Why use PSR-flyback isolated converters in dual-battery mHEV systems

By Timothy Hegarty
Applications Engineer

Introduction

With the growing power demands of automotive systems, the increasingly strict government mandates for greenhouse gas emissions, and the conversion from mechanical components to electrical functions for reduced size and weight, the traditional 12-V automotive lead-acid battery has reached its usable power limit.[1, 2] To address this power limitation, automakers are developing a dual-voltage electrical platform that combines a smaller 12-V battery (for compatibility with existing systems) with a 48-V lithium-ion battery pack that runs high power loads that includes:

- Powertrain—electric supercharging and regenerative braking.
- Chassis/safety—active roll stabilization and automated driving systems such as radar, camera, LIDAR and ultrasonic sensor systems.

This dual-bus architecture, as presented in Figure 1, provides a pathway to improve the performance of conventional internal combustion engine (ICE) gasoline or diesel vehicles with less of the cost-weight penalty incurred by installing a full hybrid drivetrain.[3, 4] This mild-hybrid electric vehicle (mHEV) architecture involves a relatively unobtrusive electrification of the powertrain. Also, with steady-state voltages less than 60 V, the system is not designated as "high voltage."

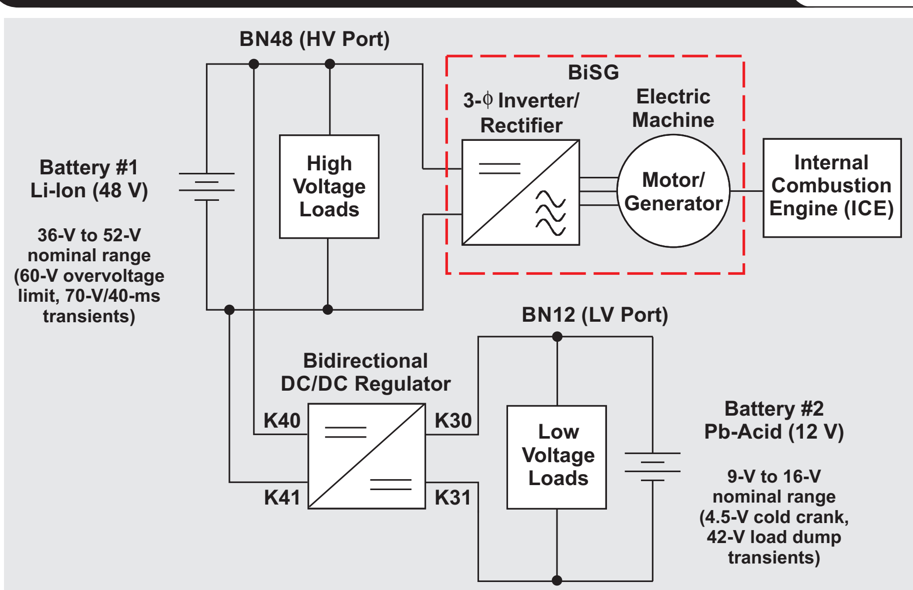
As a result, an mHEV system requires:

- Much less effort in terms of insulation protection.
- Electrical components that are smaller and have a lower incremental cost.
- A more compact design, given the lower clearance spacing between individual components compared to a solution with high-voltage hybridization.

As depicted in Figure 1, a belt-integrated starter-generator (BiSG) delivers recuperated energy to the 48-V board net (BN48) and battery. This configuration also enables some level of torque assist through belt coupling to the engine's front-end accessory drive. This is known as a P0 configuration.[5, 6] Other topologies are designated as P1, P2, P3 or P4, where the electric machine may couple to the crankshaft, transmission or rear axle drive.

A current-controlled buck/boost regulator (plus safety switches)[2, 7] provides bidirectional power transfer capability between the BN12 (12-V) and BN48 (48-V) ports in Figure 1, which enables both batteries to simultaneously supply power if needed. The basic half-bridge switching cell of the regulator is scalable to meet higher current demands by supporting multiple phases connected in parallel. Note that there is a common ground for low- and high-voltage systems, and the ground terminals are attached via physically separate grounding bolts/connections.[3, 4]

Figure 1. Simplified example of a mHEV dual-battery system



This article focuses on the isolated supply that powers the signal path and control circuits on the 48-V side. The primary-side regulated (PSR) flyback converter family as described offers simplicity, versatility, small solution size, low noise, high reliability and low bill-of-materials cost.

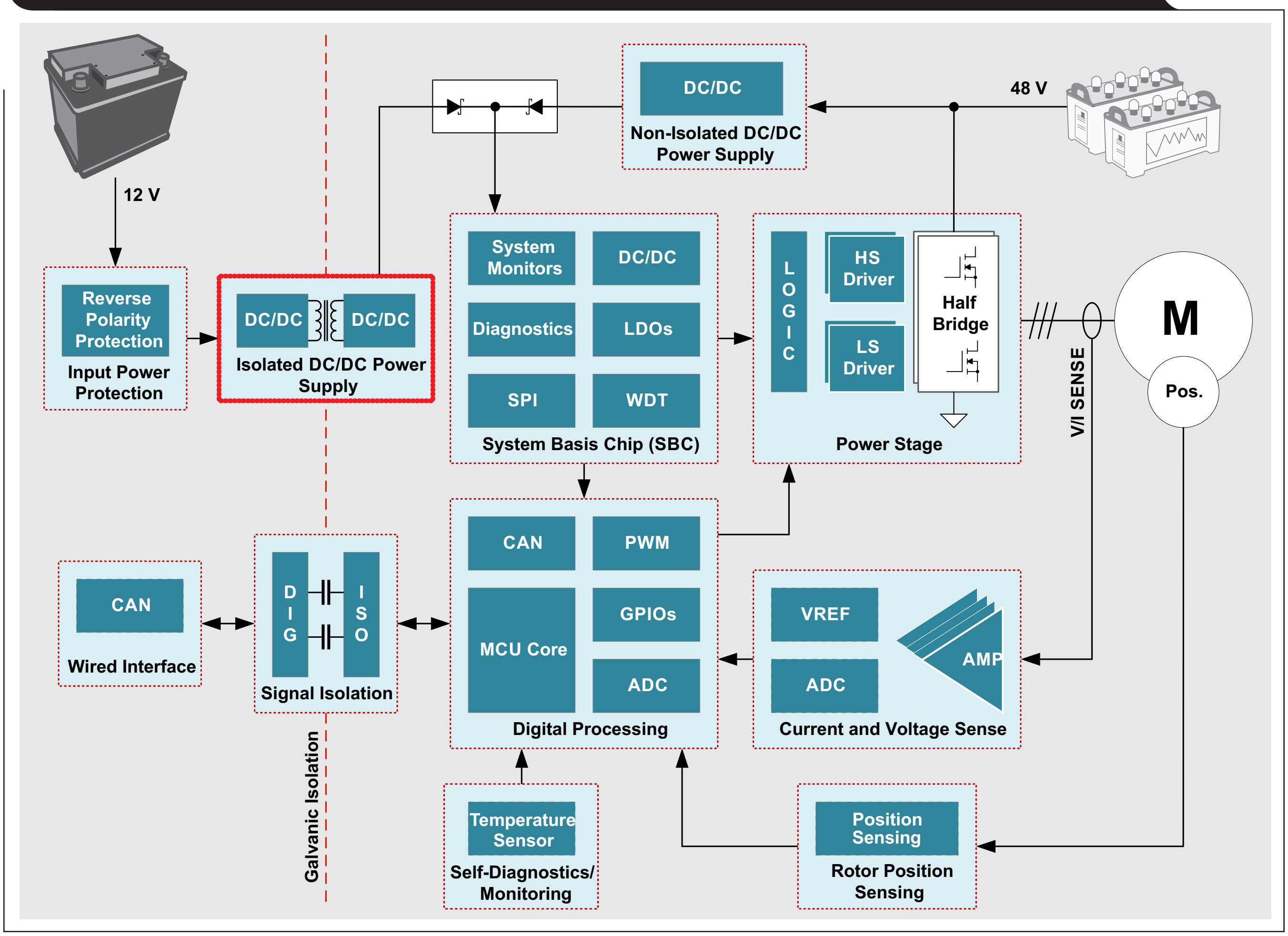
Functional isolation in mHEV systems

Unlike high-voltage HEV systems that require a reinforced grade of isolation for electric shock protection and safety, the power stages in an mHEV are non-isolated, hence lowering overall system and maintenance costs. However, functional-grade isolation of the control circuits in an mHEV system improves robustness by increasing noise immunity, especially given the high slew-rate switched voltages and currents in the inverter/rectifier and DC/DC power stages. Isolation also reduces ground loops between various subsystems and mitigates electrostatic discharge and electric fast transients. Specific areas of concern related to arcing and fusing are also significant. To add some perspective, Figure 2 details the essential subsystems of a starter-generator system.[6, 7]

Figure 2 has a red dashed line that indicates the isolation boundary separating the 12-V and 48-V sides. An isolated power source derived from the 12-V battery, typically implemented as a flyback converter, provides redundant and fault-tolerant backup for an auxiliary-bias supply rail on the 48-V side, with a typical output voltage setpoint of 12 V. This auxiliary supply rail, normally derived from the 48-V battery using a buck converter, supplies the system-basis chip that subsequently powers the embedded processing subsystem, as well as various monitoring and sensing circuits. Depending on the state of charge of each battery (for example, after long-term parking), startup considerations, fault management and other factors, the powertrain control unit may enable or disable the flyback converter as needed.

Having isolation is also useful for the vehicle communication network, especially to deal with ground voltage offsets or loss-of-ground faults on either the 12-V or 48-V side.[3] Finally, as power levels of the motor-generator in mHEV systems increase toward 30 kW, the high-side switch gate drivers of the inverter/rectifier stage integrated in the motor-generator also benefit from isolation. An example of an isolated dual-channel gate driver for 48-V applications is the UCC20225A-Q1. The multi-output capability of a flyback converter is useful here, especially if floating or bipolar gate-drive voltages are required.

Figure 2. Block diagram of a starter-generator system (Isolated DC/DC stage highlighted in red)

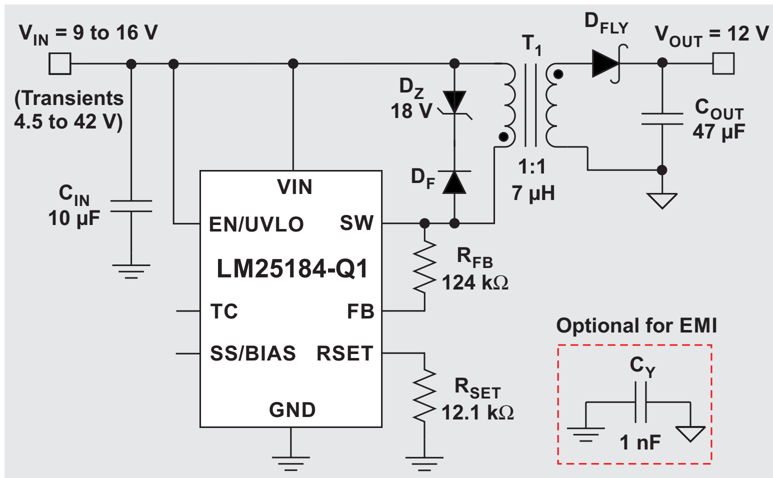


PSR flyback implementation

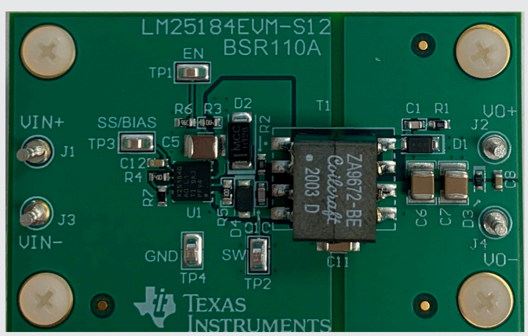
Suitable for low-power isolated rails in mHEVs, Figure 3a shows a schematic using the LM25184-Q1, a flyback converter with an integrated power switch and loop compensation that uses PSR for output voltage control. Depending on the load current, the PSR flyback converter operates in boundary conduction mode (BCM) or discontinuous conduction mode. A Zener diode circuit across the primary winding supports a clamped reset of the transformer leakage inductance. Figure 3b shows an implementation[8, 9] that uses a flyback transformer with a 1-to-1 turns ratio, a magnetizing inductance of 7 µH and an 11- by 13-mm footprint.

The PSR architecture is an observer-based approach to estimate the output voltage of a flyback converter using a primary-referenced winding. Appropriately timed sensing of the switch voltage at its knee position provides a suitable proxy of the output voltage that enables the output to have very tight regulation accuracy across line, load and temperature ranges. Not using an optocoupler for feedback eliminates the need for a component to cross the isolation barrier and provides a more cost-effective solution. Moreover, an auxiliary winding for output sensing is not required, thus enabling a simpler magnetic structure with lower leakage inductance[10] and opening up more choices in terms of off-the-shelf components that include Q-grade compliance.

Figure 3. Auxless PSR flyback converter with a 12-V output



(a) Schematic

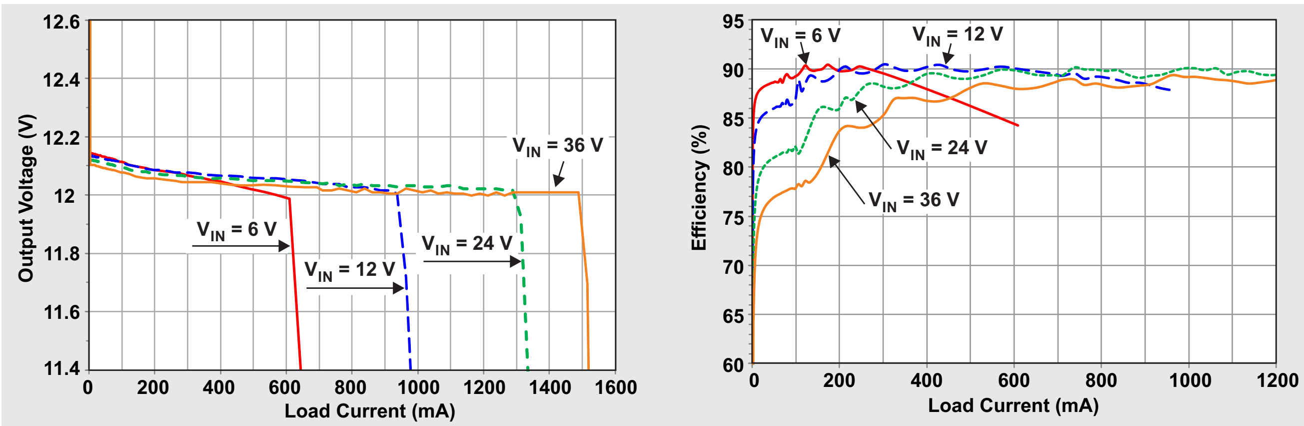


(b) Hardware implementation

With nominal design effort, the regulation performance can rival that of conventional opto-isolated solutions without the added solution size, cost and reliability concerns. As a result, this PSR technique supports improved converter performance, higher temperature operation, greater manufacturability and robust protection against fault conditions—important attributes for mHEV applications. Figure 4 presents the load regulation and efficiency curves for several input voltages and a 12-V nominal output.

In terms of electromagnetic interference (EMI), the primary-side switch always turns on at zero current, thus avoiding undesirable reverse recovery of the flyback rectifier diode. Moreover, the switch turn-off in BCM is a quasi-resonant soft transition. This supports lower total switching losses and reduced conducted and radiated noise signatures. Figure 5 shows Comité International Spécial des Perturbations Radioélectriques (CISPR) 25 Class 5 conducted EMI results of the flyback converter, with the optional Y-capacitor installed between primary and secondary grounds (as shown in Figure 3a) to reduce the common-node noise signature.

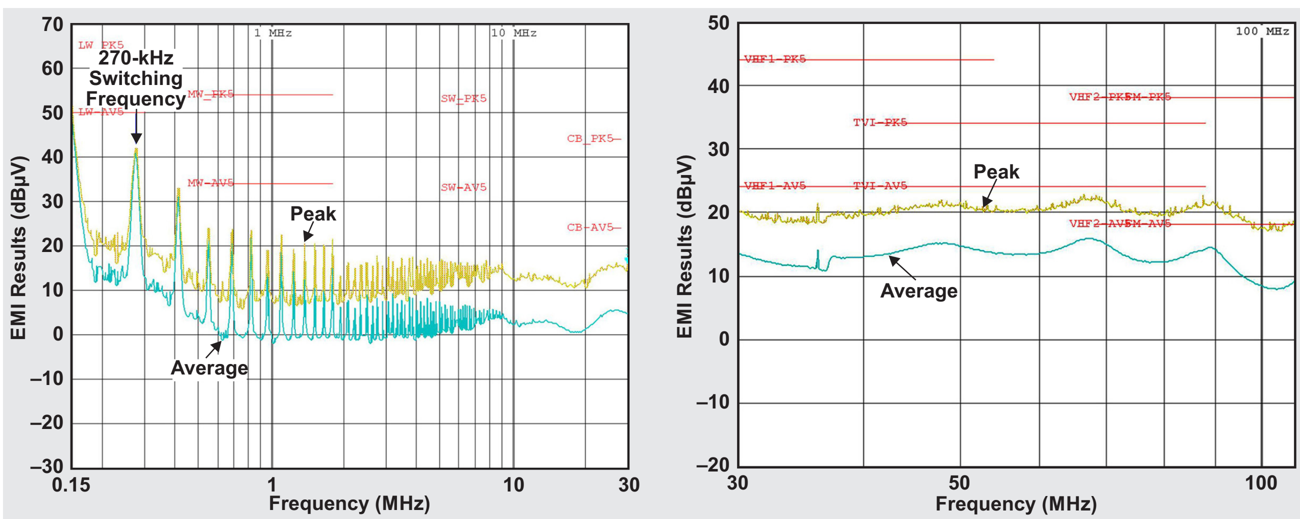
Figure 4. PSR flyback converter performance with a 12-V output



(a) Load regulation

(b) Efficiency

Figure 5. CISPR 25 Class 5 EMI measurements of the PSR flyback converter (V_{IN} = 13.5 V, I_{OUT} = 700 mA)



(a) 150 kHz to 30 MHz

(b) 30 MHz to 108 MHz

Table 1. TI's PSR flyback converter family targets several current levels

PSR Flyback Converter	Input Voltage Range	Peak Switch Current (typ)	Maximum Load Current*	
			V_{IN} = 4.5 V	V_{IN} = 13.5 V
LM5181-Q1	4.5 V to 65 V	0.75 A	90 mA	180 mA
LM5180-Q1	4.5 V to 65 V	1.5 A	180 mA	360 mA
LM25180-Q1	4.5 V to 42 V	1.5 A	180 mA	360 mA
LM25183-Q1	4.5 V to 42 V	2.5 A	300 mA	600 mA
LM25184-Q1	4.5 V to 42 V	4.1 A	500 mA	1 A

*V_{OUT} = 12 V, N_{PS} = 1

Table 1 identifies the specifics for a footprint-compatible family of automotive-qualified PSR-flyback converters intended for a range of mHEV isolated power applications. Assuming a 12-V output and a transformer with 1-to-1 turns ratio, the table specifies the maximum load currents at input voltages of 4.5 V and 13.5 V, corresponding to the low-voltage battery transient cold-crank and steady-state operating conditions, respectively.

Equation 1 gives the maximum load current of a flyback converter in BCM:

$$I_{OUT(max)} = \frac{\eta}{2} \times \frac{I_{SW(pk)}}{\frac{V_{OUT}}{V_{IN}} + \frac{1}{N_{PS}}} \qquad (1)$$

where N_{PS} is the transformer turns ratio, η is the efficiency and $I_{SW(pk)}$ is the switch peak current rating.

The PSR flyback solution is easily scalable by adjusting the transformer[10] and the secondary-side components; the primary-side design remains largely unchanged. Connecting an input clamp circuit[11] allows input voltage swings above 65 V to manage, for example, the transient overvoltage defined in the 48-V automotive specifications[3, 4] of 70 V for 40 ms.

Summary

The affordable cost of mild hybrid designs and their ability to retrofit existing ICE drivetrains is accelerating the demand for power electronics in electric mobility applications. A low- to high-voltage-side isolating power supply in mHEV powertrain applications increases performance, robustness, redundancy and fault tolerance. A testament to its excellent regulation, multi-output capability, EMI compliance, small form factor and low component count, the auxless PSR flyback converter finds increasing relevance in mHEV electric powertrain architectures. Magnetic sensing of the output voltage eliminates the optocoupler, which eliminates a component that crosses the isolation barrier and resulting in a cost-effective solution with higher reliability.

References

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Related websites

LM5180-Q1
LM5181-Q1
LM25180-Q1
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