POWER designer

Expert tips, tricks, and techniques for powerful designs

No. 111

Buck Regulator Topologies for Wide Input/Output Voltage Differentials

— By Bob Bell, Applications Engineer and David Pace, Design Manager

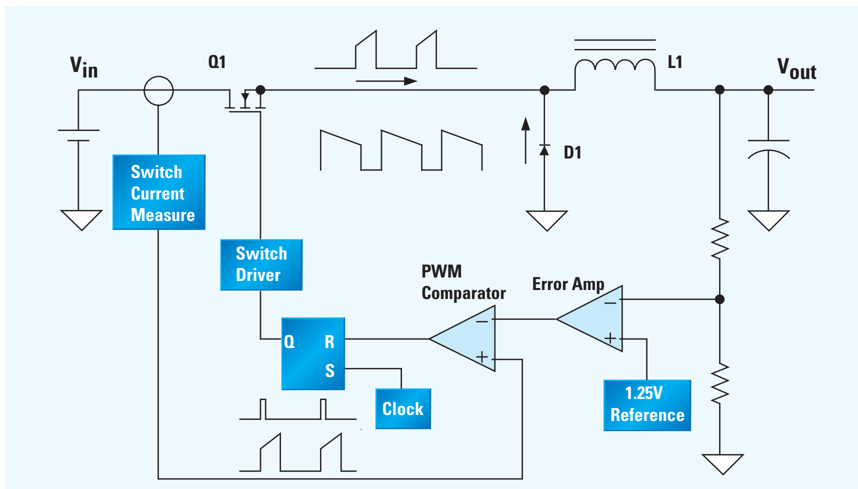


Figure 1. Buck Regulator Using Current-Mode Control

Buck regulators are used to efficiently step down a higher level, unregulated input voltage to a regulated output voltage. In applications requiring DC-DC conversion from a high input voltage, the buck regulator dramatically improves conversion efficiency relative to linear regulator alternatives. However, applying the buck regulator to applications with high input-to-output step-down ratios creates significant challenges for the pulse-width modulation (PWM) controller. Because the duty cycle of the buck regulator switch is approximately equal to V_{OUT}/V_{IN}, a buck DC-DC converter with high input/output voltage ratio must control very narrow PWM pulses. The switching frequency of a buck regulator is generally set to a high level to reduce the size of the inductor and capacitors. High switching frequency and low duty cycle translates to very short pulse durations in the controller. For example, a buck regulator with an input voltage of 66V and an output voltage of 3.3V will require a buck switch duty cycle of approximately 5%. At a typical switching frequency of 300 kHz, the required PWM on-time of the buck switch is a mere 166 ns.

Control methods or topologies used in buck regulators include Voltage-

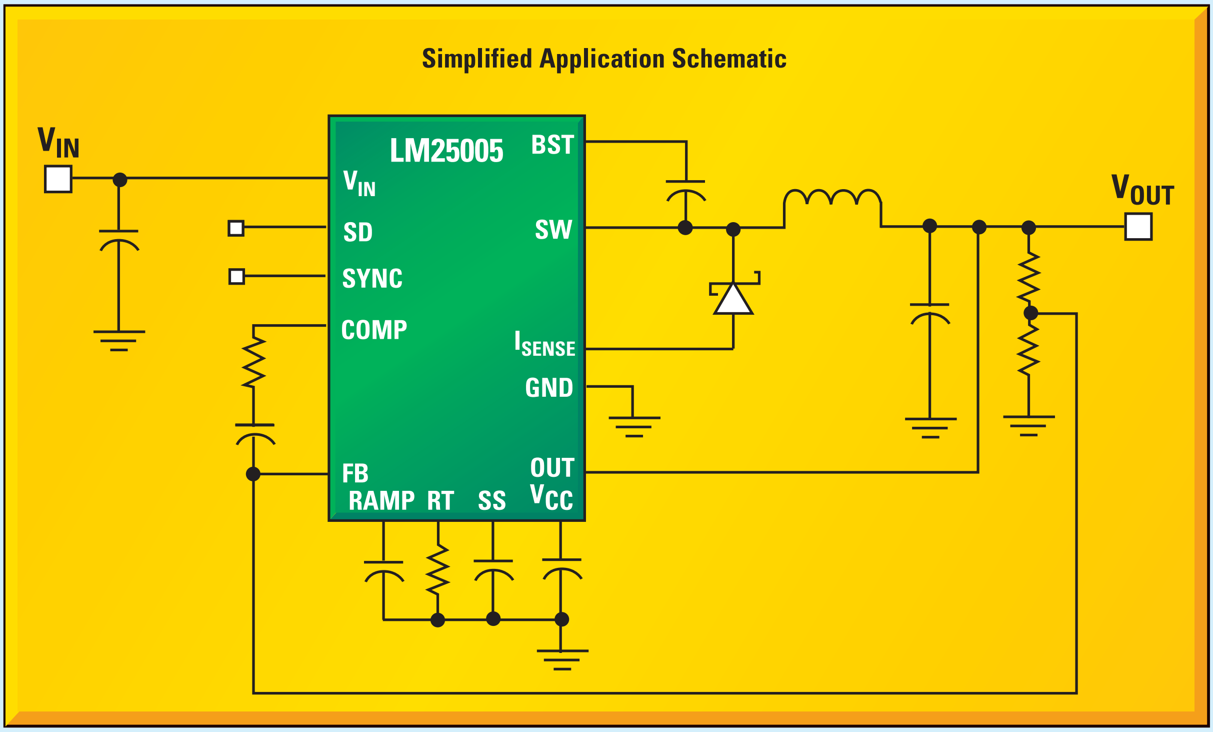
NEXT ISSUE:

Trade-offs in Synchronous Design

National Semiconductor

Integrated 42V, 2.5A Buck Switching Regulator

National's LM25005 With Emulated Current-Mode Control Reduces Noise Sensitivity and Enables Reliable Control of Small Duty Cycles at High Input Voltages



LM25005 Features

- Ultra-wide V_{IN} from 7V to 42V, supports load currents up to 2.5A
- Adjustable output voltage from 1.225V
- 1.5% feedback reference accuracy
- Current mode control with emulated inductor current ramp
- Programmable switching frequency with bi-directional synchronization capability simplifies system design
- Simulation support available
- Available in TSSOP-20EP (Exposed Pad) packaging AVAILABLE LEAD-FREE

Ideal for use in consumer electronics, telecommunications, data communications systems, automotive power systems, and distributed power applications

Product Highlight:

Allows multiple devices to self-synchronize or synchronize to an external clock

LM5005 High voltage version allows 75V max input voltage

For FREE samples, datasheets, and more information, visit www.national.com/pf/LM/LM25005.html

Buck Regulator Topologies for Wide Input/Output Voltage Differentials

Mode (VM), Current-Mode (CM), Hysteretic, and Constant-On-Time (COT) control. Current-mode control provides ease of loop compensation, FET switch protection, and inherent line feed-forward compensation. This makes current-mode control a favorite among power designers.

Hysteretic and Constant-on-Time controllers respond more quickly to load transients but do not operate at constant switching frequency. Constant-on-Time, a variant of hysteretic control, provides improved stability and less variation in switching frequency.

Current-Mode Control

Buck regulator ICs intended for high input/output step-down ratios must provide robust noise immunity when operating with very narrow duty cycles. In a current-mode topology, the challenge is the measurement and scaling of the inductor current. ***Figure 1*** shows the block diagram of a current-mode buck regulator. The output voltage is monitored and compared to a reference, with the error signal applied to the PWM comparator. The modulating ramp is a signal proportional to the buck switch current. When the buck switch is turned on, the inductor current flows through it with a slope of $(V_{IN} - V_{OUT}) / L$. An accurate, fast measurement of the buck-switch current is necessary to create the PWM ramp signal.

Propagation delays and switching transients makes it difficult to use current-mode control for large conversion ratio applications where very small on-times are required. Even with the best design practices, current sense and level shift circuits will add significant propagation delay. In addition, when the buck switch turns on, the reverse recovery current into the free-wheeling diode (D1) causes a leading-edge current spike with an extended ringing period (See ***Figure 2***.) This spike can cause the PWM comparator to trip prematurely. Attempts to filter or blank this leading-edge spike reduces the minimum controllable on-time of the buck switch.

Emulated Current-Mode Control

The challenge of accurate and fast current measurement can be met with a new proprietary method that emulates the buck switch current without actually measuring the current. The buck-switch current waveform can be broken down into two parts—a base, or pedestal, and a ramp. The pedestal represents the minimum (or valley) inductor current level. The inductor current falls to its minimum just before the buck switch turns on. A sample-and-hold measurement of the free-wheeling diode current, taken just prior to the turn-on of the buck switch, can capture the pedestal current information.

The other part of the buck-switch current waveform is the positive ramp to the peak level. The ramping current slope is described by, ***di/dt*** = $(V_{IN}\text{-}V_{OUT}) / L$. A signal equivalent to the current ramp can be created with a current source proportional to $V_{IN}\text{-}V_{OUT}$ and a capacitor (C_{RAMP}). If the current source (I_{RAMP}) is controlled by the difference between the input and output voltages, the capacitor charging slope is: ***dv/dt*** $= K^* (V_{IN} - V_{OUT}) / C_{RAMP}$, where K is a constant scale factor for the current source. The value of C_{RAMP} can be selected to set the capacitor voltage slope proportional to the inductor current slope.

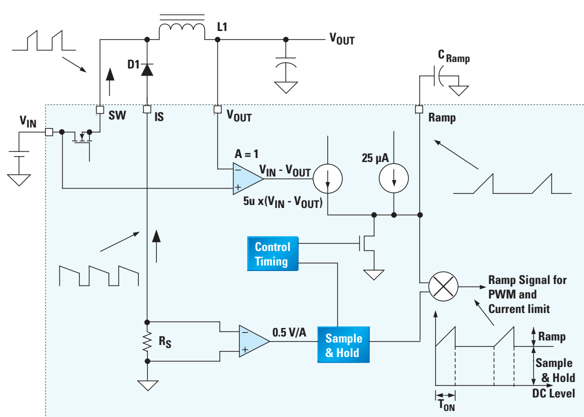
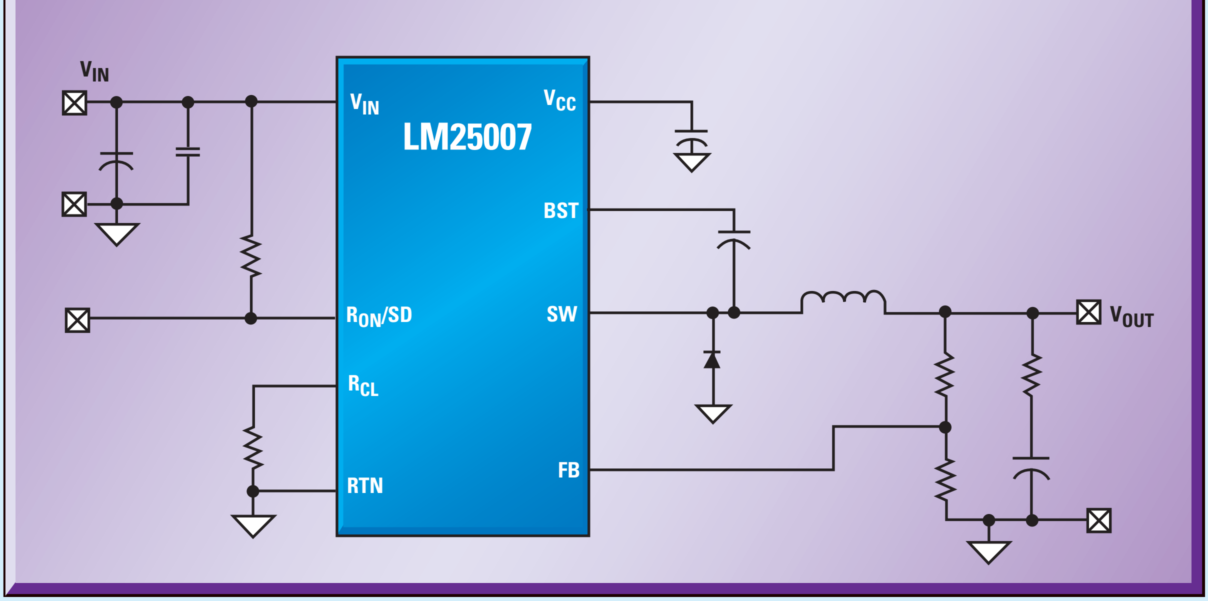


Figure 2. Emulated Current-Mode Regulator

Figure 2 presents the block diagram of the LM25005, an integrated buck regulator that implements the emulated current-mode control scheme described above. The free-wheeling diode anode is connected to ground through the

Highly Integrated 42V, 0.5A Buck Switching Regulator

LM25007 Has Constant-On-Time Architecture with V_{IN} Feed-Forward, Provides Ultra-Fast Transient Response, and Needs No External Compensation



Basic Step-Down Regulator

LM25007 Features

- Wide V_{IN} from 9V to 42V, supports load currents up to 0.5A
- Ultra-fast transient response, reduced filter capacitance
- Up to 800 kHz switching frequency
- Precise DC current limit
- ±2% accurate, 2.5V feedback from -40° to 125°C
- Integrated high voltage bias regulator
- Available in thermally enhanced MSOP-8 and LLP packaging

AVAILABLE LEAD-FREE

Ideal for use in automotive electronics, telematics, Industrial systems, consumer electronics, distributed power supplies, high-voltage post regulators, industrial power supplies, and high-efficiency point-of-load (POL) regulators

Product Highlight:

V_{IN} feed-forward provides near constant operating frequency

LM5007 High input voltage version allows 75V max input voltage

For FREE samples, datasheets, and more information, visit www.national.com/pf/LM/LM25007.html

Buck Regulator Topologies for Wide Input/Output Voltage Differentials

controller. A small-value, current-sense resistor and amplifier are used to measure the diode current. A sample-and-hold circuit captures the minimum level diode current just prior to the turn-on of the buck switch. Sampling the valley current, each cycle provides the pedestal portion of the emulated current sense signal.

The LM25005 senses the input voltage and the output voltage to generate a current source that charges an external ramp capacitor (C_{RAMP}). When the buck switch is turned on, the capacitor voltage rises linearly during each cycle. When the buck switch is turned off, the capacitor is discharged. For proper operation, the ramp capacitor is chosen in proportion to the value of the buck inductor. The LM25005 sums the sampled current pedestal and the external ramp capacitor voltage and applies this signal to the PWM comparator. The final result is a controller that behaves like a peak current-mode controller but without the delay and transient effects in the current sensing signal.

For applications operating with duty cycles greater than 50 percent, peak current-mode controllers are subject to sub-harmonic oscillation. Oscillation is normally avoided by adding an additional fixed slope ramp to the current-sense signal (slope compensation). In the LM25005, an additional fixed offset current provides an additional fixed slope to the ramp capacitor signal. For very high duty cycle applications, the ramp capacitor value can be decreased to further increase the ramp slope and prevent sub-harmonic oscillation.

LM25005 output overload protection is accomplished with a dedicated current-limit comparator which limits the emulated peak current on a cycle-by-cycle basis. The emulated current-mode method provides the added benefit of capturing inductor current information prior to the buck switch turn-on. If the current pedestal exceeds the current-limit comparator threshold due to an extreme overload condition, the buck switch skips cycles to prevent current runaway.

Figure 3 shows an LM25005 controlled buck regulator designed for an input voltage range of 7V to 42V and an output voltage of 5V with a maximum load of 2.5A.

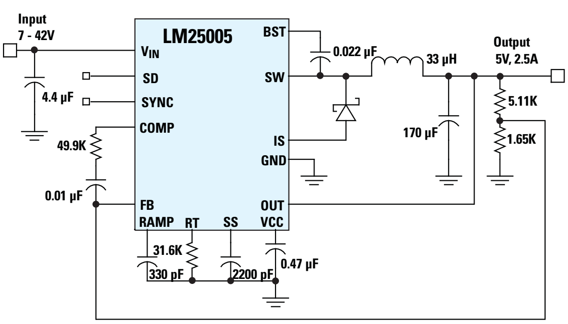


Figure 3. LM25005 Buck Regulator Schematic

Constant-On-Time Control

Another solution involving high input/output ratio buck regulators is Constant-On-Time control. This method can be thought of as a gated one-shot, where a feedback comparator triggers the next buck switch on-time when the output voltage falls below a threshold level. COT control is well suited for applications with high input/output voltage ratios because the one-shot can be programmed for a very short on-time and the feedback comparator will adjust the off-time to achieve the necessary low duty cycle. The noise sensitivity of a PWM ramp operating at low levels are completely eliminated. The COT technique has been used for many years for simple, cost-effective DC-DC converters because it requires no error amplifier or loop compensation components. The central issue of this method is frequency variation with input voltage and the possibility of sub-harmonic oscillation.

The block diagram in ***Figure 4*** illustrates the LM25010, a new member of a generation of COT buck regulators that solves these problems. The one-shot which controls the on-time is programmed by resistor R_{ON} which is connected between the unregulated input voltage and the controller. The period of the one-shot (T_{ON}) thus varies inversely with the input voltage. Using the simplified equation for the duty cycle (D) of a buck regulator, with Fs representing switching frequency:

$$D = V_{OUT}/V_{IN}$$

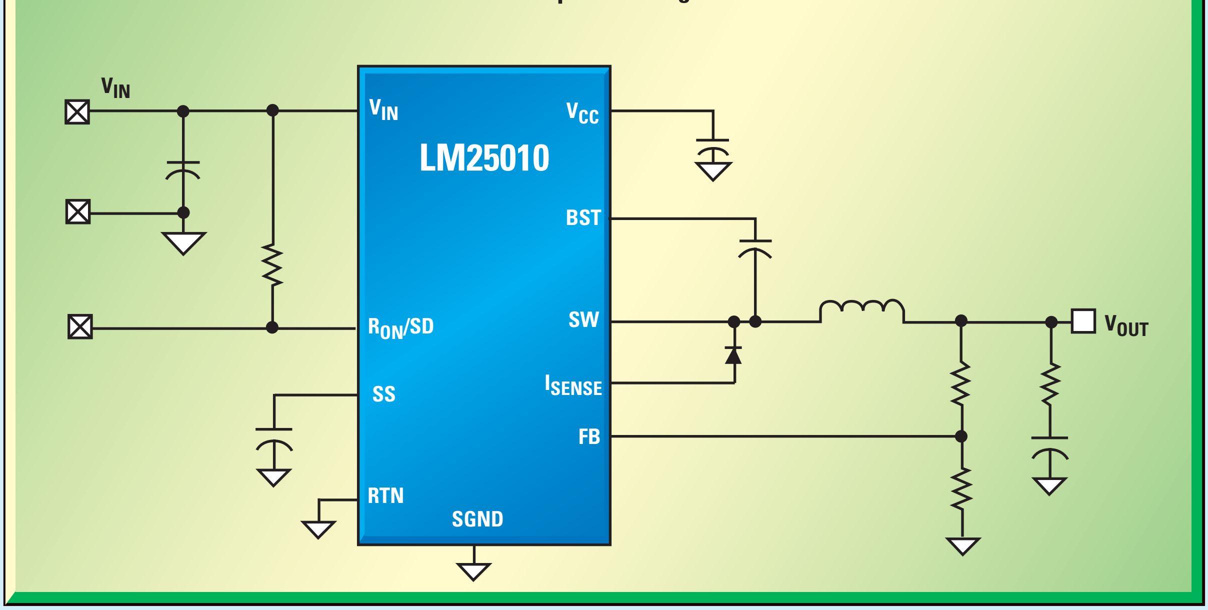
But by definition, $D = T_{ON}/(T_{ON}+T_{OFF}) = T_{ON}*Fs$

Since, $T_{ON} = K/V_{IN}$

Therefore, $Fs = V_{OUT}/K$

Highly Integrated 42V, 1.0A Buck Switching Regulator

LM25010 With Constant-On-Time Architecture and V_{IN} Feed-Forward Provides Ultra-Fast Transient Response and Near-Constant Operating Frequency



Basic Step-Down Regulator

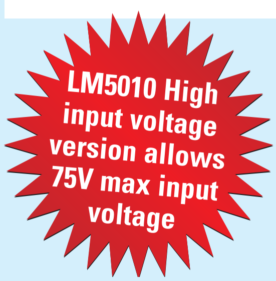
LM25010 Features

- Wide V_{IN} from 6V to 42V, supports load currents up to 1.0A
- Ultra-fast feed-forward response, modulated filter capacitance
- Switching frequency up to 1 MHz
- Valley current limiting at 1.25A
- ±2% accurate, 2.5V feedback from -40°C to 125°C
- Integrated high voltage bias regulator
- Available in exposed pad LLP-10 and TSSOP-14 packaging

Ideal for use in non-isolated telecommunications, secondary-side post regulators, and automotive electronics

Product Highlight

No control-loop compensation required



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Buck Regulator Topologies for Wide Input/Output Voltage Differentials

Thus in any application where the desired V_{OUT} is a fixed value, the on-time can be programmed to achieve a desired switching frequency and the frequency will not vary significantly with changes in the input voltage.

One challenge associated with COT regulators is current limiting. If the on-time is terminated by a current-limit circuit which senses the current in the buck switch, the output voltage will fall and the off-time will decrease to its minimum value in an attempt to maintain voltage regulation. The frequency of the regulator will increase to an extremely high value, limited only by the propagation delays, and power dissipation within the IC will become excessive. Some buck regulator solutions arbitrarily enforce a minimum off-time after current limit is detected to guarantee that the frequency does not increase excessively in overload conditions. This approach produces a fold-back in the current limit I vs V characteristic which can limit the useful load range of the regulator.

The LM25010 illustrated in ***Figure 4*** solves the current limit dilemma with a simple yet effective method. The free-wheeling diode current is routed through a sense resistor in the IC. The current in the diode is sensed by a resistor and monitored by a comparator. If the current flowing through the free-wheeling diode exceeds the current-limit threshold, the current-limit comparator will disable the buck switch until the diode current falls to an acceptable level. The off-time is automatically increased to the time required for the buck inductor current to ramp down to the desired valley current. Thus, neither the output current nor the switching frequency can run away during overload.

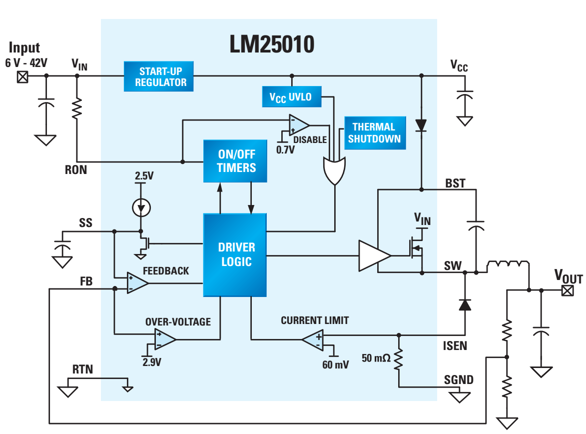


Figure 4. LM25010 COT Buck Regulator

Regulators based on COT control are subject to erratic switching behavior if there is not sufficient ripple voltage present at the Feedback (FB) pin. If the output capacitor has a large enough Equivalent Series Resistance (ESR) this issue can be avoided. In applications where a relatively large output ripple cannot be tolerated, several ripple reduction techniques are available.

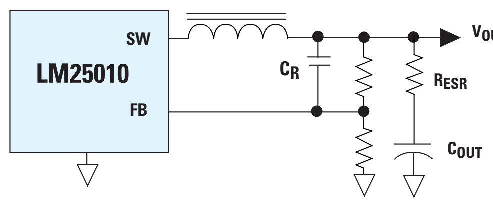


Figure 5a. COT Ripple Reduction Using C_R

In ***Figure 5a***, the ripple at V_{OUT} is fed to FB through C_R. Therefore the ripple at V_{OUT} can be less than in the standard circuit since it is not attenuated as much by the feedback resistors.

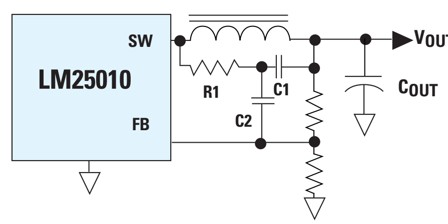
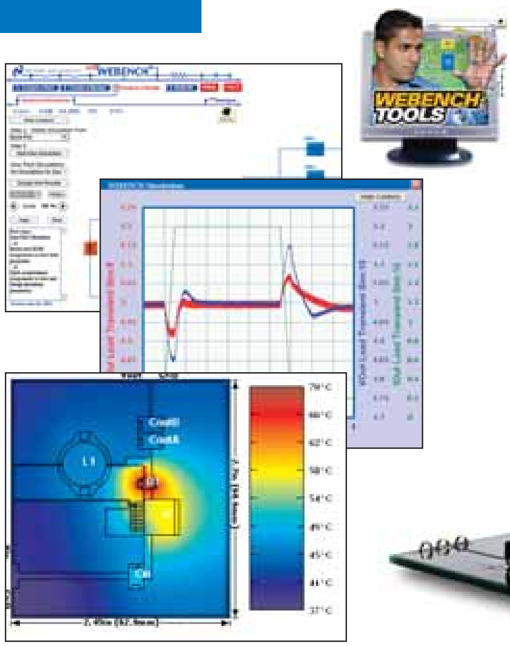


Figure 5b. COT Ripple Reduction Using R_1,C_1, and C_2

In ***Figure 5b***, the R_{ESR} is removed resulting in low ripple at V_{OUT}. The ripple required at FB is produced by R_1, C_1, and C_2. Since V_{OUT} is an AC ground, and the SW pin switches between V_{IN} and ground, a sawtooth is generated at the R_1, C_1 junction. C_2 then couples that ripple to FB.

These are some of the control methods and topologies favored by power designers. For more information on high-voltage switching power supply topologies, visit www.national.com/onlineseminars. ■

Power Design Tools



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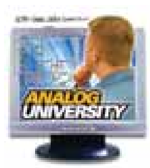

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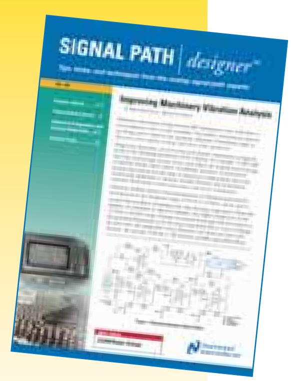

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