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Multi-Output Fly-Buck Regulator Offers Wide V_{IN}, Isolation And Low EMI

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The power management requirements in numerous industrial, medical, automotive and transportation end markets are setting new challenges for design engineers. Relating particularly to switch-mode power converters, system performance requirements dictate high density and high switching frequency coupled with increasing emphasis on a wide input voltage range, multiple output rails, galvanic isolation, and compliance with electromagnetic interference (EMI) regulations.

Certain industrial applications are further challenged with additional requirements. Examples include intelligent sensor transmitters[1], building and factory automation, smart e-meters, interface power for isolated RS-485 and CAN transceivers,[2] and electronic trip units (ETUs) used in air circuit breakers (ACB) or molded-case circuit breakers (MCCB).[3] Each of these products must seamlessly adhere to stringent transient and safety standards.

For instance, IEC 61000-4, a common transient immunity specification for industrial applications, describes low- and high-frequency input disturbances (ESD, burst, lightning/surge, and conducted and radiated immunity). Also consider requirements within automotive such as low-noise sensor transducers, electric vehicle (EV) battery management systems (BMS), and insulated gate bipolar transistor (IGBT) floating gate driver supplies[4] for motor drives in electric power steering (EPS) and braking.

Very clearly, a "must have" for these circuits is one or more isolated voltage rails. Given this requirement, the Fly-Buck—a convenient portmanteau to infer synchronous buck and flyback converter behaviors—has gained prominence as a solution to provide low-current auxiliary and bias outputs from a wide-ranging input supply up to 100 V, especially if both isolated and non-isolated rails are required.[5, 6] At the heart of this is the Fly-Buck value proposition relative to conventional flyback or push-pull topologies: simplicity, versatility, small solution size, high reliability, and low bill-of-materials (BOM) cost. This article discusses the advantages of the Fly-Buck in the context of a multi-output Fly-Buck design example.

Fly-Buck Regulator Overview

In general, a Fly-Buck solution provides two or more buck-derived outputs. Shown in Fig. 1 is the typical schematic of a Fly-Buck regulator. An alternative configuration, the Fly-Buck-boost, with negative primary-side output voltage is presented for comparison. The isolation barrier between primary and secondary is delineated in red.

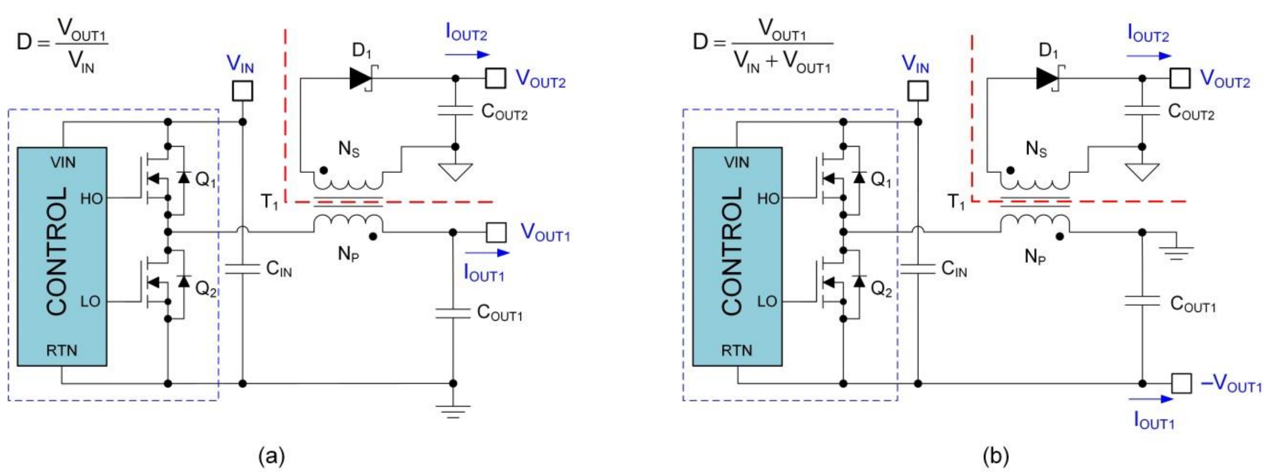

Fig. 1. Fly-Buck (a) and Fly-Buck-boost (b) power stages with primary- and secondary-referenced outputs designated V_{OUT1} and V_{OUT2}, respectively.

The main output, designated V_{OUT1}, has feedback regulation and is recognized simply as a buck converter output. The slave output, designated V_{OUT2} and referenced to the secondary side, is regulated based on the chosen turns ratio, $N = N_P/N_S$, of transformer, T_1. Of course, the voltage drops of the power semiconductors and the transformer windings also come into play. Referring to Fig. 1, the secondary-side output voltage V_{OUT2} is given by equation (1), where the transformer winding resistances, MOSFET on-state resistances, and rectifier diode forward voltage drop are aptly designated.

$$V_{OUT2} = N\left[V_{OUT1} + I_{OUT1}\left(R_{PRI} + R_{DS(on)Q2}\right)\right] - I_{OUT2}R_{SEC} - V_{D1} \tag{1}$$

Unlike its sister topology—the traditional flyback converter—the Fly-Buck master output is primary-side referenced and tightly regulated by simple closed-loop feedback. A compensated error amplifier is not needed, so optocoupler or auxiliary winding feedback is avoided. Simple control loop architectures that deliver low quiescent current consumption and fast transient dynamics, such as constant on-time (COT) control, are well-suited to the Fly-Buck.[7] Switching frequency is kept steady with line feedforward and continuous conduction-mode (CCM) operation. (Note: an inherent right-half plane zero generally complicates compensation and transient performance of the CCM flyback converter.)

To customize a Fly-Buck for additional outputs, simply add a transformer secondary winding with the requisite number of turns, a rectifier diode, and an output capacitor. Dual, triple, quad, even octal[4] outputs are easily obtained, with a small-size magnetic component best for space-constrained designs.

EMC-Compliant, Multi-Output Fly-Buck Implementation

Fig. 2 shows a Fly-Buck power solution for industrial applications that delivers ±15-V isolated rails from a center-tapped secondary winding to power bipolar supplies for high-precision operational amplifiers (op amps) and data converters. A 10-V primary-side-regulated rail sends bias power to VCC to reduce quiescent power loss at high V_{IN}.

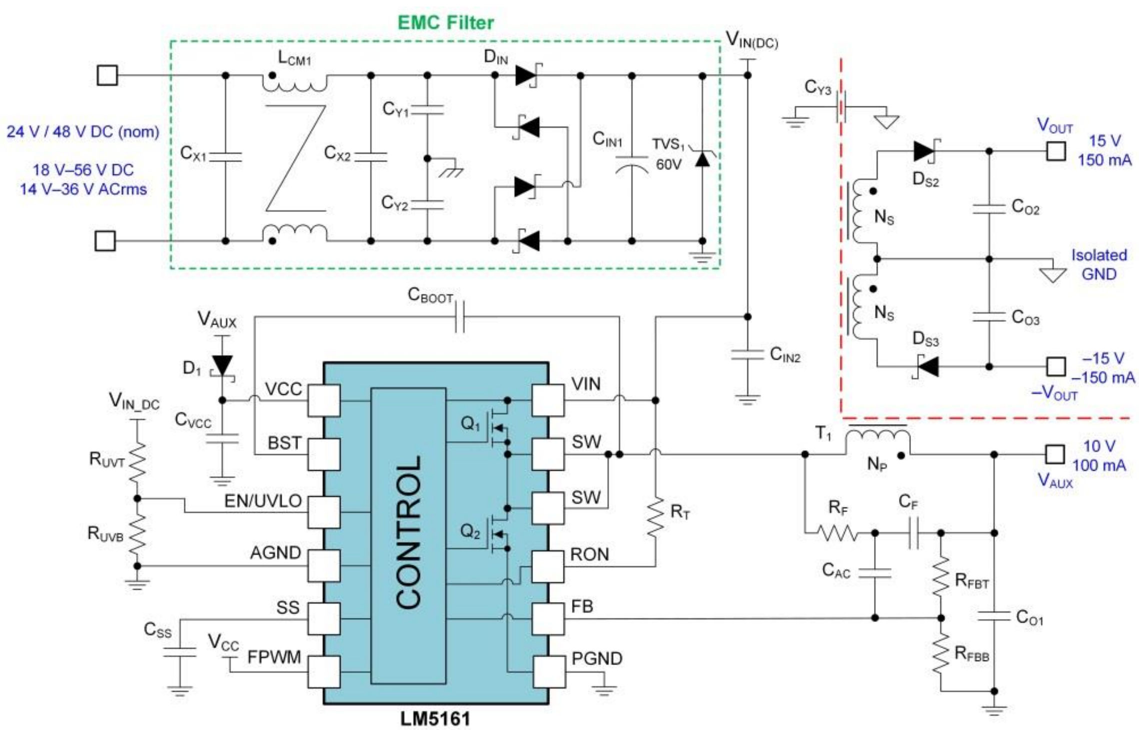

Fig. 2. An EMC-compliant, ac- or dc-powered Fly-Buck solution providing isolated ±15-V rails.

Available in an HTSSOP-14 leaded package, the LM5161 synchronous dc-dc converter from TI is rated for 1-A continuous current across a 20:1 V_{IN} range.[7] Capable of sustaining repetitive 100-V surges, the converter's output voltage is immune to large and noisy voltage swings at the input. Such transient immunity performance is critical in applications where high reliability and extended product life cycle are mandatory.

Various features have been integrated in the LM5161 to enable reduced size and enhanced reliability. These include an externally-adjustable output soft start (SS), a precision enable with customizable hysteresis for programmable line undervoltage lockout (UVLO), and an option to select CCM or diode emulation operating modes. Cycle-by-cycle peak (positive) and valley (negative) current limits, complemented by a peak current limit off-timer specific for Fly-Buck applications, provide fault protection from output overload and short circuit events. Let's examine some important elements of the Fly-Buck converter from Fig. 2.

Input Filter And Protection

Within the green dotted box in Fig. 2 is an EMC filter with common-mode inductor, X- and Y-capacitors, bridge rectifier and transient voltage suppression (TVS) clamp. A low-pass LC filter and TVS diode are typically used as a first line of defense to attenuate input voltage transients. X-capacitors, denoted as C_{XI} and C_{X2} in Fig. 2, provide differential-mode filtering. Meanwhile, Y-capacitors, denoted as C_{YI} and C_{Y2}, filter common-mode currents and shunt transient energy from the input lines to the system's chassis ground.

Note that a typical SMB-sized 60-V TVS diode clamps at approximately 95 V given a surge current of 6 A. As a result, the circuits located downstream from the protection network must still survive high-voltage transients without damage and also function seamlessly through such transients without interruption. In general, a Fly-Buck regulator with wide-V_{IN} capability permits a lower-cost TVS with higher clamp voltage, lower power rating and/or smaller footprint.

Fly-Buck Magnetics

A Fly-Buck transformer/coupled inductor with functional isolation to 500 Vdc continuous is usually sufficient, if the input rail is double or reinforced insulated (as with most 24-V industrial rails). For basic or reinforced isolation requirements, when powering digital isolators for instance, select the magnetic component that meets the isolation-grade requirement and design the PCB with the relevant creepage and clearance specification of the referencing standard.[6] Low-cost, off-the-shelf transformers are readily available with a slim form factor and an isolation rating up to 4.5 kV peak based on the requisite creepage and clearance. Of course, larger isolation ratings dictate increased winding spacing and, thus, higher leakage inductance.

Transformer Parasitics

An understanding of the magnetic component's parasitics is imperative to meet output voltage regulation and EMI specifications.[8] For example, output voltage cross-regulation, as shown by equation (1), depends on transformer winding resistances. Also, transformer parasitic leakage inductance accrues as a leading-edge spike on the secondary winding voltage that causes peak charging of the output at light loads, impacting load regulation. Moreover, leakage inductance at heavier load currents reduces the effective volt-seconds applied to the primary winding, resulting in an increased duty cycle, shorter rectifier diode conduction time, and higher peak and RMS values of secondary winding current.

Fortunately, the Fly-Buck is much more tolerant of leakage inductance than an equivalent flyback converter, resulting in a comparatively benign EMI signature. Fig. 3 shows the Fly-Buck converter schematic with MOSFET parasitic capacitance as well as (primary-side referred) transformer magnetizing and leakage inductances denoted explicitly.

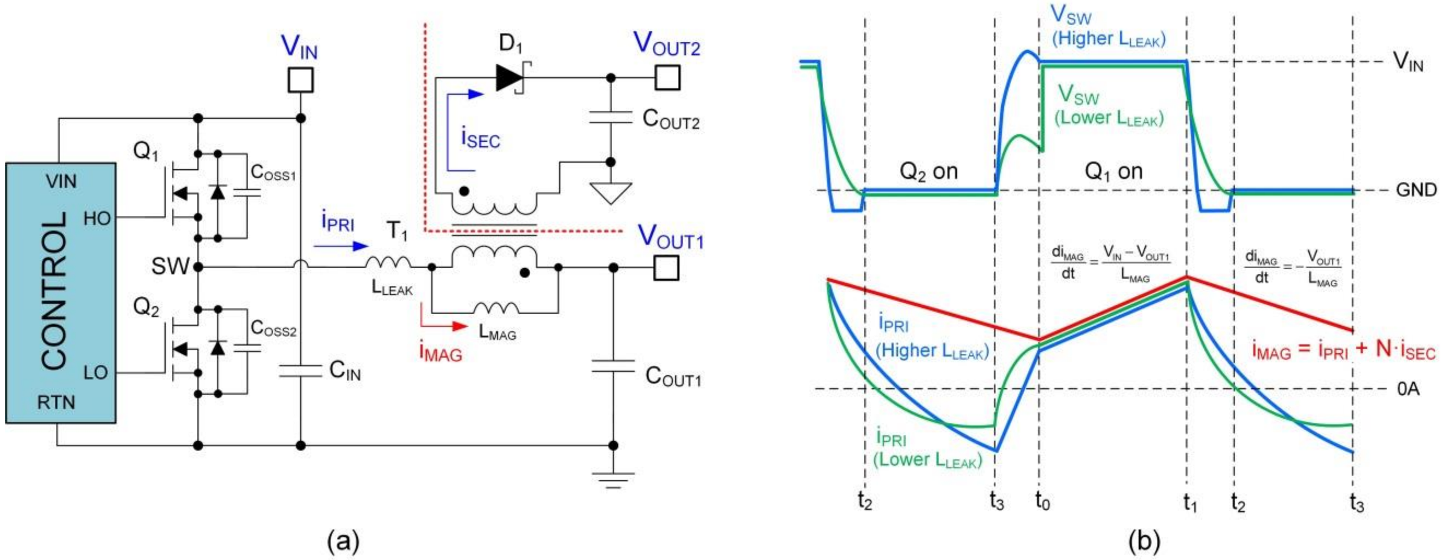

Fig. 3. Fly-Buck converter power stage (a) and switching waveforms with low and high values of transformer leakage inductance (b).

Unlike the flyback, the Fly-Buck converter avoids overshoot and ringing of the switch (SW) node voltage, which is induced by the leakage inductance. Eliminating this overshoot and ringing provides increased operating voltage margin against input voltage transients and lowers conducted and radiated emissions, particularly in the frequency range of 50 MHz to 300 MHz where EMI filtering is difficult.[9]

Also depicted in Fig. 3 are the Fly-Buck's quasi-resonant switching waveforms for the case when the primary-side output is lightly loaded. Once Q_2 turns off, the negative current into the SW node resonantly charges the effective SW node capacitance to achieve a soft commutation for MOSFETs Q_1 and Q_2 and secondary diode D_1. The upshot is that the Fly-Buck's voltage and current waveforms have generally lower harmonic content versus the flyback.[10] Another Fly-Buck benefit relates to the increase in efficiency as switching losses, including body-diode reverse-recovery loss, are curtailed.

Low-Profile Fly-Buck Implementation

Solution footprint and height are critical in space-constrained applications, meaning system designers must explore all avenues to conserve valuable PCB real estate. Fig. 4 shows a 300-kHz Fly-Buck converter implementation with small solution size, and low BOM cost using a standard two-layer FR-4 PCB.[11] The table details the important power stage components.

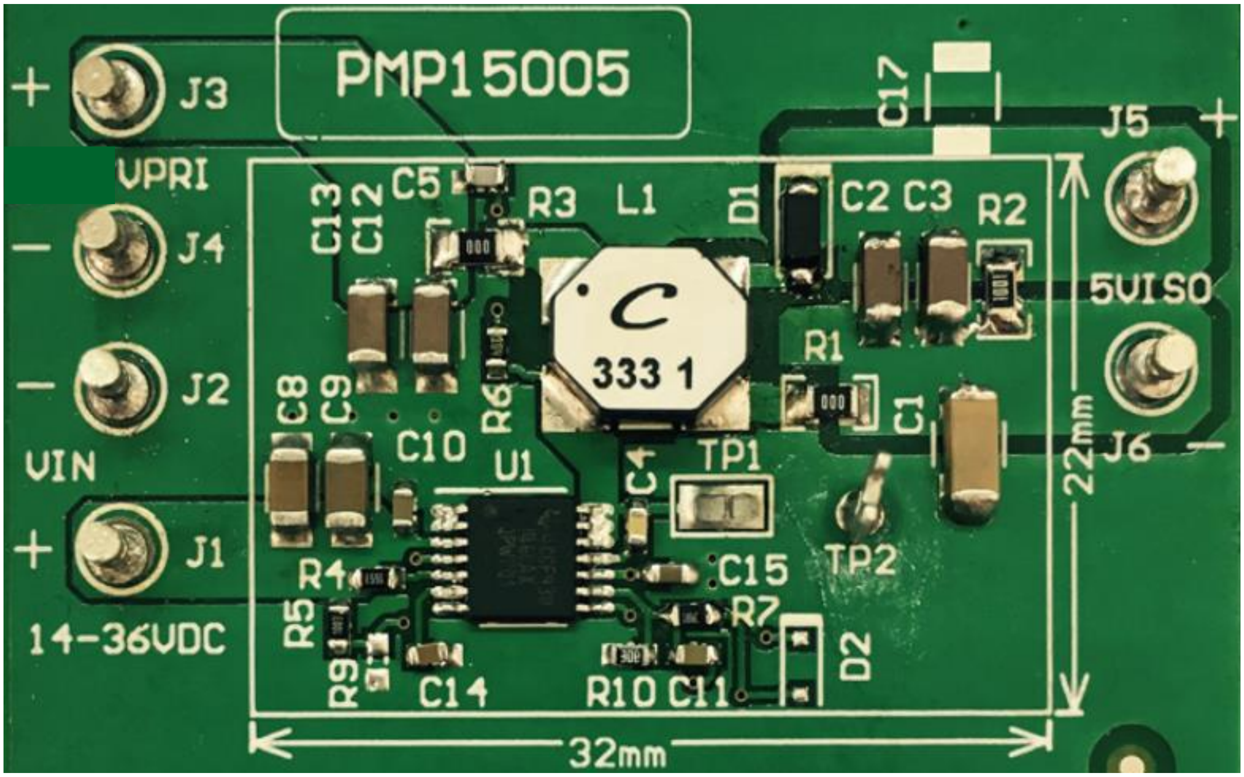

Fig. 4. Photo of Fly-Buck converter implementation.[11] The schematic for this converter is similar to that shown in Fig. 2 but does not include the input filter.

Table 1. Fly-Buck converter component details.

Component	**Part number**	**Size (mm)**
Wide V_{IN} synchronous buck converter	Texas Instruments LM5160APWP	5.0 x 6.3 x 1.2
Coupled-inductor, 33 µH, 1 A, 0.6 Ω, 1500 Vrms	Coilcraft LPD8035V-333MR	8.0 x 6.4 x 3.5
Input capacitors, 2.2 µF, 100 V, X7R	Murata GRM31CR72A225K	3.2 x 1.6 x 1.8 (EIA 1206)
Output capacitors, 10 µF, 25 V, X7R	Würth Elektronik 885012208069	3.2 x 1.6 x 1.6 (EIA 1206)

The circuit accommodates an input voltage from 14 V to 36 V. With the primary-side output set nominally at 5.4 V, the isolated output is 5 V. Using a 33-µH coupled inductor with 1:1 turns ratio, a profile of 3.5-mm, 1500-Vrms primary-to-secondary isolation, and maximum leakage inductance of 350 nH, the rated load current for both primary and secondary outputs is 225 mA. The molded-case inductor with composite core material has a distributed airgap that minimizes fringing flux, the result of which is a significantly improved radiated EMI profile.

Conclusion

Fly-Buck converters with a wide input voltage range, EMC compliance, isolated outputs, low noise and proven EMI performance are indispensable when total solution cost and time-to-market are predominant concerns for the system designer. As an extension of the synchronous buck topology, the Fly-Buck's value proposition is anchored in its feature set and versatility to address a wide variety of isolated and non-isolated power requirements:

- Reliable synchronous converter topology offers choice of Fly-Buck or Fly-Buck-boost.
- Wide-V_{IN} range provides extra margin to survive input rail transient voltages disturbances.
- Simple, cost-effective BOM needs no loop compensation, error amplifier, auxiliary winding or optocoupler components.
- Readily available, off-the-shelf magnetic components are available for space-constrained designs.
- Configuration is easily modified for additional outputs.
- Absence of primary-side voltage spike and ringing related to leakage inductance reduces broadband EMI, obviating the need for snubber components.
- Monolithic converter IC solutions are available depending on V_{IN}, I_{OUT} and thermal specifications.

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Timothy Hegarty is a systems engineer in the Power Products Solutions Business Unit at Texas Instruments. He received his bachelor's and master's degrees in electrical engineering from University College Cork, Ireland. With 20 years of power management engineering experience, he has written numerous conference papers, articles, application notes and blogs. His areas of interest are high-efficiency isolated and non-isolated converters, wide input-voltage-range PWM regulators and controllers with low quiescent current, renewable energy systems, and system-level simulation for industrial and automotive applications. He is a member of the IEEE Power Electronics Society and can be reached at ti_timhegarty@list.ti.com.

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