

How an auxless PSR-flyback converter can increase PLC reliability and density

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Introduction

The primary challenge when sensing process variables in harsh industrial environments is the capacity to condition low-amplitude sensor signals in the presence of high noise and large surge voltages. To this end, programmable logic controllers (PLCs), which include a flexible number of analog input/output (I/O) modules with isolated power and signal paths, have been widely adopted for use in factory automation and industrial robotic applications.^[1-5] Functional safety, long service life and high reliability are paramount in these applications. This article examines the isolated power stage for PLCs. With its wide input-voltage range and multioutput capability, a flyback converter is an ideal fit for PLCs that need a high level of integration, especially if the PLC channel count and functional density increase while the enclosure gets smaller.

A conventional flyback converter uses a transformer and an optocoupler to achieve galvanic isolation in the power stage and feedback path, respectively. Although an optocoupler offers a convenient way to capture output-voltage error information, its transfer function is highly nonlinear

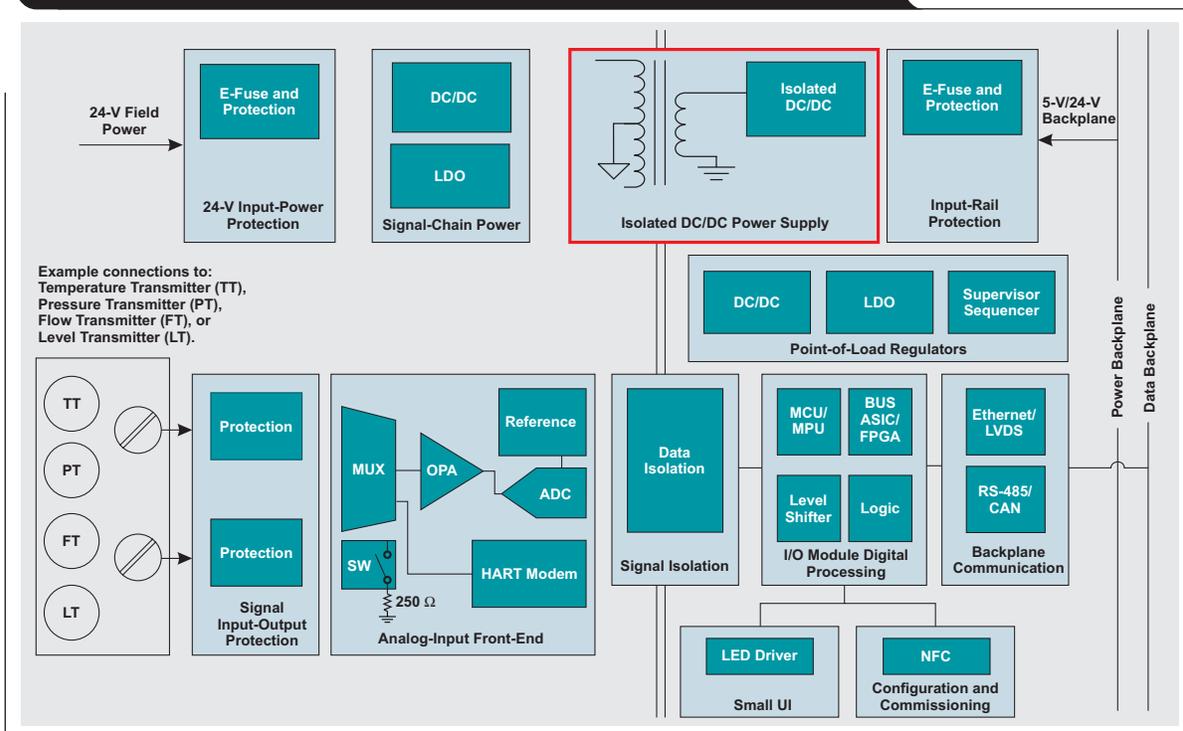
and dependent on both time and temperature. This drawback imposes an upper constraint on the converter's operating temperature and increases total solution size. Therefore, a "no-opto" design can bring significant improvements in system performance and size.

A flyback solution that uses an auxiliary-less ("auxless") primary-side regulation (PSR) feature can simplify magnetic design and improve performance of the output-voltage static regulation.^[6] Moreover, magnetic sensing of the output voltage eliminates the optoisolator component, resulting in a cost-effective solution with a lower component count and higher reliability.

A PLC analog-input module

To add some perspective, Figure 1 is a block diagram^[4] of a PLC analog-input module used to measure temperature, pressure, flow, level and many other process variables. Used in modular rack-based PLC systems, an I/O module establishes the physical connection between the PLC and the factory or field equipment. The rack can accept various types of I/O modules that effectively slide into slots in the rack to connect to the power and data backplanes.

Figure 1. Universal analog-input module for a PLC; the isolated DC/DC conversion stage that powers the field side is highlighted in red



The analog front end shown in Figure 1 is galvanically isolated from the embedded-processing subsystem to break ground loops between the module and its sensor inputs or remotely connected systems. Signal isolation also improves measurement accuracy, as it removes noise and helps with electrostatic discharge, electrical fast-transient and surge protection of the inputs.^[5]

The field side of the module usually has one or more front-end components (analog-to-digital converters, references, amplifiers and power switches) that require power from the field-side supply. Depending on whether the module has a field power connection, an isolated power source derived from the back-plane source is typically required.

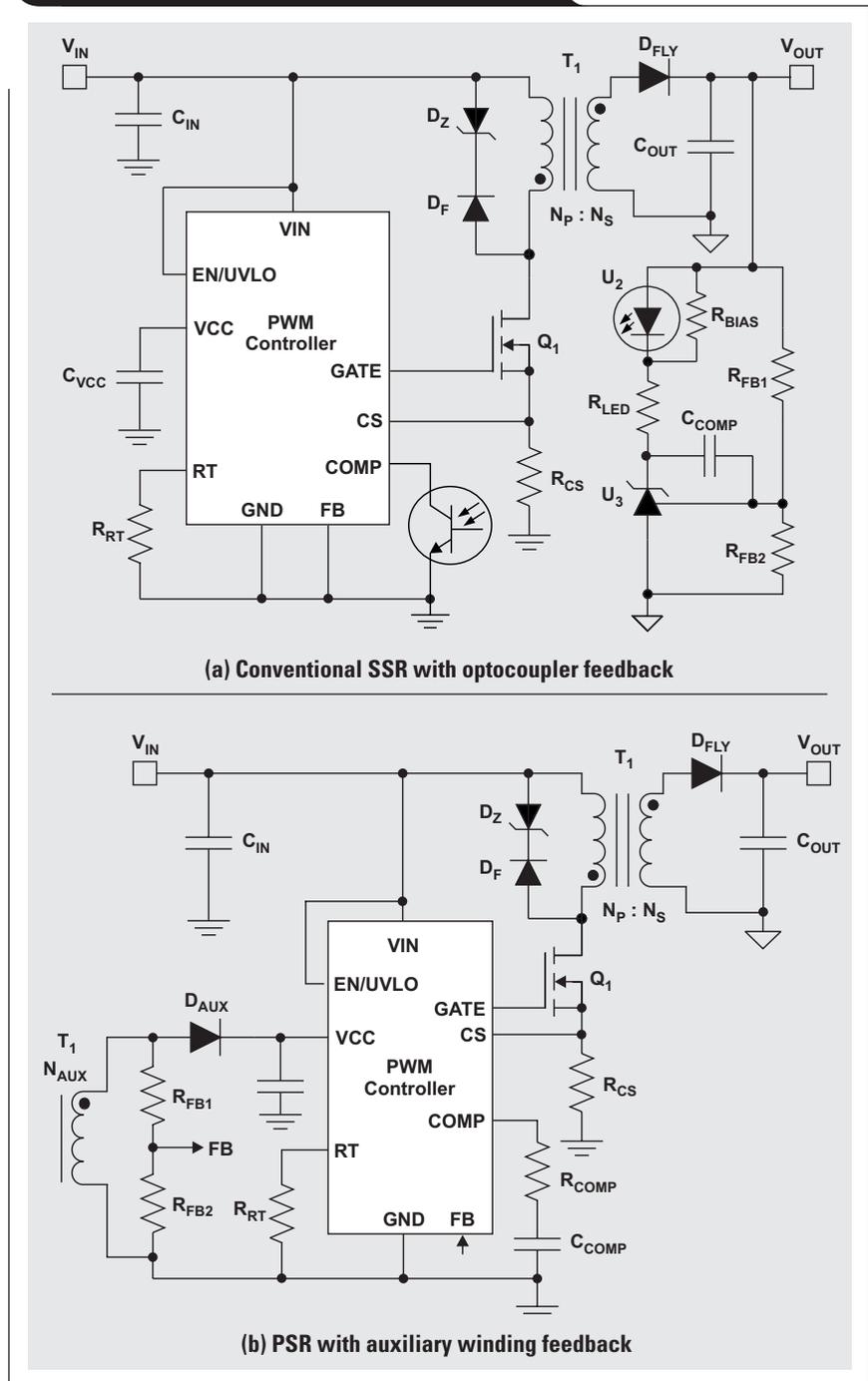
Conventional PSR and SSR flyback regulators

The conventional secondary-side regulated (SSR) flyback regulator shown in Figure 2a uses an optocoupler to achieve galvanic isolation in the feedback path. However, most optocouplers suffer from variations in the current transfer ratio (CTR) and lifetime degradation at high temperatures. This CTR variation represents a serious limitation for flyback designs in industrial applications with operating temperatures up to 125°C. Also, the optocoupler introduces an additional pole in the feedback loop, which restricts the achievable transient performance. Another disadvantage is that secondary-side biasing and compensation become challenging for outputs less than 3.3 V.

Meanwhile, PSR is an observer-based approach that is designed to estimate the output voltage of a flyback regulator via a primary-referenced winding. Various observer laws exist for flyback regulators operating in discontinuous conduction mode (DCM) and/or continuous conduction mode.^[7, 8] PSR is often employed in applications below 20 W that are designed to operate in DCM quasi-resonant mode.

The traditional PSR flyback regulator shown in Figure 2b senses an aux winding voltage to indirectly obtain output-voltage information. The advantages of PSR are evident in terms of the reduction in component count because it eliminates the secondary-side reference and error

Figure 2. SSR and PSR flyback regulators



amplifier (often implemented as a TL431 shunt-regulator device), associated resistors and capacitors for the feedback divider and compensation, and the optocoupler for secondary-to-primary feedback. Only one component, the transformer, crosses the isolation barrier. PSR also removes the associated biasing losses of an optocoupler and the TL431.

Neglecting cross-regulation effects of the secondary-to-aux winding, Equation 1 gives the aux winding voltage during the flyback diode conduction interval:

$$V_S(i_{SEC}) = \frac{R_{FB2}}{R_{FB1} + R_{FB2}} \times \frac{N_{AUX}}{N_S} \times \left[V_{OUT} + V_D(i_{SEC}) + R_{SEC} \times i_{SEC} - L_{LK(sec)} \frac{di_{SEC}}{dt} \right] \quad (1)$$

where N_S and N_{AUX} are the transformer secondary and aux winding turns, respectively; V_D is the flyback diode voltage drop for a given secondary current, i_{SEC} ; R_{SEC} is the secondary winding DC resistance (DCR); and $L_{LK(sec)}$ is the secondary-to-aux leakage inductance.

As Equation 1 reveals, it is challenging to accurately extract the output voltage from the aux winding voltage, particularly with “fixed sampling point” schemes.^[7] In order to tightly regulate the output voltage, the aux-winding voltage must be sampled when the secondary current reaches zero, thus eliminating the current dependencies in Equation 1.

An aux winding is very useful in AC/DC offline applications because it provides an efficient bias function and acts as a common-mode noise shield between the primary and secondary winding layers. On the other hand, it represents a drawback for low-voltage (less than 100 V) DC/DC converters where an integrated bias regulator can supply the relatively-low bias current requirement. Electromagnetic compatibility is not as challenging given the lower-amplitude switching voltages. Clearly, an auxless transformer design enables a simpler magnetic structure with lower leakage inductance and opens up more choices in terms of low-cost, small-sized, off-the-shelf components.

An auxless PSR-flyback regulator

By enabling adaptive cycle-by-cycle examination of the primary-side switch-node voltage waveform, auxless PSR-flyback regulators achieve precise regulation and control of critical power supply parameters. Appropriately timed sensing of the switch-node voltage provides a suitable proxy of the output voltage that enables very tight regulation accuracy of the output voltage across line, load and temperature ranges. As a result, this primary-side control technique results in improved converter performance, greater manufacturability and robust protection against fault conditions.

Figure 3 shows the schematic of the auxless PSR-flyback regulator. There is no need for an optoisolator, TL431 regulator, or transformer auxiliary winding for output voltage sensing. The switch-node voltage is sensed instead, as it contains a scaled version of the output voltage during the power-switch off-state when the flyback diode is conducting. Signal-discrimination techniques are used to sample the switch-node voltage at the end of the diode conduction (or demagnetization) interval when the secondary winding current reaches zero. This negates the error voltages related to secondary winding DCR, leakage inductance and diode dynamic resistance.

Equation 2 gives the switch-node voltage at the end of the diode conduction interval when the secondary current decreases to zero. N_{PS} is the transformer primary-to-secondary turns ratio and V_D is the diode forward voltage drop at near zero current. It is possible to accurately retrieve the output voltage, as the diode voltage only causes a steady-state error that can be easily eliminated by proper tuning.

$$V_{SW}|_{i_{SEC} \rightarrow 0} = V_{IN} + N_{PS}(V_{OUT} + V_D) \quad (2)$$

Figure 3. Schematic for auxless PSR-flyback regulator

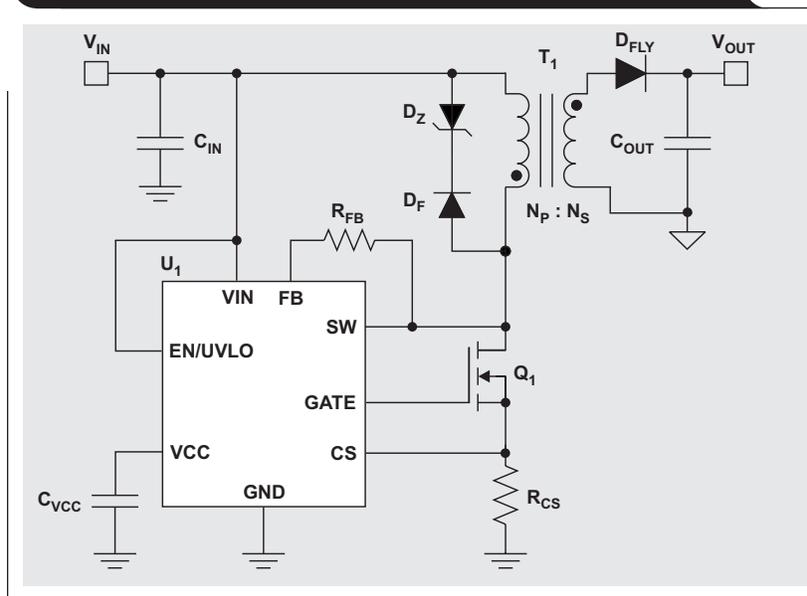


Figure 4 shows the relevant waveforms during operation. The sensing method relies on a sample-and-hold of the level-shifted flyback voltage detected at the knee position of the switch-node voltage corresponding to the zero-cross (ZX) of the secondary current. When i_{SEC} decreases to zero at the end of the demagnetization interval, denoted as the “knee position” in Figure 4, V_{SW} starts to resonate and decreases as a damped cosine function given by Equation 3. The resonant period depends on the magnetizing inductance and the effective switch-node capacitance (that is, the sum of the switch parasitic output capacitance, transformer intrawinding capacitance and diode-junction reflected capacitance).

$$V_{SW}(t) = V_{IN} + N_{PS}(V_{OUT} + V_D) \times e^{-\alpha t} \times \cos(2\pi f_r \times t) \quad (3)$$

Various techniques to calculate this knee position include voltage inspection using an envelope detector or integration of the winding voltage to estimate the ZX of the transformer magnetic flux (and thus the magnetizing current). Ultimately, the sampled value of the level-shifted switch-node voltage is converted to a continuous analog level that is then used as the input to a voltage-loop error amplifier. An outer voltage loop provides the command for an inner current loop that is variable-frequency, peak-current-mode (VFPCM) controlled.

Practical implementation

Suitable for PLCs, Figure 5a shows a schematic using the LM5180, an auxless PSR-flyback converter^[6] with an integrated power switch and loop compensation. The Zener clamp circuit across the primary winding is optional (depending on leakage inductance), as is the Y-capacitor between primary and secondary grounds to reduce common-node noise. The photo of Figure 5b shows an implementation^[9] using an off-the-shelf coupled inductor with unity turns ratio. This coupled inductor has magnetizing and leakage inductances of 22 μ H and 150 nH, respectively; a 6- by 6-mm footprint; and a 3.5-mm height.

The converter operates in boundary conduction mode (BCM) at heavy loads. The primary switch turns on when the magnetizing current reaches zero and subsequently turns off when an amplified version of the peak primary current reaches the level dictated by the current-loop error amplifier. As the load decreases, the frequency increases in order to maintain BCM operation.

Eventually, the loop clamps to the maximum switching frequency, 350 kHz in this design, by

Figure 4. Waveforms for auxless PSR-flyback regulator in DCM at $V_{IN} = 24$ V

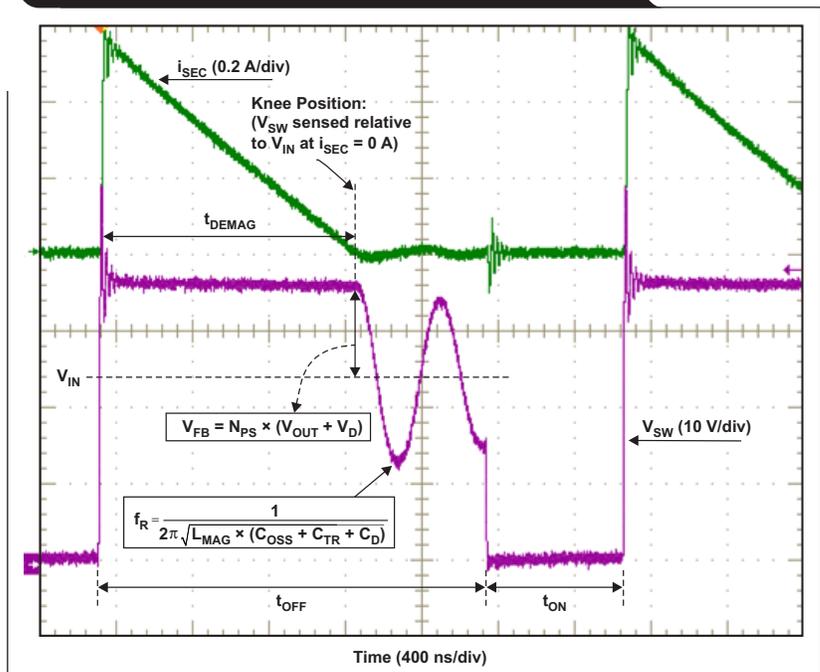
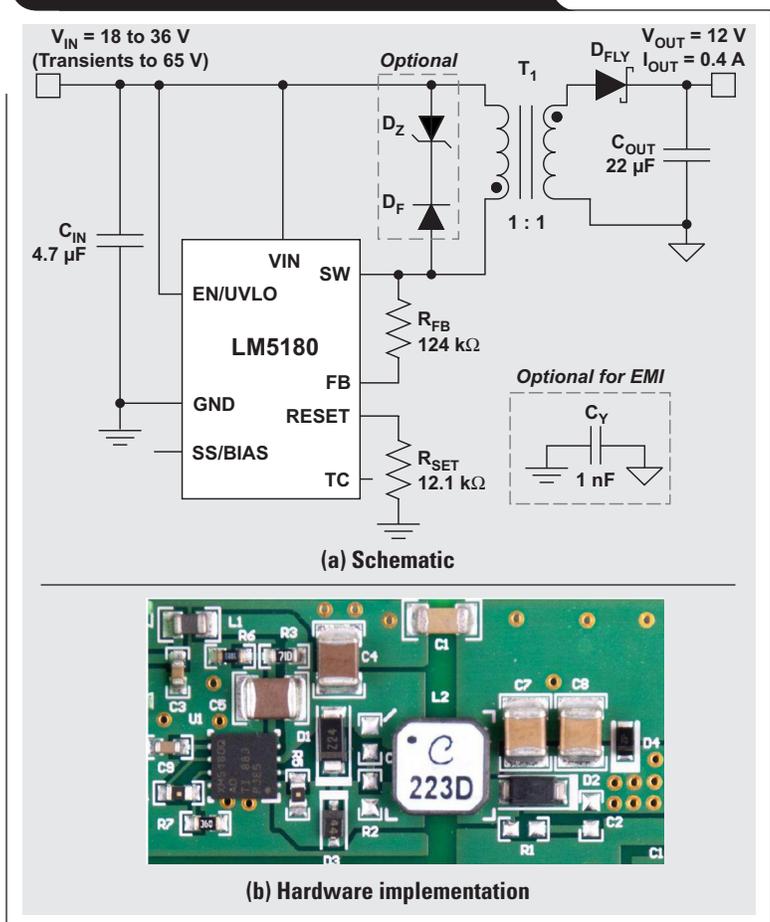


Figure 5. Auxless PSR-flyback converter

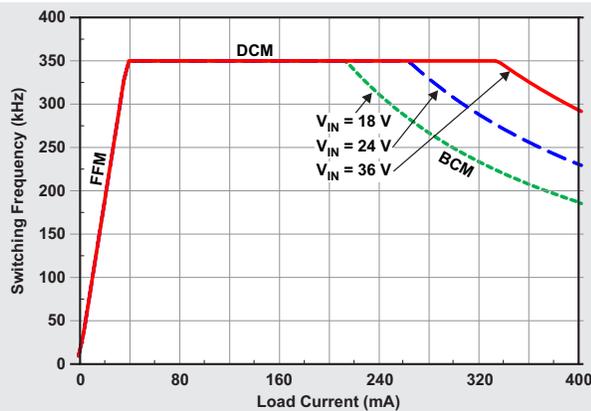


allowing a wait state after transformer demagnetization has occurred, and the converter enters DCM. The power delivered to the output in DCM is proportional to the peak primary current squared. Thus, as the load decreases, the peak current reduces to maintain regulation with a constant switching frequency.

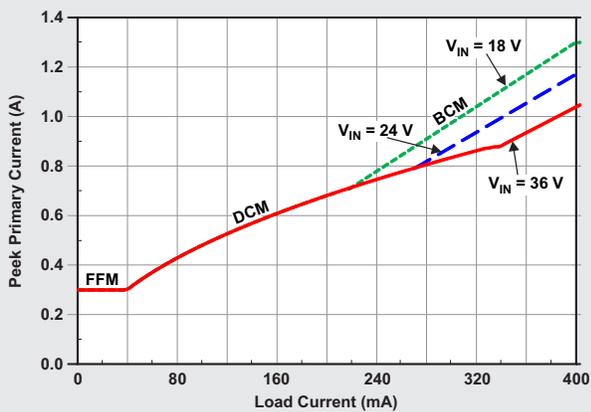
At even lighter loads, the peak current decreases to a minimum level that is 20% of the maximum peak current, and the switch off-time extends to maintain the output load requirement. The system operates in frequency fold-back mode (FFM) and the switching frequency decreases as the load is reduced. Figure 6 illustrates the variation of switching frequency and peak primary current over the load and line range and shows the three distinct, seamless modes of operation. The output power is controlled using frequency modulation in terms of cycles per unit time, and/or amplitude modulation based on energy transferred per cycle.

Figure 7 shows the typical switching voltage and current waveforms for each operating mode—FFM, DCM and BCM—where D_1 and D_2 denote the switch and diode conduction intervals, respectively.

Figure 6. Waveforms for auxless PSR-flyback converter



(a) Switching frequency vs. load



(b) Peak primary current vs. load

Figure 7. Switching waveforms for auxless PSR-flyback converter at $V_{IN} = 24\text{ V}$

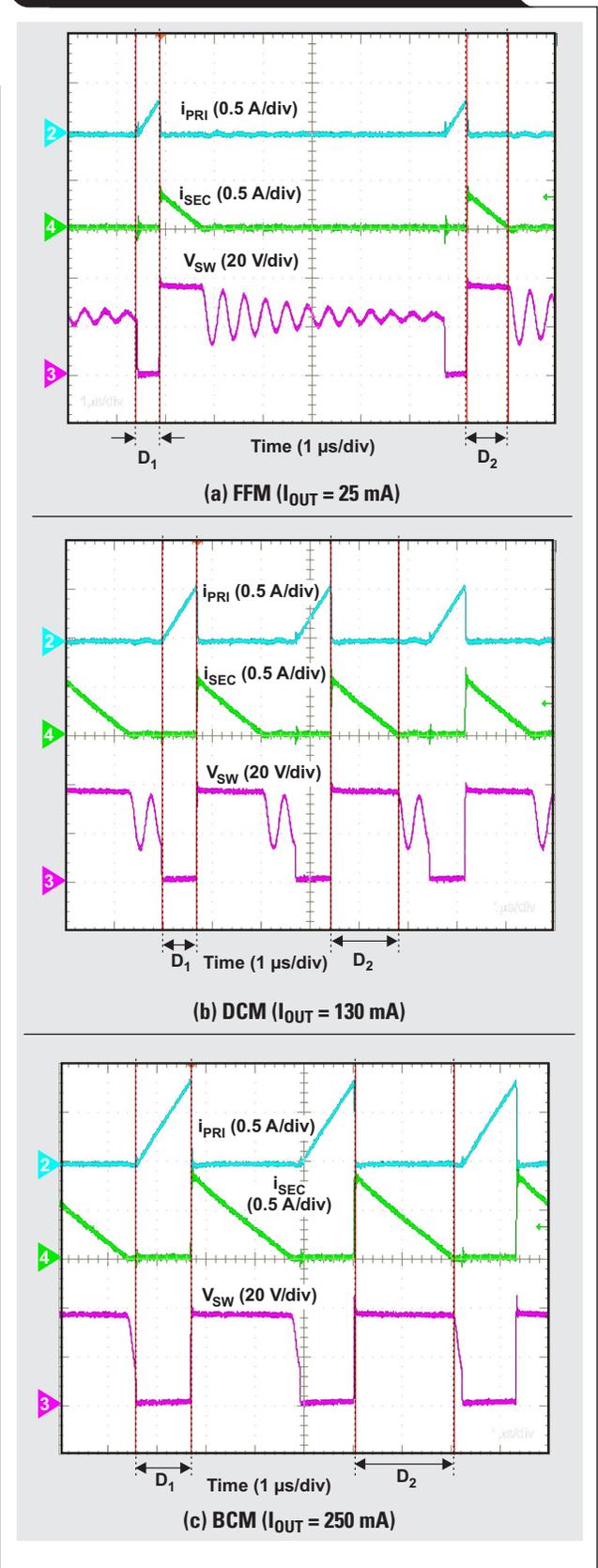


Figure 8 presents the load regulation and efficiency performance for several input voltages for a 12-V nominal output. Better than 1% load regulation is achieved.

With the VFPCM control architecture as described, 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.^[8] This supports lower total switching losses and improved conducted- and radiated-noise signatures.

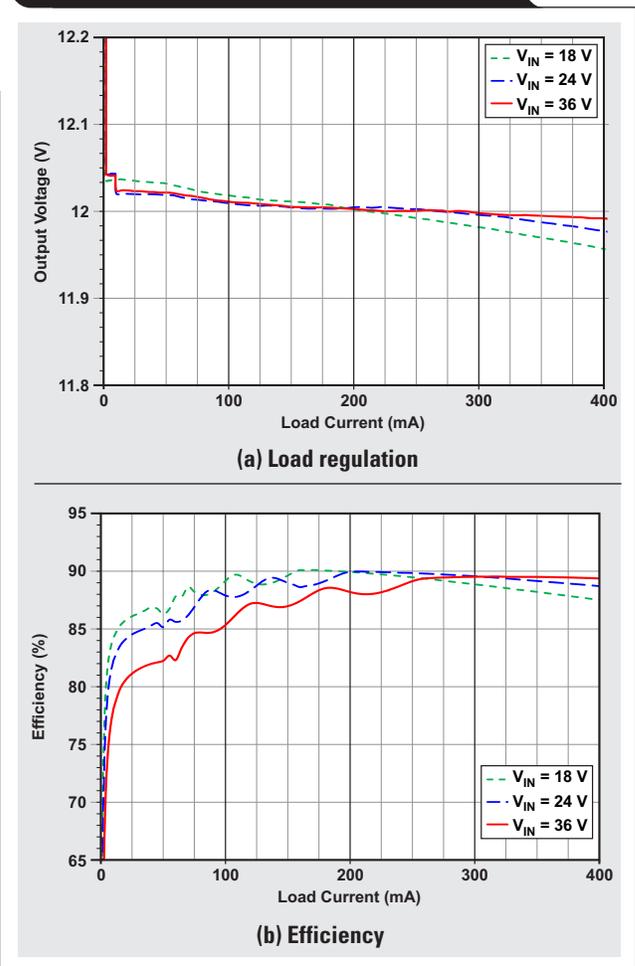
Conclusion

Testament to their excellent regulation performance, multioutput capability, small form factor, safety isolation and low overall bill-of-materials cost, auxless PSR-flyback converters are finding increasing relevance to power high-density PLCs. Using knee-position detection of the switch-node voltage and a sample-and-hold circuit to observe the output voltage, it is possible to achieve very accurate output regulation over wide load, line and temperature ranges. With minimal design effort, the regulation performance can rival that of traditional optoisolated solutions without the associated cost, solution size and reliability concerns.

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Figure 8. Waveforms for auxless PSR-flyback converter with $V_{OUT} = 12\text{ V}$



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