≥16 V), the buck-boost converter offers low ripple at the input and provides overload and short-circuit protection, as well as inrush current limiting. A buck-boost power stage also eliminates the need for bulky low-frequency passive filters otherwise required to suppress the superimposed alternative voltage that happens on the 12-V battery rail due to rectification of alternator AC output.

For regulated outputs below the nominal battery voltage (5 V, 3.3 V), the buck-boost topology provides a single-stage solution with higher efficiency than the pre-boost + buck architecture. However, the size advantage of a single-inductor buck-boost is somewhat tempered by the fact that it typically requires a larger EMI filter.

For automotive systems, the buck-boost converter of Figure 5 is an ideal pre-regulator. This converter combines the benefits of a boost-converter front stage, such as low-input ripple (for 16- to 24-V output range, Figure 4c) and cranking protection. This converter also includes load-dump protection (V_{IN} excursions) and overcurrent/short-circuit protection typically associated with a buck converter. Additionally, it offers true input-output disconnection when in shutdown mode.

Figure 5. Wide-V_{IN} four-switch buck-boost converter



Reverse-polarity protection

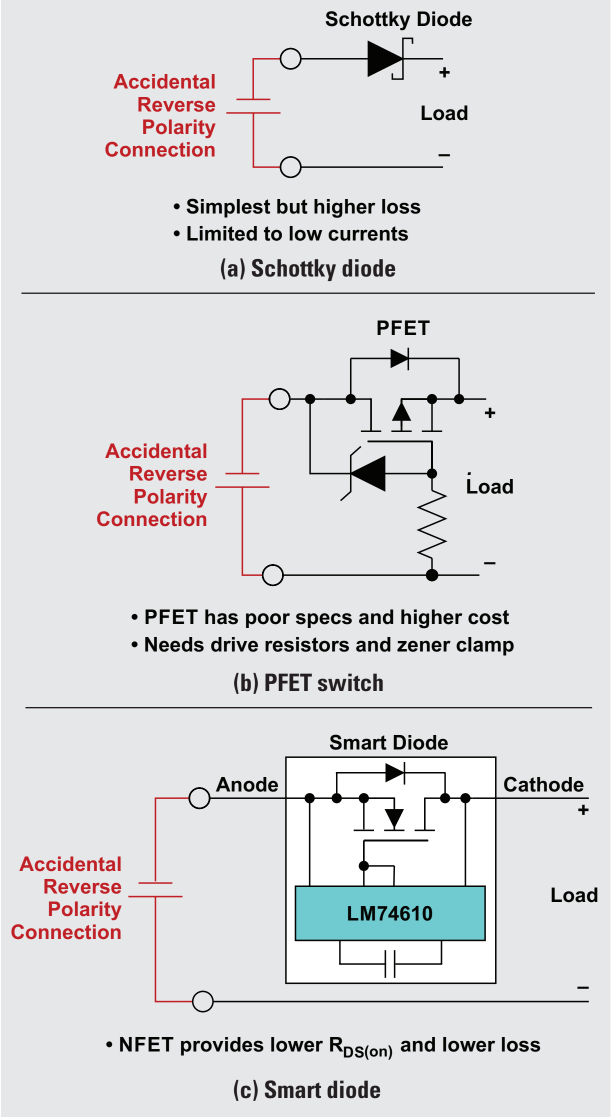
A reverse-polarity protection circuit is needed in the front end to protect the components connected to battery rail from negative voltage, which can result from improper connection of an external power supply to start the vehicle. Many approaches are taken in automotive systems to prevent reverse-current damage, ranging from fuses, Schottky diodes, p-channel field-effect transistors (PFETs), and n-channel FETS (NFETs) as shown in Figure 6.

For lower current applications, a simple Schottky diode can be used for reverse-polarity protection. PFETs can handle higher current, but the driver circuit usually requires a pull-down resistor and a zener clamp that dissipates power. Furthermore, PFETs have inferior $R_{DS(on)}$ characteristics compared to NFETs and usually are more expensive. Smart-diode controllers combine the best performance of an n-channel MOSFET with the simplicity of a diode connection.

Conclusions

The front-end power-conversion stage for automotive off-battery applications must deal with a wide voltage variations on the input-voltage or battery rail. The tests to simulate these variations are covered in automotive standards and OEM-specific documents. Examples of the stress tests that are required in the power-stage design are reverse-polarity connection, cold and warm cranks during engine start/re-start, load dump, and superimposed AC within the nominal battery voltage range. The positive voltage transients and operating-voltage variations on the battery rail necessitate the use of DC/DC converters with a wide-input voltage rating to regulate or pre-regulate the bus. Depending on the load and sub-systems being powered, designers can design the power stage using a pre-boost, pre-boost and a buck, or a single-stage buck-boost converter. A four-switch, buck-boost converter provides the best combination of versatility, small size, and high efficiency. There are many approaches to reverse-polarity protection but smart diodes provide the best performance and a simple design.

Figure 6. Reverse-polarity protection methods



(a) Schottky diode

(b) PFET switch

(c) Smart diode

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