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Virtual-current mode: current-mode control without the noise

THIS NEW DC/DC-SWITCHING-REGULATOR DESIGN APPROACH COMBINES THE BEST FEATURES OF CURRENT- AND VOLTAGE-MODE CONTROL.

The two most common forms of control in dc/dc switching power converters are CM (current-mode) and VM (voltage-mode) control. Each method has its own advantages and disadvantages. CM control provides the ease of loop compensation and inherent line feedforward, which makes this method a favorite among designers. VM control is more immune to noise. This characteristic is important in large-step-down-ratio applications in which the switch has a short on-time that is susceptible to noise pickup. The ideal approach that has been eluding designers is a practical CM-controlled regulator without noise-susceptibility challenges.

Figure 1 shows a buck regulator using VM control. The system monitors the output voltage and compares it with a reference voltage. The resulting error signal and a modulating ramp form a PWM (pulse-width modulator), which controls the buck switch. In each cycle, the clock turns on the buck switch, which the PWM comparator then turns off. A first-order approximation for the buck-switch duty cycle, D, is $D=V_{OUT}/V_{IN}$. The modulating ramp in VM control is a dedicated sawtooth-ramp-oscillator circuit. The modulation is more stable and less noise-sensitive if you use a fixed sawtooth ramp, because the ramp amplitude is fairly large—often, 2 to 3V peak. The disadvantages of VM control are difficulties in designing the loop compensation and the inherent lack of feedforward.

Figure 2 shows a buck regulator using CM control. The system monitors the output voltage, compares it with a reference, and applies the resulting error signal to the PWM. The origin of the modulating ramp is an area in which VM and CM control differ. The modulating ramp in CM control is a signal proportional to the buck-switch current. When you turn on the buck switch, the inductor current flows through it. During this time, the inductor current has a positive slope of $(V_{IN}-V_{OUT})/L$. An accurate fast measurement of the buck-switch current is necessary to create the modulating-ramp signal. The main disadvantage of CM control is the difficulty of creating the buck-switch-current signal.

ALMOST IMPOSSIBLE

Propagation delays and noise susceptibility make it almost impossible to use CM control for high-input-voltage, large-step-down applications that require small on-times. For example, a buck regulator with an input voltage of 66V and an output voltage of 3.3V requires a buck-switch duty cycle of 5%. If the clock frequency is 300 kHz with a period of 3.3 μsec, the required on-time for the buck switch is only 166 nsec. Therefore, during each cycle, the buck switch must turn on, the ramping buck-switch current must be measured and level-shifted, the PWM comparator must change state, and the buck switch must turn off—all within 166 nsec.

The buck regulator's modulating switch is floating; that is, none of the switch terminals connect to ground. The buck switch's source terminal is at the input potential, V_{IN}, when the switch is on and is at approximately −1V when the switch is off. Measuring the switch current is challenging. The measurement choices are to place a shunt resistor or a current-sense transformer in the buck-switch drain, to make a measurement across the buck switch's on-resistance, or to use a current-mirror circuit coupled to the buck switch. Each of these methods requires a level shift to transpose the measured signal down to the ground reference for appli-

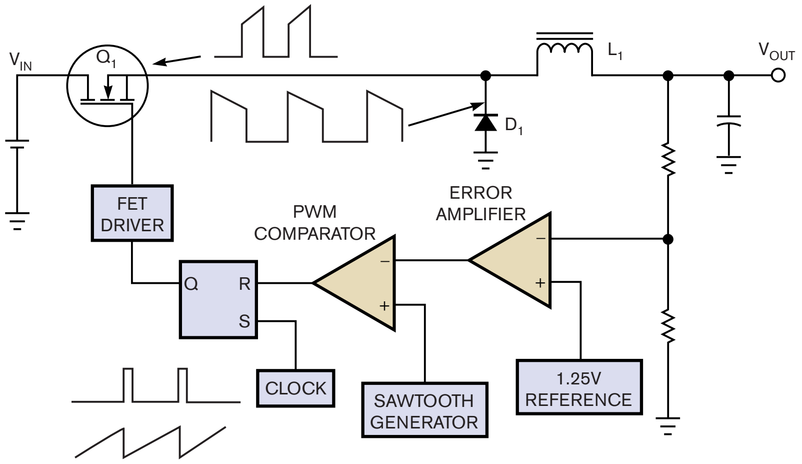

Figure 1 In this voltage-mode buck regulator, the error signal and a modulating ramp form a pulse-width modulator, which controls the buck switch.

cation to the PWM comparator. Even with the best design practices, the level-shift circuit inserts a significant propagation delay. Higher input-voltage applications exaggerate this delay.

Even if you can design a fast, accurate current-measurement circuit and a level shifter, numerous challenges remain. When the buck switch turns on, the free-wheel diode, D_1, turns off. To turn off the diode, an appreciable amount of reverse charge flows during the recovery time in the form of a reverse-recovery current. This diode's reverse current also flows through the buck switch, causing a leading-edge current spike and an extended ringing period. This spike can cause the PWM comparator to trip prematurely and cause erratic operation. The most common approach to solving this problem is to add filtering or leading-edge blanking to the current-sense signal. This blanking and filtering further limit the minimum controllable buck-switch on-time.

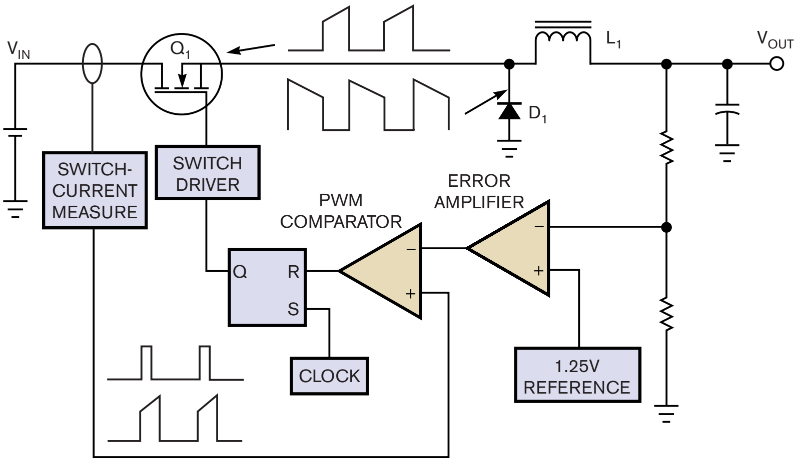

Figure 2 The principal difference between this current-mode regulator and the voltage-mode circuit is in the source of the modulating ramp. In this circuit, the ramp voltage is proportional to the buck-switch voltage.

EMULATED CURRENT-SENSE SIGNAL

An alternative approach to measuring the actual current flowing through the buck switch is to develop a signal that emulates the buck-switch current without making an actual current measurement. The three main current waveforms in a buck regulator are the buck-switch current, the free-wheel-diode current, and the inductor current. The buck-switch and the diode currents sum to form the inductor current (**Figure 3**). Taking a closer look at the characteristics of the buck-switch-current waveform, you can see that the signal breaks down into two parts—a base pedestal and a ramp. The pedestal represents the minimum inductor-current value over the switching cycle. The inductor current is at its minimum the instant the free-wheel diode turns off, just as the buck switch turns on. In each switching cycle, the buck switch and the diode have the same minimum-current value, which occurs when the inductor current is at its lowest value. Taking a sample-and-hold measurement of the free-wheel-diode current just before the buck switch turns on can capture the pedestal-level information.

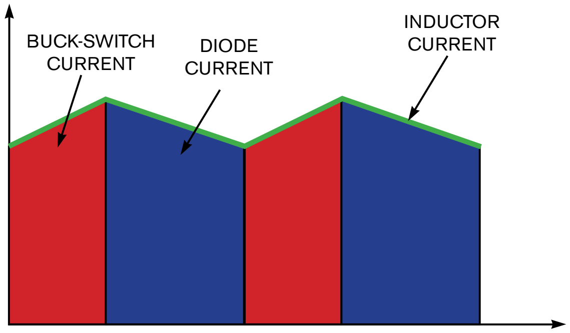

Figure 3 The three main current waveforms in a buck regulator are the buck-switch current, the free-wheel-diode current, and the inductor current. The buck-switch and the diode currents sum to form the inductor current.

The other part of the buck-switch-current signal is the ramp. When the buck switch turns on, the voltage across the output inductor is the difference between the input, V_{IN}, and the output, V_{OUT}, voltages. This voltage difference forces a positively ramping current through the inductor and the buck switch. The ramping current's slope is equal to: $di/dt=(V_{IN}-V_{OUT})/L$. A voltage-controlled current source, I_{RAMP}, and a ramp capacitor, C_{RAMP}, can create an equivalent signal.

The slope of the rising voltage across a capacitor, which current source I_{RAMP} drives, equals $dv/dt=I_{RAMP}/C_{RAMP}$. If the difference between the input and the output voltages controls the current source, the slope of the capacitor-ramp voltage equals $dv/dt=K\times(V_{IN}-V_{OUT})/C_{RAMP}$, where K is the current-source scale factor.

Figure 4 shows a practical controller that emulates the buck-switch-current signal and uses that signal for CM control. The top portion of the diagram shows the normal buck-regulator power-switching components. The free-wheel diode's anode connects to ground through the controller. A small-value current-sense resistor and amplifier measure the diode current. The combined sense-resistor/amplifier scale factor is 0.5V/A. A sample-and-hold circuit captures the diode-current minimum value just before the buck switch turns on. Sampling each cycle, this circuit captures the pedestal portion of the emulated buck-switch current-sense signal.

CONTROLLED CURRENT SOURCE

The controller also senses the input and output voltages. The difference between these two signals controls a current source. This current source charges the external ramp capacitor. In each cycle, when the buck switch turns on, the capacitor voltage rises linearly. When the buck switch turns off, the capacitor rapidly discharges and shunts the current source to ground. The current-source scale factor is: $I_{RAMP}=(5\times10^{-6}\times(V_{IN}-V_{OUT}))$. The desired overall scale factor for the emulated ramp signal is

0.5V/A. For proper operation, set the ramp-capacitor value proportional to the output-inductor value. A good starting point is to select $C_{RAMP}=L\times10^{-5}$, where the units of L are henries and those of C_{RAMP} are farads. Using this value scales the capacitor-ramp voltage to half the output-inductor current, consistent with the sample-and-hold-circuit scale factor. The derivation is as follows. Set inductor slope equal to the capacitor slope:

$$\frac{di}{dt}=\frac{dv}{dt}.$$

$$\frac{(V_{IN}-V_{OUT})}{L}=\frac{5\times10^{-6}\times(V_{IN}-V_{OUT})}{C_{RAMP}}.$$

$$C_{RAMP}=L\times5\times10^{-6}.$$

For a scale factor of 0.5V/A, the value of C_{RAMP} is $L\times10^{-5}$.

The final step in generating the emulated buck-switch-current signal is to sum the pedestal information (from the sample and hold) with the ramp-capacitor-voltage signal. **Figure 5** shows the final summed waveform. This signal is now ready for use in the PWM comparator, as well as in the current-limit comparator.

For applications that operate with duty cycles greater than 50%, CM-controlled circuits are subject to subharmonic oscillation. By adding another fixed-slope voltage-ramp signal (slope compensation) to the current-sense signal, you can avoid this oscillation. Referring to the ramp-generator circuit, an additional, fixed, 25-µA offset current provides some fixed slope to the capacitor-voltage-ramp signal. Very-high-duty-cycle applications may require additional slope. For these applications, you can decrease the ramp-capacitor value to increase the ramp slope and prevent subharmonic oscillation.

You can accomplish output-overload protection by either clamping the error signal or providing a dedicated current-limit comparator. This type of overload protection, cycle-by-cycle current limiting, yields an almost-immediate response, which protects the buck switch. Virtual CM has an added benefit of capturing the pedestal information before the buck switch turns on. During extreme overloads at high input voltage, the buck switch skips cycles, preventing possible runaway current conditions.

A CM-controlled regulator's control-to-output transfer function has a single-pole characteristic despite an output stage that

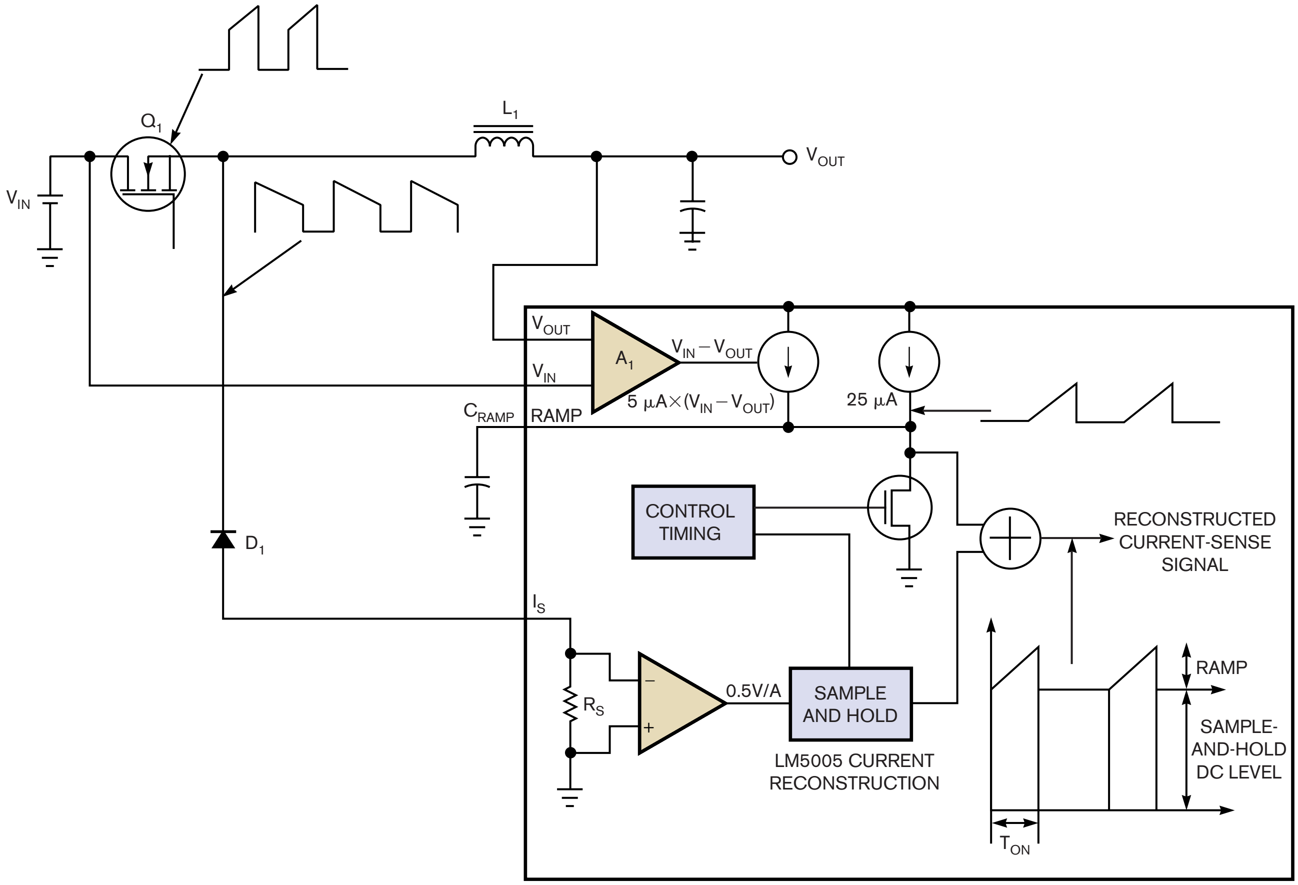

Figure 4 This practical controller overcomes current-mode regulators' noise susceptibility by emulating the buck-switch-current signal and using the emulated signal for current-mode control.

comprises two main elements, L and C. The characteristic has only one pole because there are two control loops: a voltage loop, which keeps the output voltage constant, and an inner current loop. The current loop monitors and controls the inductor current, forcing the inductor to act as a constant-current source programmed by the voltage loop. Because the inductor behaves as a constant-current source, the control-to-output transfer function has only one pole, which the output capacitor, C_O, and load resistance, R_L, establish. This pole occurs at a frequency of $f_P=1/(2\pi C_O R_L)$. There is also a zero at $f_Z=1/(2\pi C_O R_{ESR})$ because of the output capacitor's ESR (equivalent series resistance). Hence, the required error-amplifier compensation comprises an integrator for good line/load regulation and low output impedance; a zero to cancel the load pole; and if necessary, a pole to cancel the ESR zero.

During light loading, the inductor current decays to zero for part of the cycle. This light-load mode is referred to as discontinuous operation. An advantage of CM control is that no stability problems exist in the discontinuous-conduction mode because the regulator remains a single-pole, single-zero system under both continuous and discontinuous operating modes. Another advantage of CM control is inherent feedforward, because the inductor-current ramp is a function of the input voltage. Any input-voltage change immediately changes the modulating-ramp slope and corrects the duty cycle without the need for the regulation loop to react—that is, to feed forward.

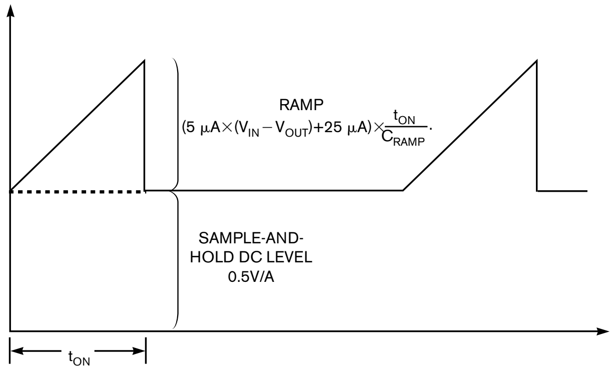

Figure 5 The final summed waveform is ready for use in the pulse-width-modulator comparator, as well as in the current-limit comparator.

TEST RESULTS

A buck regulator with an input-voltage range of 7 to 75V, an output voltage of 5V, and a 2.5A current capability demonstrates the emulated-CM-control operation (**Figure 6**). The 300-kHz operating frequency represents a good trade-off between efficiency and component size. A conventional Type II pole-zero compensation network commonly used for CM control accomplishes loop compensation. The resulting loop-bandwidth-crossover frequency is 20 kHz. At 75V input, the step-down ratio is 15-to-1, requiring a buck-switch on-time of 222 nsec in continuous-mode operation. Measured, stable on-times of approximately 100 nsec occur during discontinuous-mode operation.

Emulated CM control applies not only to buck regulators, but also to isolated buck-regulator-based topologies, such as forward, half-bridge, and full-bridge.**EDN**

AUTHOR'S BIOGRAPHY

Robert Bell is the applications-engineering manager for National Semiconductor's Design Center (Phoenix), where he has worked for four years. The center's products include next-generation PWM power controllers, gate drivers, and hot-swap and load-share controllers. Before joining National Semiconductor, Bell designed power converters for military and space applications. In his spare time, he enjoys hiking, camping, tennis, and travel.

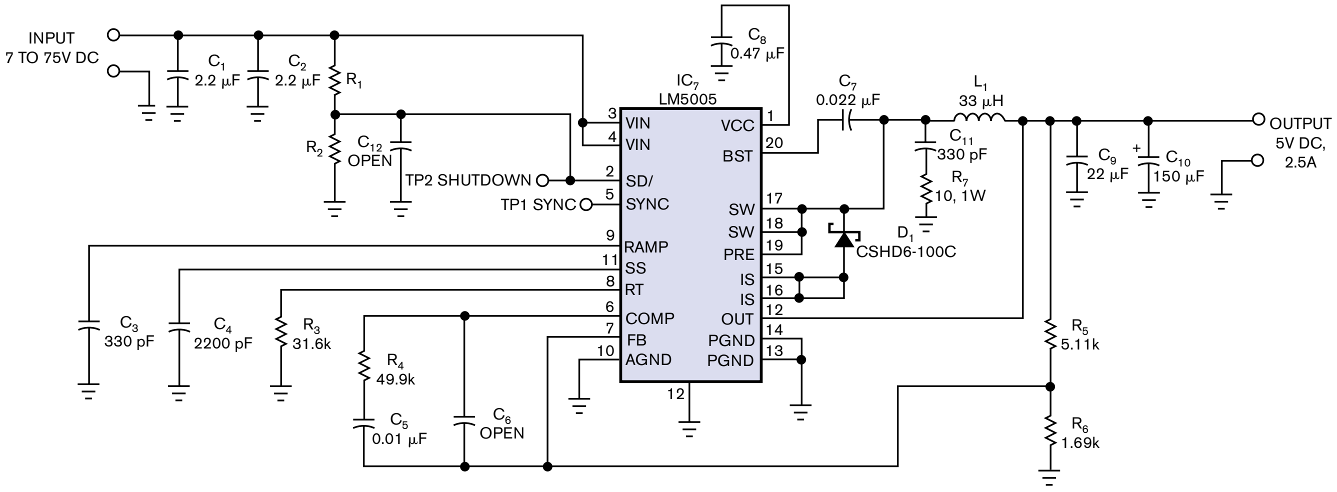

Figure 6 During discontinuous-mode operation, this regulator achieves stable on-times as low as approximately 100 nsec.