POWER *designer*

Expert tips, tricks, and techniques for powerful designs

Inside Current-Mode Control

— By Mark Hartman, Applications Engineer

Current-mode control has been used in power supplies since the late 1970s. Although this method of control has been in use for over two decades, its operation and characteristics are not generally well known. Most engineers learn about switching power supplies in terms of the more familiar voltage-mode control, while current-mode control is left for more advanced studies. This is unfortunate because a power supply engineer should know at least the basic differences between voltage-mode and current-mode control to know when to use each control architecture. In this paper, we will go inside current-mode control.
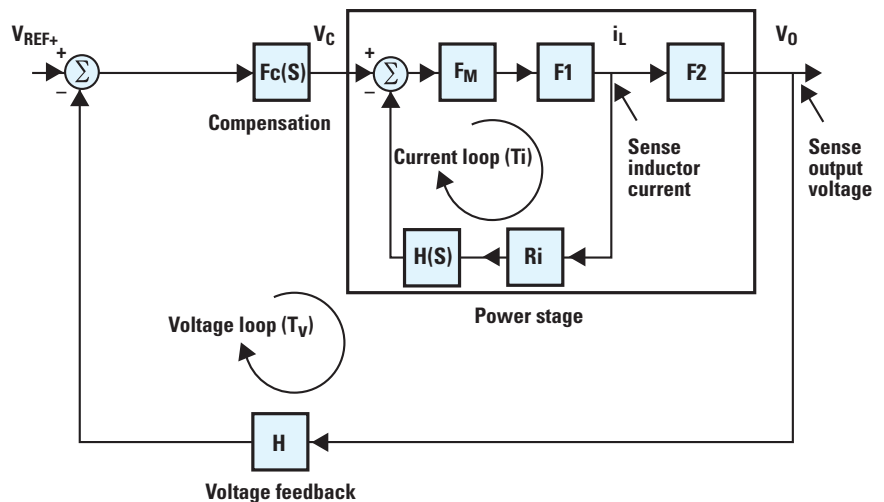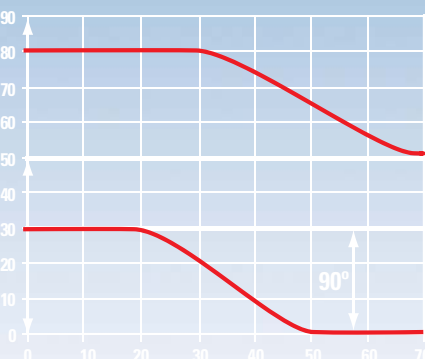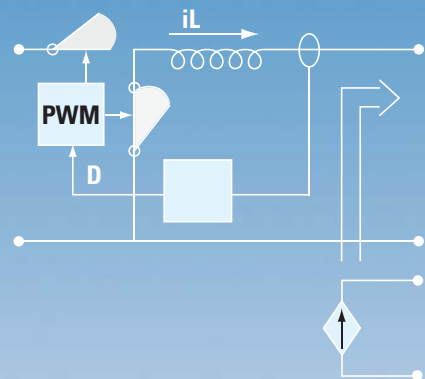

Figure 1: Control block diagram of a current-mode controller

Current-mode control employs an inductor current feedback loop in addition to the voltage feedback. A current-mode control converter uses the inductor current, as well as the output voltage error signal, as input signals to the PWM modulator. *Figure 1* shows a simple schematic of peak current-mode control, where the peak inductor current is controlled along with the output voltage. The inductor current is sensed by some means and is compared to a control voltage V_C, which is derived from the output voltage error.

NEXT ISSUE:

Analyzing Power Modules

National Semiconductor

The Sight & Sound of Information

Single-ended current-mode AC-DC PWM controller

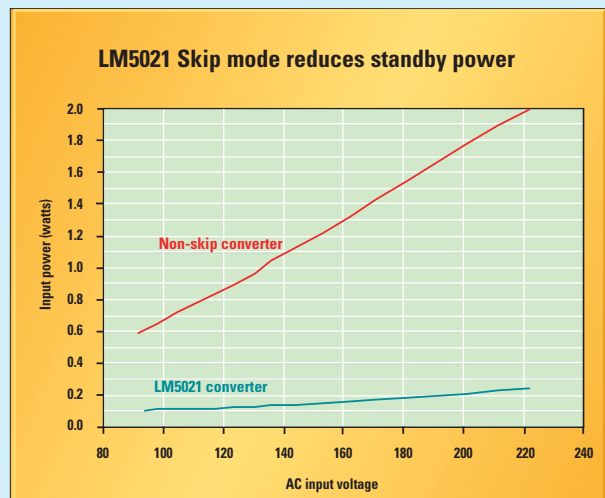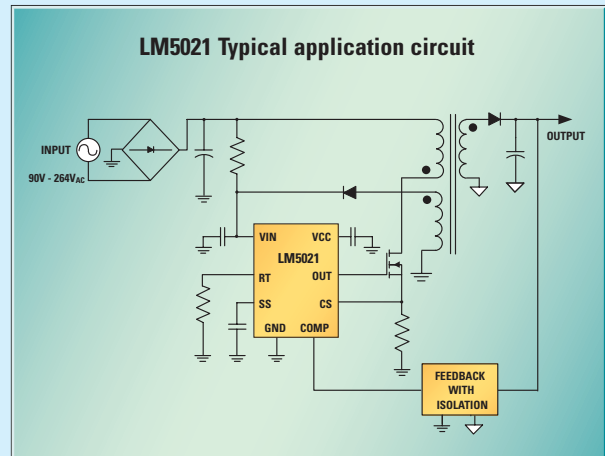## Easy-to-use, fully integrated LM5021 for offline power supplies

Features

- Current-mode PWM control with internal slope compensation
- Low-current bootstrap start-up with wide hysteresis
- Cycle-by-cycle current limiting and hiccup mode fault protection
- Integrated 0.7A MOSFET gate driver
- Adjustable oscillator which can be synchronized to an external clock
- Available in small MSOP-8 and DIP-8 packaging

Ideal for telecommunications and networking equipment power systems, consumer power supplies and industrial power supplies, as well as flyback and forward AC-DC converters

Product Highlight:

Cycle-skipping burst mode reduces no load power dissipation (green mode)

LM5021 Typical application circuit

LM5021 Skip mode reduces standby power

POWER designer

Inside Current-Mode Control

The PWM comparator will output high (power switch on) until the sensed inductor current equals the control voltage. As soon as this equality is met, the PWM comparator goes low and turns the switch off. The beginning of the next period is initiated by setting an RS latch from a fixed frequency clock signal. In this way, the peak current of the inductor is precisely controlled by the control voltage. Intuitively, the current loop causes the inductor to act like a current source, which contributes to many of the characteristics of current-mode control.

While it is apparent from the schematic in *Figure 2* that the duty cycle (D) is derived from the inductor current and the output voltage, it is difficult to grasp what effect this will have on the performance of the converter. An intuitive understanding of the important characteristics of current-mode control is best analyzed from the small signal behavior.

A small signal block diagram of peak current mode control is shown in *Figure 1*. There are two feedback loops: The outer feedback loop (T_V) feeds back voltage information, while the inner feedback loop (T_i) feeds back current information. The voltage loop is derived as in the voltage-mode control (producing a compensated control voltage from the output voltage error).

The current loop, T_i, is the distinguishing element of the current-mode control architecture. The input to the current loop is the control voltage, V_C, which is compared to the sensed inductor current and sets the duty cycle. The duty cycle is passed to the power stage (switching elements, inductor, and output capacitor), which produces a corresponding inductor current and output voltage. The inductor current is fed back through a sensing gain Ri and returns to be compared with V_C.

A seemingly paradoxical situation arises when the current loop is closed: a second order system with two reactive elements (L and C_{OUT}) becomes a single pole system! Feedback theory provides the rational for this. The fact that a feedback loop is controlling the inductor current is effectively like having a current source feeding the output capacitor and load. Therefore, at frequencies below the current loop bandwidth, the current mode power stage has only one pole dominated by the $C_{OUT} \| R_{LOAD}$ impedance.

The effect of the current loop to the power stage is not only at low frequencies, however. Analysis of a small signal current perturbation in the current loop shows that it is very similar to a discrete-time sampled data system. Such a sample and hold system has complex pole pairs at multiples of the
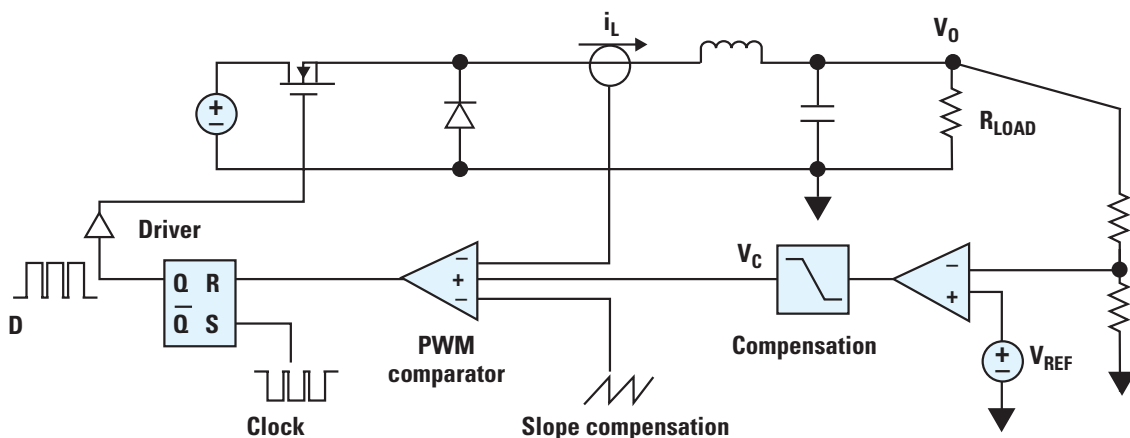

Figure 2: Buck converter schematic with current-mode control (both output voltage and inductor current are sensed)

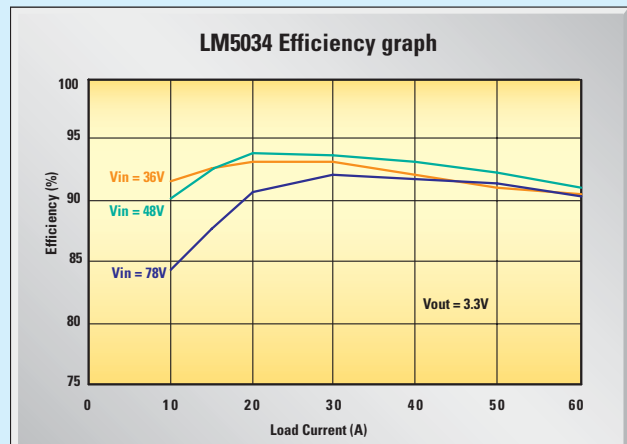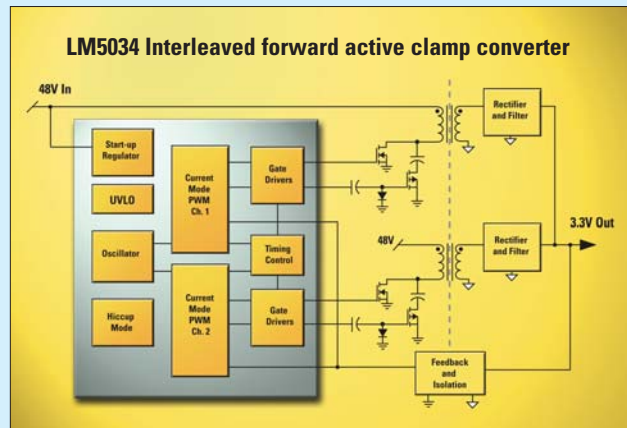# Dual interleaved active clamp current-mode controllers

Highly integrated, high-voltage LM5032/34 controllers

- Two independent current-mode controllers
- Interleaved single or dual output operation
- Compound 2.5A main FET gate drivers
- Active clamp FET gate drivers (LM5034)
- Integrated 100V start-up regulator
- Up to 1 MHz switching frequency programmed by a single resistor
- Programmable maximum duty cycle
- Adjustable soft-start and input under-voltage sensing
- Adjustable deadtime between main and active clamp gate drivers (LM5034)
- Available in TSSOP-16 (LM5032) and TSSOP-20 (LM5034) packaging

Ideal for achieving high efficiency and power density in 200W to 500W DC-DC converters

Product Highlight:
Maximize efficiency and density of DC-DC converters

LM5034 Interleaved forward active clamp converter

LM5034 Efficiency graph

POWER | *designer*
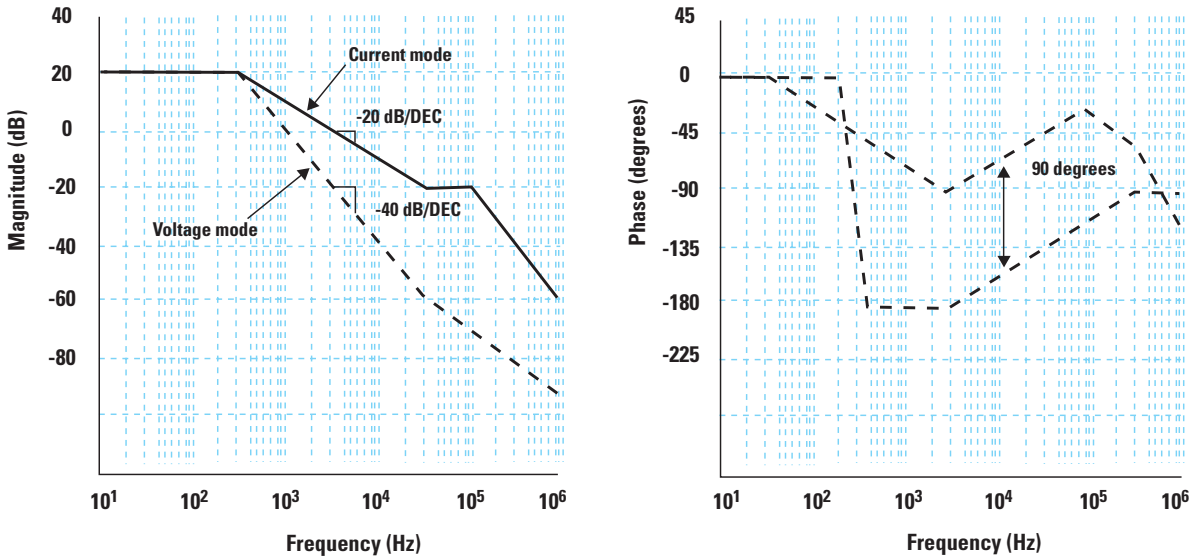
Inside Current-Mode Control

Figure 3: Control-to-output bode plots for voltage and current mode converters.
(The current mode converter has an extra 90 degrees of phase.)

sampling (switching) frequency. A second order approximation of the sample-and-hold gives accurate results up to half the switching frequency, which is the theoretical limit to the bandwidth of a power supply. The sampling effects of the current loop will be examined in a later article.

Several performance enhancements are achieved in peak current-mode control. Key advantages with current mode control are superb line regulation, simple compensation design, robustness to large load variations, and inherent cycle-by-cycle current limiting. Line regulation is the change in the output voltage caused by a change in the input voltage, and is influenced by the gain of the control-to-output transfer function (the power stage in *Figure 1*). The gain of the control-to-output transfer function in a current-mode architecture is independent of V_{IN}, thus the line regulation is very good. As a comparison, the control-to-output transfer function in a voltage-mode architecture has a factor of V_{IN} in its expression. This implies that the gain is directly proportional to V_{IN}, and line regulation will suffer.

The compensation network in a current-mode architecture can be made very simple. The reason is that the control-to-output transfer function contains only one low-frequency pole, compared to a double pole in voltage mode architectures (see *Figure 3*). This results in an additional 90-degree phase shift in a current-mode architecture. A simple explanation for this difference is that the inductor current is being monitored and controlled by the current loop. In the case of a buck converter, the power stage can be approximated as a current source feeding the parallel combination of the output capacitor and the load, producing a single low-frequency pole. In voltage-mode control the inductor current is not controlled and the power stage has a double pole due to the LC filter. With only a single pole in the low frequency characteristic of the power stage, the compensation needs only DC gain, a single pole role off, and a single zero for phase lead (a type I, or lag compensator). This can be easily implemented using an error amplifier and a single capacitor and resistor. For a simple compensation scheme, one may place the

Wide input range current-mode dual output buck regulator

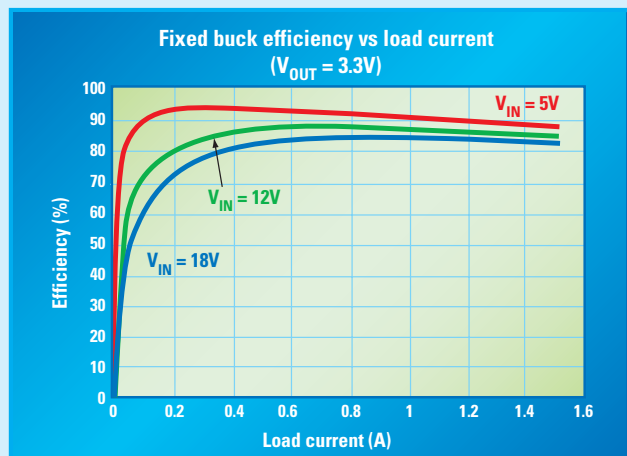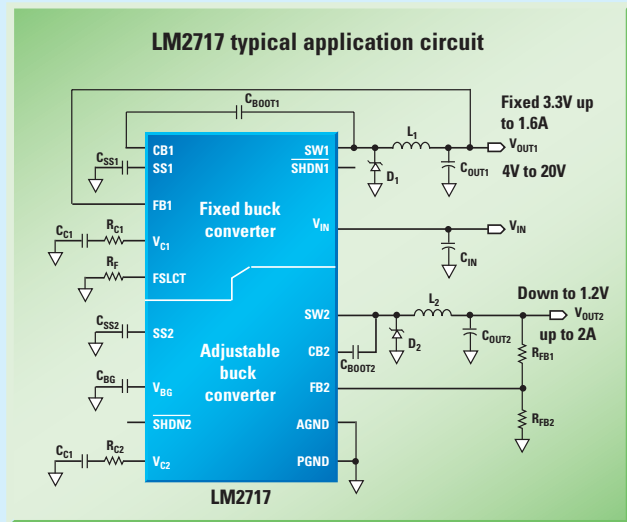## Fully integrated 4V to 20V LM2717 dual step-down converter

Features

- High efficiency over complete load range (90% typ. at 1A, 5V_{OUT}) reduces power dissipation in stand-by mode and extends battery life
- Adjustable frequency up to 600 kHz allows use of small external components
- Extremely low R_{DS-ON} (160 mΩ) maximizes efficiency
- External compensation optimizes transient response
- External softstart for each converter allows application-specific programming times
- Independent shutdown allows ease of sequencing
- TSSOP-24 package ensures an overall low-profile solution

Ideal for use in disk drives, DSP power supplies, wall transformer and distributed power regulation, DSL and cable modems, telecom systems, and laptop computers

Product Highlight:
High switch current limit (2.2A fixed / 3A adjustable) for high-power applications

LM2717 typical application circuit

Fixed buck efficiency vs load current (V_{OUT} = 3.3V)

Inside Current-Mode Control

compensation zero such that it cancels the power stage pole, and –20 dB/Dec roll-off is achieved in the open loop response of T_V.

The compensator is designed around the power stage to achieve the desired dynamic performance. However, the frequency response of the power stage changes when the converter transitions between continuous conduction mode (CCM) and discontinuous conduction mode (DCM) operation. In CCM, the inductor current is continuous and does not reach zero, while in DCM, the inductor current is discontinuous and is zero for a portion of the switching period. As the load current decreases, there is a point where the converter transitions from CCM to DCM. In voltage-mode control, the power stage transitions between a 2 and 1 pole system at the boundary of CCM/DCM. A first and second order system require very different compensation networks to be optimized. A great advantage of the current-mode architecture is that the transfer function of the power stage is very similar in DCM and CCM (first order at low to mid frequencies). Therefore, over large load ranges, where the converter operates in both DCM and CCM, the dynamic perform-ance of the converter does not change drastically.

Yet another benefit from the current loop is inherent current limiting. No additional circuitry is needed to sense the inductor current as it is already in place from the current feedback loop.
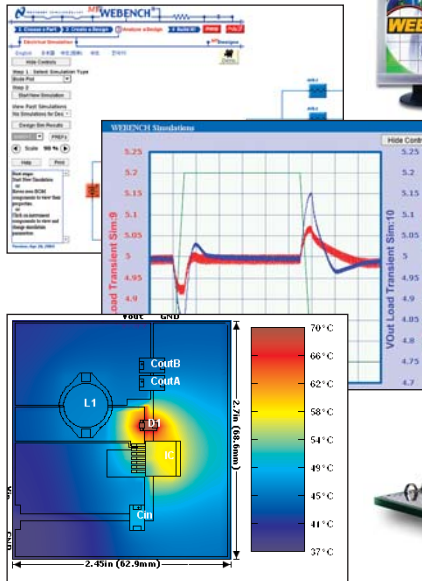
Conclusion

Current-mode control in power supplies can be difficult to analyze because of its multi-loop architecture. However, the circuit can be simplified by recognizing that the current loop transforms the inductor into a controlled current source. This provides a more intuitive understanding of the current-mode architecture. The current feedback loop results in some unique advantages over a voltage-mode controller. Line regulation is improved, the compensation network is simple, dynamic performance traits change little between CCM and DCM operation, and current limiting is

built into the architecture. In many cases current-mode control can enhance performance of a power supply. ∎

FURTHER READING:

1. **R. B. Ridley,** "*A New Small-Signal Model for Current-Mode Control.*" Ph.D dissertation, November 27, 1990.

2. **D. M. Sable, R. B. Ridley, and B. H. Cho,** "*Comparison of Performance of Single-Loop and Current-Injection-Control for PWM Converters which Operate in Both Continuous and Discontinuous Modes of Operation.*" Proceedings of the IEEE Power Electronics Specialists Conference and Exposition, June 1990.

3. **V. Vorpérian,** "*Analysis of Current-Mode Controlled PWM Converters Using the Model of the Current-Controlled PWM Switch.*" Power Conversion and Intelligent Motion, October 1990.

4. **W. Tang, F. C. Lee, and R. B. Ridley,** "*Small-Signal Modeling of Average Current-Mode Control.*" Applied Power Electronics Conference, February 1992.

5. **V. Vorpérian,** "*Fast Analytical Techniques forElectrical and Electronic Circuits.*" Cambridge University Press, 2002.

6. **R. W. Erickson and D Maksimovi,** "*Fundamentals of Power Electronics, second edition.*" Kluwer Academic Publishers, 2001.
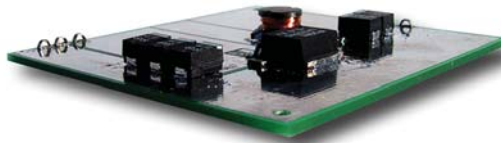
Power design tools

WEBENCH® online design environment

Our design and prototyping environment simplifies and expedites the entire design process.

1. Choose a part
2. Create a design
3. Analyze a power supply design
   – Perform electrical simulation
   – Simulate thermal behavior
4. Build it
   – Receive your custom prototype kit 24 hours later

webench.national.com

Analog University®

Expand your knowledge and understanding of analog with our free online educational training tool.

analogU.national.com

National Semiconductor
2900 Semiconductor Drive
PO Box 58090
Santa Clara, CA 95052
1 800 272 9959

Visit our website at:
power.national.com

For more information, send email to:
new.feedback@nsc.com

Don't miss a single issue!

Subscribe now to receive email alerts when new issues of Power Designer are available:

power.national.com/designer

Introducing our new Signal Path Designer! View online today at:

signalpath.national.com/designer

National Semiconductor
The Sight & Sound of Information

©2005, National Semiconductor Corporation. National Semiconductor, N, WEBENCH, LLP and Analog University are registered trademarks of National Semiconductor. All other brand or product names are trademarks or registered trademarks of their respective holders. All rights reserved.

550263-006