Synchronous buck regulator design using the TI TPS5211 high-frequency hysteretic controller

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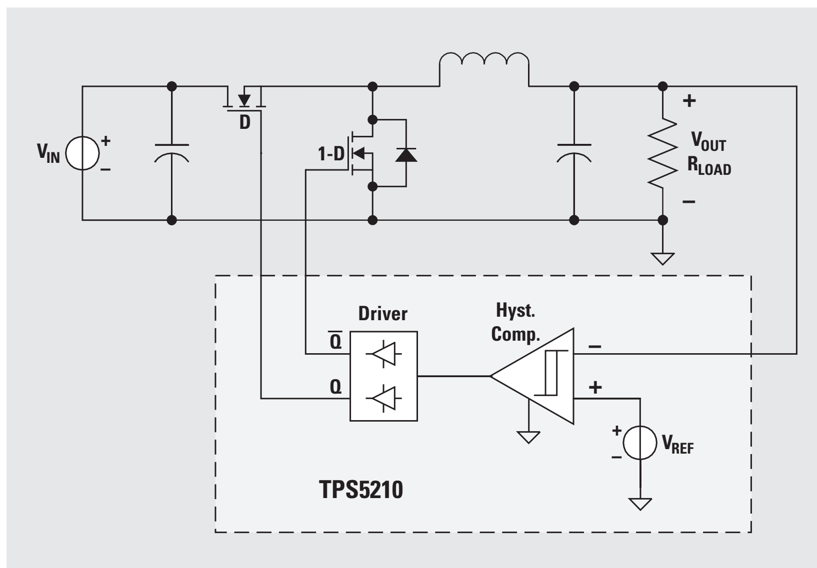
Hysteretic mode control, which is implemented in TI's TPS5210 family of controllers, has become very popular for use in fast-transient-response power supplies for microprocessors and DSPs or other high-slew-rate transition loads, because it is a very simple solution with excellent dynamic characteristics. An example of a synchronous buck converter using a hysteretic controller is shown in Figure 1.

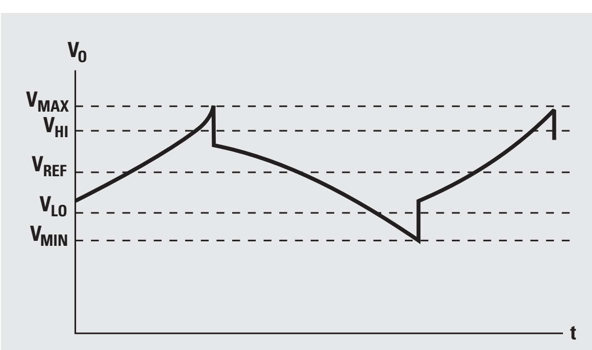
A hysteretic controller is a self-oscillation circuit that regulates output voltage by keeping it within a hysteresis window set by a reference voltage regulator and comparator. The actual output ripple voltage is the combination of the hysteresis voltage, overshoot caused by internal delays, and the output capacitor characteristics. Figure 2 shows a hysteresis window voltage (V_{HI} to V_{LO}) and the output voltage ripple (V_{MAX} to V_{MIN}).

Figure 1. Hysteretic control approach with a fast feedback loop



Unlike other control approaches, this device does not have a slow feedback loop and reacts on the load current transient in the same switching cycle that the transient occurs. The transient response time depends only on delays in the hysteretic comparator and drive circuitry. The high-frequency noise filter in the input of the comparator also adds some delay. These delays depend on the level of selected technology and therefore, the hysteretic control has the fastest transient response compared to other control approaches. The other advantage of the hysteretic controller is that its duty cycle covers the entire range from zero to one. It does not have any restrictions on the power switch conduction interval that most of the other control approaches have. Because of that, the recovery time of the output voltage after the load current transient is shortest. Excellent dynamic characteristics of hysteretic control result in smaller size and lower cost of output filtering.

Figure 2. Output ripple of hysteretic regulator



The switching frequency for this control approach depends on the output filter characteristics, input and output voltage, hysteresis window, and internal delays. The simplified equation for the switching frequency is

$$f_S \cong \frac{[V_{OUT} \times (V_{IN} - V_{OUT}) \times ESR]}{(V_{IN} \times L \times \text{Hysteresis window})},$$

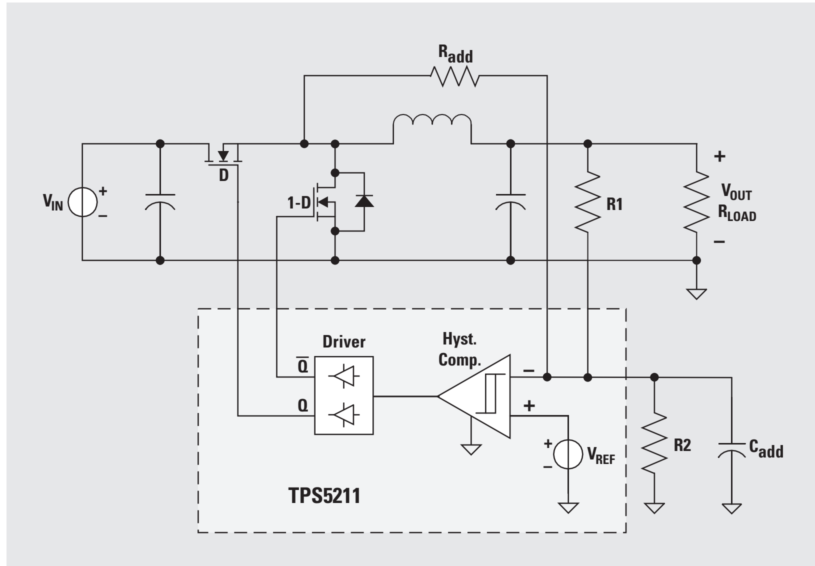
where ESR is equivalent series resistance of the output capacitor and L is the output inductor value.

For high-frequency operation (>400 kHz) the hysteresis window might be decreased, but frequency variation becomes significant because of output capacitor parasitics, delays, and noise influence. The other problem relates to the type of output capacitor. One can see from the switching frequency equation that it is proportional to ESR. This means that using an "ideal" capacitor with very low ESR (like connecting many ceramic capacitors in parallel) is a problem because the operating frequency becomes relatively low. The TI TPS5211 hysteretic controller overcomes these problems.

TPS5211 description

A functional block diagram of the TPS5211 controller is the same as for the TPS5210. The differences relate to parameters and characteristics specified for higher-frequency operation (up to 700 kHz). Also, there are a few external components that have to be added to a dc-to-dc converter. A simplified diagram of an asynchronous buck converter using the TPS5211 hysteretic controller is shown in Figure 3.

Figure 3. Synchronous buck converter with TPS5211 hysteretic controller



The additional R_{add} - C_{add} circuitry is added to the dc-to-dc regulator. R_{add} is connected between the input of the hysteresis comparator and the midpoint of the power switches. C_{add} is connected between the input of the comparator and the ground. This R_{add} - C_{add} circuitry forms an additional ramp signal through the input of the hysteretic comparator. The two signals are summed through the inputs of the comparator—the ramp signal from R_{add} - C_{add} circuitry and the signal from the output of converter. By proper selection of R_{add} and C_{add} one can get the amplitude of the additional ramp signal which is greater than the output ripple of the converter. As the result, the switching frequency is higher while the output ripple becomes lower. The switching frequency depends on R_{add} - C_{add} values and does not depend on the output filter characteristics including the ESR, ESL, and C of the output capacitor. The simplified equation for the switching frequency of the TPS5211 controller is

$$f_S = 1/T_S,$$

$$T_S \cong \frac{V_{IN} \times R_{add} \times C_{add} \times \text{Hysteresis window}}{V_{REF} \times (V_{IN} - V_{REF})} + T_{DELAY} \times \left(2 + \frac{V_{REF}}{V_{IN} - V_{REF}} + \frac{V_{IN} - V_{REF}}{V_{REF}}\right),$$

where T_{DELAY} characterizes comparator and drive circuitry delays.

At the same time, the dc feedback signal from the output of the converter controls the dc level of the output voltage, which is defined by

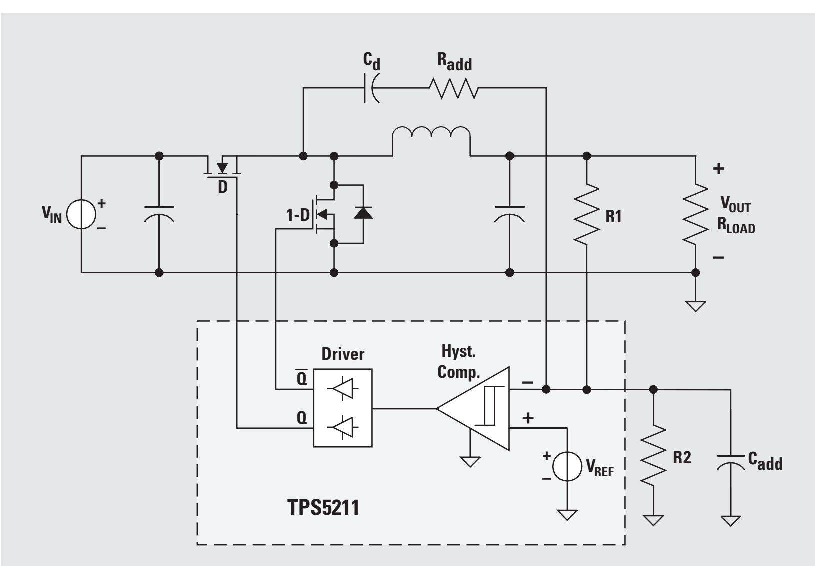
$$V_{OUT} = V_{REF} \times \left[1 + \frac{R1 \times R_{add}}{R2 \times (R1 + R_{add})}\right].$$

One can see that the output voltage V_{OUT} depends on the additional resistor R_{add}. To avoid this dependence, the dc decoupling capacitor C_d can be added in series with R_{add} as shown in Figure 4. The value of this capacitor has to be much higher than C_{add}.

With the decoupling capacitior C_d, the output voltage is defined by

$$V_{OUT} = V_{REF} \times \left(1 + \frac{R1}{R2}\right).$$

Figure 4. Synchronous buck converter with dc decoupling capacitor C_d



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The switching frequency does not depend on output capacitor characteristics, so high-frequency, low-cost ceramic or film capacitors can be used in this dc-to-dc converter, maintaining the same excellent load current transient response characteristics.

The R_{add} - C_{add} circuitry adds feed-forward properties to the controller, which also improves the input voltage transient response characteristics. The design aspects, which are specific for the TPS5211 controller (compared to the TPS5210), are described in this application note. The remaining design topics, including the power-train components selection, setting of the hysteresis window, active voltage droop positioning, and overcurrent protection limit are described in the application information section of the product datasheet.[1]

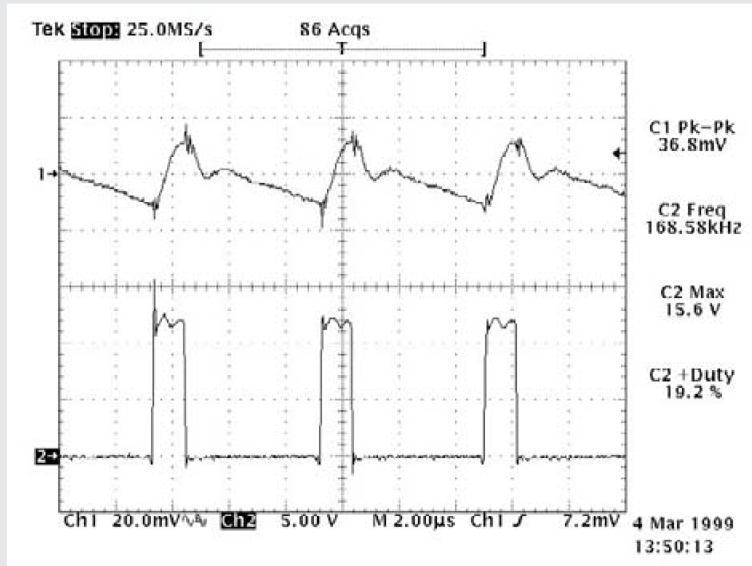
Comparison of TPS5210 and TPS5211 controllers and their application areas

The output voltage ripple and power-switches midpoint waveforms of the same dc-to-dc converter using the TPS5210 or TPS5211 controllers are shown in Figure 5. The converter using the TPS5210 is optimized for low power losses and high efficiency and operates at 168 kHz, while the same converter using the TPS5211 operates at 450 kHz. In spite of that, the hysteresis window has been set at the same level (20 mV for both controllers) and the peak-to-peak output ripple is 36.8 mV for the TPS5210 and 9.6 mV for the TPS5211. The much lower output ripple for a converter using the TPS5211 does not depend on a hysteresis window.

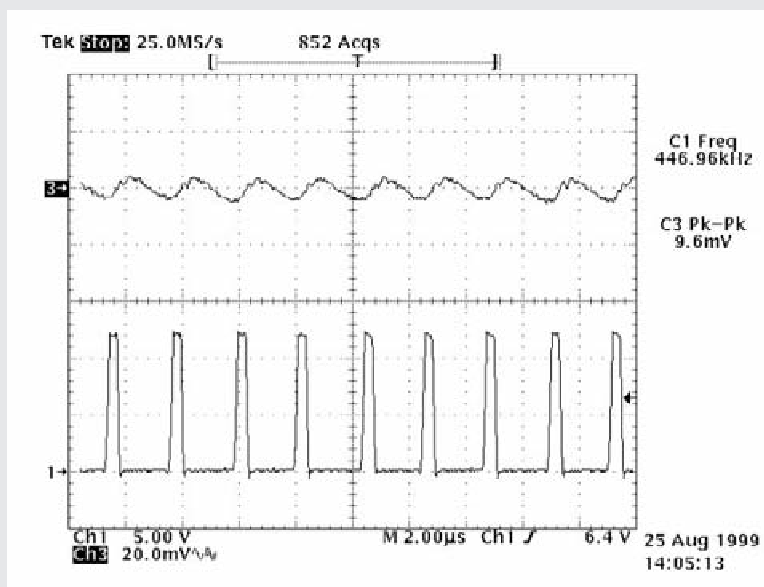
The load current transient response waveforms shown in Figure 6 illustrate that the TPS5211 has the same excellent load current transient response characteristics as the TPS5210.

Both hysteretic controllers have excellent load current transient response characteristics compared with other types of controllers having slow feedback loops like the PWM voltage and current modes. There are application areas where each hysteretic controller has advantages over the other. There are trade- offs relative to which controller is preferable for a specific application and customer requirements. Table 1 compares application areas for TPS5210 and TPS5211 controllers.

Figure 5. TPS5210 and TPS5211 switching waveforms



(A)



(B)

Output voltage ripple and power-switches midpoint waveforms of the same converter using (A) the TPS5210 controller and (B) the TPS5211 with external R_{add} - C_{add} circuitry

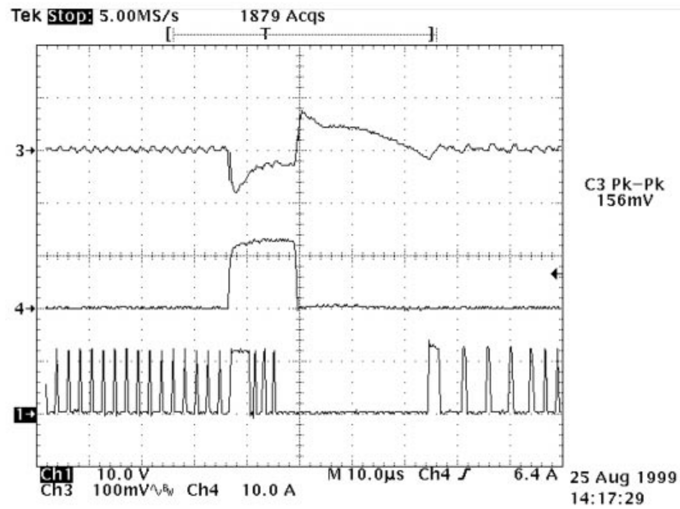
Conclusion

The modified hysteretic control approach using TI's TPS5211 controller is described. It is shown that adding simple external circuitry that applies an additional ramp signal to the hysteresis comparator input significantly changes the properties of the dc-to-dc regulator. Its switching frequency becomes independent of output filter characteristics and parasitics, while the output ripple is lower than the hysteresis window. A high switching frequency along with fast transient response enables tight supply voltage tolerance requirements for the next-generation microprocessors and DSPs with a 50–60% lower cost for output filtering.

References

1. http://www.ti.com/sc/docs/products/msp/pwrmgmt/index.htm
2. D. Briggs, R. Martinez, R. Miftakhutdinov, and D. Skelton, "A Fast, Efficient Synchronous-Buck Controller for Microprocessor Power Supplies," *Proc. of High Frequency Power Conversion Conference* (1998), pp. 182-198.
3. "Designing Fast Response Synchronous Buck Regulator Using the TPS5210," Application Report, Texas Instruments Inc., March 1999, literature number SLVA044.
4. "TPS5211 High Frequency Programmable Synchronous-Buck Regulator Controller," Texas Instruments Inc., September 1999, literature number SLVS243.

Figure 6. Output voltage transient response



The output voltage transient response of a converter with the TPS5211 controller. The load current has a 14-A step with a slew rate of 30 A/µS.
Ch.1: Drain-source voltage (10 V/div.)
Ch.3: Output voltage (100 mV/div.)
Ch.4: Load current (10 A/div.)

Table 1. Comparison of the TPS5210 and TPS5211 and their applications

CONTROLLER	TPS5210	TPS5211
Switching frequency (kHz)	100–400	400–700
Frequency variation	Depends on output filter characteristics	Independent of output filter and easy to evaluate
Output current (A)	Up to 40	Up to 18–20 (can be increased in multiphase configuration)
Efficiency (%) (Depends on frequency, output current, V_{IN}, V_{OUT}, components, etc.)	85–95	75–85
Input and output filter	Requires bulk electrolytic capacitors, especially if I_{OUT} > 12 A, and large inductor	Surface-mount ceramic and POSCAP type capacitors and 40–65% smaller inductors
Components cost	20–40% lower for TPS5211	
System cost including reliability, power losses, cooling, etc.	Can be estimated only during design for a given specific application	
Layout and design	Special attention to the noise-sensitive places like hysteresis comparator and sample-hold circuitry	Special attention not to exceed frequency and I_{CC} limits. High-frequency dc-to-dc converter design rules.
Compatibility with the whole system	For high-current applications it is difficult to meet high-density, minimum-size requirements	A dc-to-dc converter can be placed close to microprocessor or DSP to decrease the number of decoupling capacitors

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