Internally Compensated Advanced Current Mode (ACM)

Texas Instruments

New low-noise DC/DC control mode benefits enterprise rack server and hardware accelerator applications that need fast transient response as well as active antenna systems (AAS) requiring fixed-frequency modulation and synchronization.

DC/DC control modes fall into two categories based on their methods of modulation:

- Constant on time (COT), where the on time is a function of V_{IN}, V_{OUT} and switching frequency (switching frequency can vary when responding to a load- or line-transient event).
- Fixed frequency, offered by either voltage or current modes, where a preset clock oscillator determines the switching frequency, but the on-time pulse can vary with respect to the control loop during a load- or line-transient event.

Each DC/DC control mode offers certain benefits, with associated trade-offs. For example, the server market prefers COT because it offers a fast transient response with no compensation requirement, but at the cost of higher electromagnetic interference (EMI)/noise. The telecommunications market prefers voltage/current mode because it offers low EMI/noise via true fixed frequency, but at the cost of a slower transient response. Voltage- or current-mode control with a fixed-frequency modulator also requires Type II/III compensation circuitry to achieve acceptable bandwidth and phase margins for stability, increasing solution complexity, size and cost.

While external compensation for voltage or current mode has been extensively studied, with several application notes and data sheets offering very detailed recommendations for designing and optimizing the control loop, a control mode that eliminates the need for external compensation would facilitate a simpler, more dense and cost-effective solution. Plus, the ability to synchronize to an external clock for true fixed frequency while still offering a fast transient response would give traditional COT users low EMI/noise performance.

This white paper introduces a new control topology based on a fixed-frequency modulator without the complicated external compensation design, while having very fast loop response to a load-transient event. The new topology combines the best of COT and voltage/current modes while minimizing the respective trade-offs and saving board space, while its ease of use shortens the production cycle.

Traditional fixed-frequency control modes

Voltage-mode control employs a single voltage loop with a fixed clock ramp. A relatively complex Type III network with two poles and two zeros compensates the loop to boost to a higher than 90-degree phase margin at inductor-capacitor (LC) frequency. Unlike voltage-mode control, current-mode control needs a secondary inner current loop, which samples the inductor current information for the pulse-width-modulation (PWM) comparator. This inner current loop transforms the inductor into a voltage-controlled current source that splits the LC double-pole “peak” into two distinct poles: one at DC/low frequency and one at high frequency. By sufficiently separating the poles, you can ignore the high-frequency pole. With this special characteristic, current-mode control effectively becomes a single-pole system. The external voltage loop employs a simpler Type II compensation network to boost the phase margin up to 90 degrees.

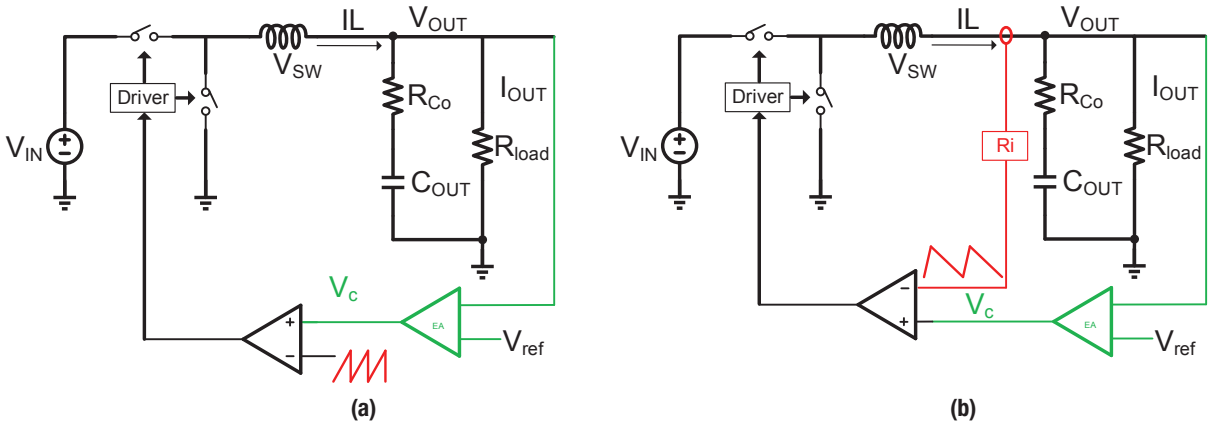


Figure 1. *Control structure: voltage-mode control (a); current-mode control (b).*

Figure 1 shows the basic control structure for the two most common fixed-frequency control schemes. There is a voltage loop for voltage mode and a voltage loop plus an inner current loop for current mode.

Figure 2 shows the Type III and Type II compensation networks. While most power design engineers are familiar with designing the compensation by tweaking the external R_S and C_S, the complexity is hardly negligible. Changing design parameters will require new compensation designs to meet new specifications. And with increasing power rails on an already congested system board, higher power-density requirements make a conservative approach to additional components more and more critical.

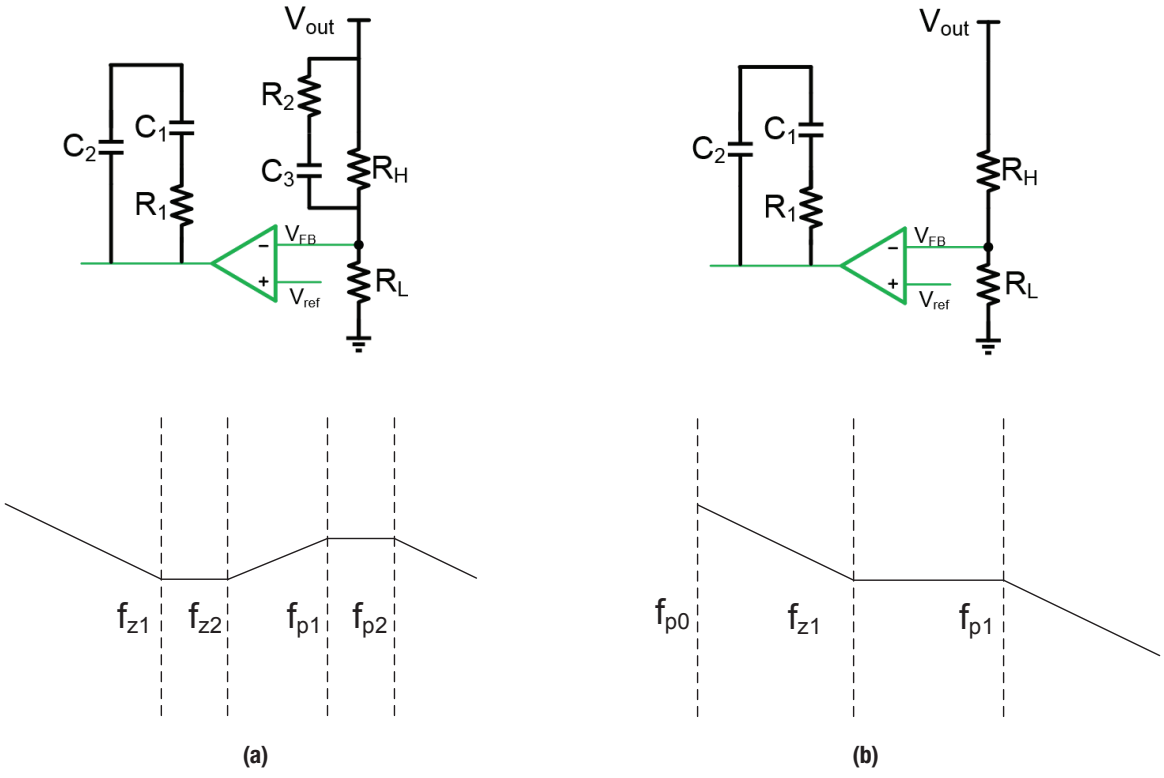


Figure 2. *Type III compensation for voltage-mode control and compensation curve (a); Type II compensation for current-mode control and compensation curve (b).*

Current-mode control variations and pseudo current-mode control

Traditional current-mode control implements current information in three ways: peak current mode (PCM), valley current mode (VCM) and average current mode. PCM is the most common and widely used, as shown in **Figure 3a**. It is regulated by comparing inductor peak current information with control voltage, and when duty cycle is larger than 50 percent, it requires slope compensation. In comparison, VCM as shown in **Figure 3b**, is regulated by comparing valley inductor current information with control voltage, and it requires slope compensation when duty cycle is smaller than 50 percent. PCM provides a relatively fast transient response (compared to average current mode) and has inherent cycle-by-cycle current protection.

A major challenge of PCM – especially in high-frequency operation – is the minimum on time required to properly sense the current information to overcome large noise compared to the small sensed signal. Furthermore, the current sensing and slope compensation circuitry bandwidth needs to be very high in order to process the sensed current information and support megahertz switching frequencies.

Figure 3c shows the modulation scheme of COT, which is a pseudo current mode. It uses the equivalent series resistance (ESR) and inductor current ripple to create a pseudo inductor current ramp, and provides almost instantaneous transient response compared to traditional PCM. COT control can maintain a relatively constant switching frequency during steady state. When a transient occurs, the switching frequency will increase during load step up and decrease during load step down to help with the transient response, with the on time fixed by the input and output voltage for a given switching frequency. Better transient performance doesn't come for free, however. The large switching-frequency variation and relatively larger jitter introduce EMI, which is a concern for EMI-sensitive applications like those in the telecom industry.

ACM control

The new control topology is based on the PCM control scheme. It keeps all of the good features from traditional PCM and COT control while reducing the drawbacks.

The key features and benefits of ACM control include:

- True fixed-frequency modulation: better jitter performance and predictable frequency for easier EMI filter designs.
- Emulated peak current information, plus adequate DC current information to achieve the pole-splitting effect, more stability with a higher loop bandwidth and more phase margin.

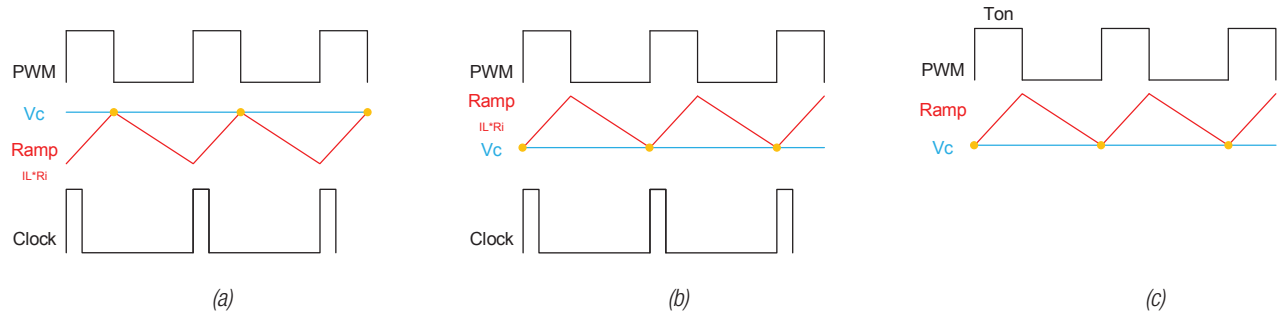


Figure 3. *Control scheme waveform: PCM (a); valley current mode (b); COT (pseudo current mode) (c).*

- A larger signal-to-noise ratio to achieve multi-megahertz switching frequency, while a high emulated ramp-voltage amplitude provides very good noise immunity.
- Integrated internal compensation covering a wide stability range (for F_{SW}, load current, etc.) for high-current applications. Internal compensation eliminates the need for an external compensation network, increases ease of use through a greatly simplified design procedure, and saves components and board space.

Figure 4a shows the simplified ACM system structure for a buck converter, which is similar to traditional current mode. The error between the output feedback voltage and internal reference voltage passes through a gain block and generates the control signal. The gain is well-defined by R_{n1} and R_{n2}, as shown in **Figure 4b**. **Equation 1** calculates the control voltage, while **Figure 4c** shows the V_{FB} to V_{ctrl} waveform.

$$Vcrtl = \frac{R_{n2} + R_{n1}}{R_{n2}}\left(V_{REF-INT} - V_{FB}\right) + V_{COM} \quad (1)$$

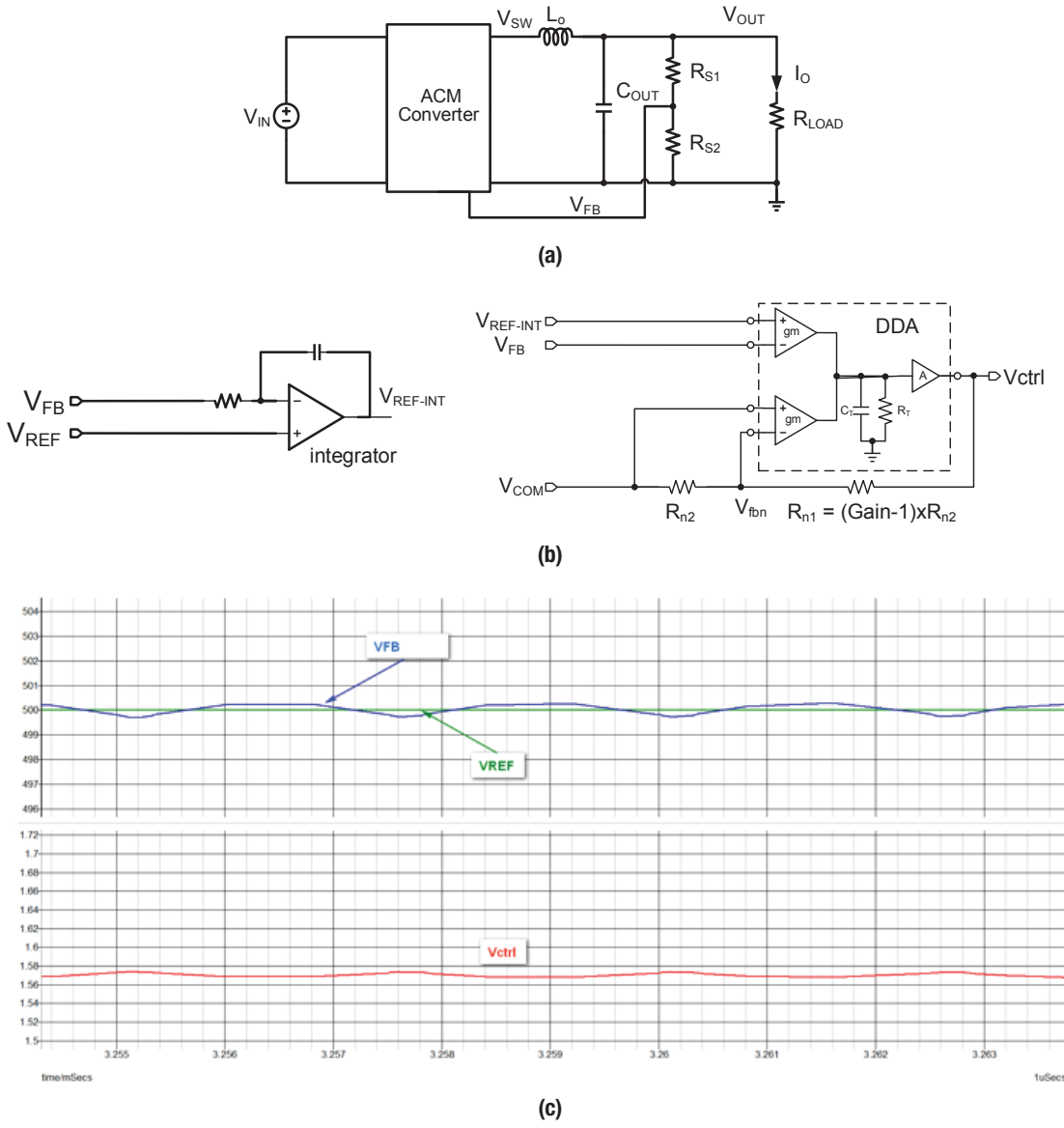


Figure 4. *Simplified buck converter with ACM (a); circuit block for control voltage (b); simulation waveform from VFB to control voltage (c).*

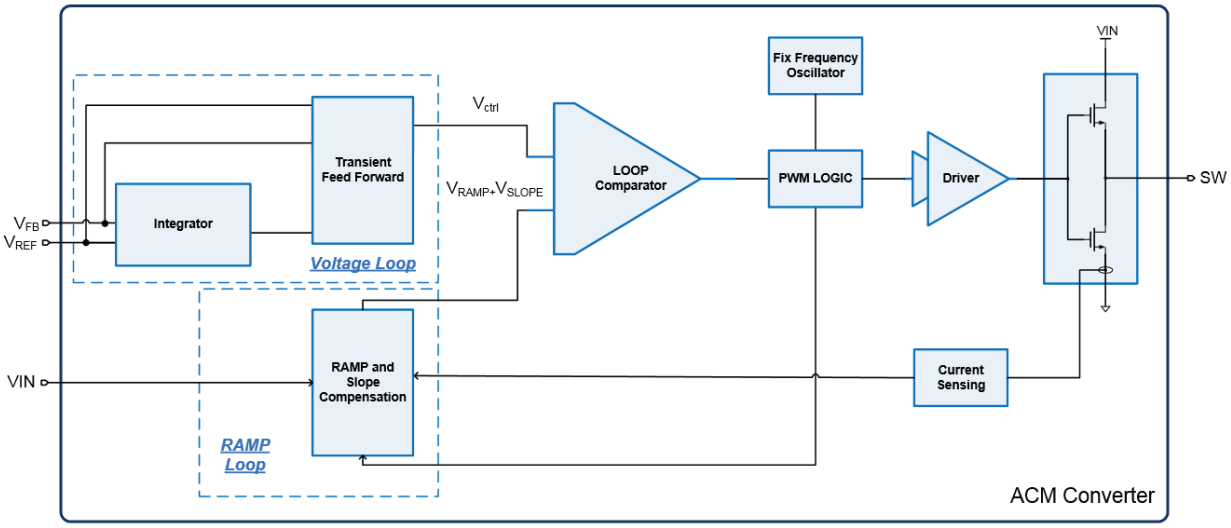


Figure 5. *ACM control block diagram.*

Figure 5 shows the simplified control block of ACM. The control core consists of a voltage loop that generates the control voltage with true output-voltage error information, and a ramp loop that includes the pseudo inductor current information along with a small portion of the DC current information. For the voltage loop, an integrator first eliminates any DC error; then an accurately programmed gain and level shifter amplifies the signal to generate the control signal. Adding a transient feed-forward block improves the transient response. A ramp loop processes the input voltage and PWM signal together with slope compensation to create the emulated peak current signal. The ramp voltage is big enough that it's less sensitive to noise.

The loop comparator shown in **Figure 5** adds up all of the outputs from the voltage and ramp loop. Each PWM cycle terminates when the sum of the positive inputs is higher than the sum of the negative inputs. In addition to the control voltage, the DC current information from the low-side FET is sensed and held, and then fed back to the loop comparator to optimize the damping of the Q factor of the inductor to mitigate the double-pole peak. The PWM logic block generates a PWM signal according to a preset fixed-frequency clock and the output of loop comparator.

Figure 6 shows the control signal waveforms. If you program the ramp generator and slope compensation properly, V_{SLOPE} will always equal half of the downslope of the ramp voltage, which provides the best slope compensation without sacrificing too much on transient performance.

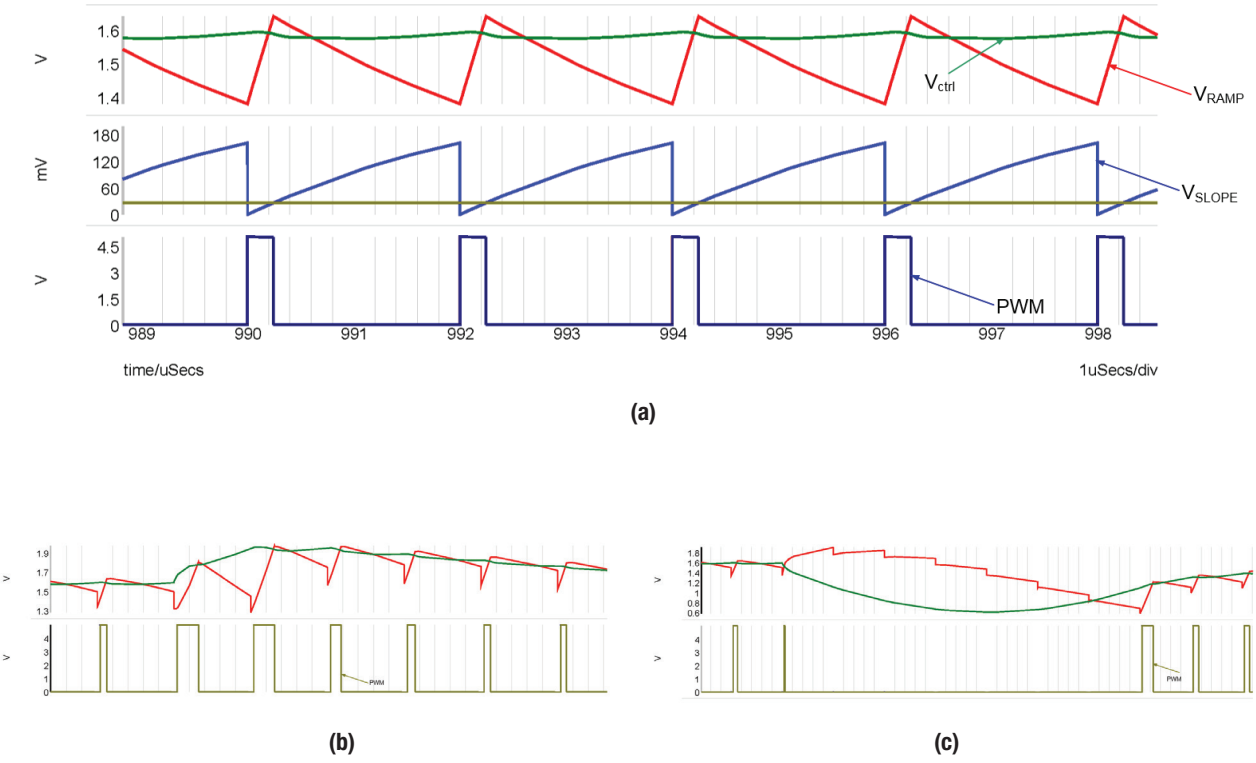


Figure 6. *Key control signal waveforms: steady state (a); load step up (b); load step down (c).*

The internal DC current feedback provides an additional benefit to the loop during transient: with just enough DC current information, it helps optimize the control voltage. This makes a slow integrator for error correction possible, while helping with damping the double-pole peak to reduce the phase dipping at the LC resonant frequency. **Figure 7** shows silicon test data with proper amounts of DC information. Too much DC information will cause a slower transient recovery time.

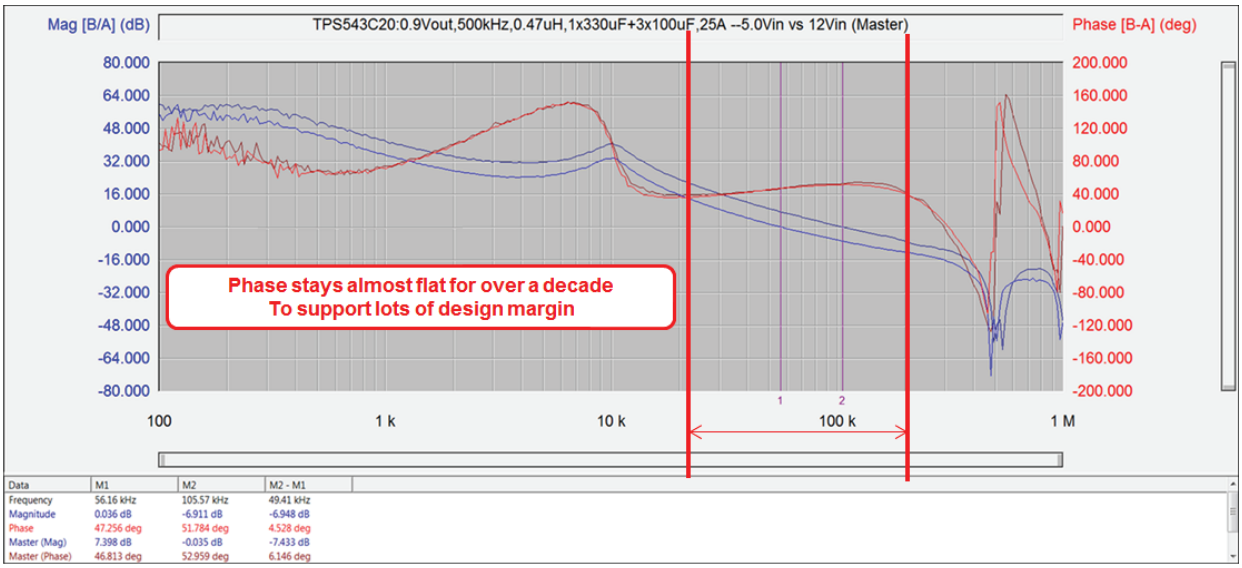
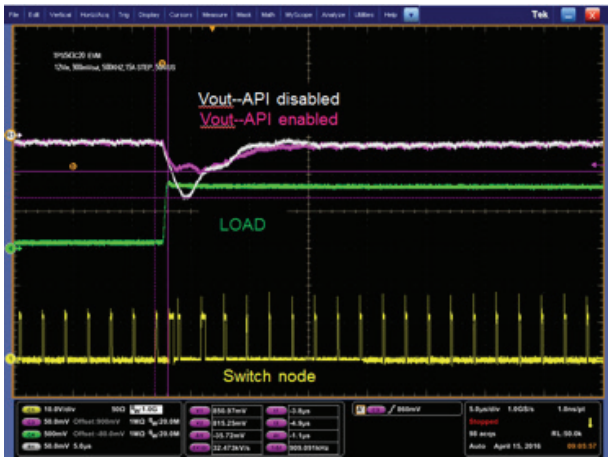


Figure 7. *AC response with DC current information.*

Figure 8 shows the transient response for the TI TPS543C20 with ACM control implemented. During load step up (**Figure 8a**), the best the loop can do for fixed-frequency control is extend the on time for the first pulse after load step up. During load step down (**Figure 8b**), the best it can do is to terminate the on pulse after load release. You can further improve transient performance by other nonlinear methods such as asynchronous pulse insertion and body brake, as shown in **Figure 8c** and **Figure 8d**.

(a)

(b)



(c)

(d)

Figure 8. *Load step-up response (a); load step-down response (b); comparing asynchronous pulse insertion/body brake enable and disable (c) and (d).*

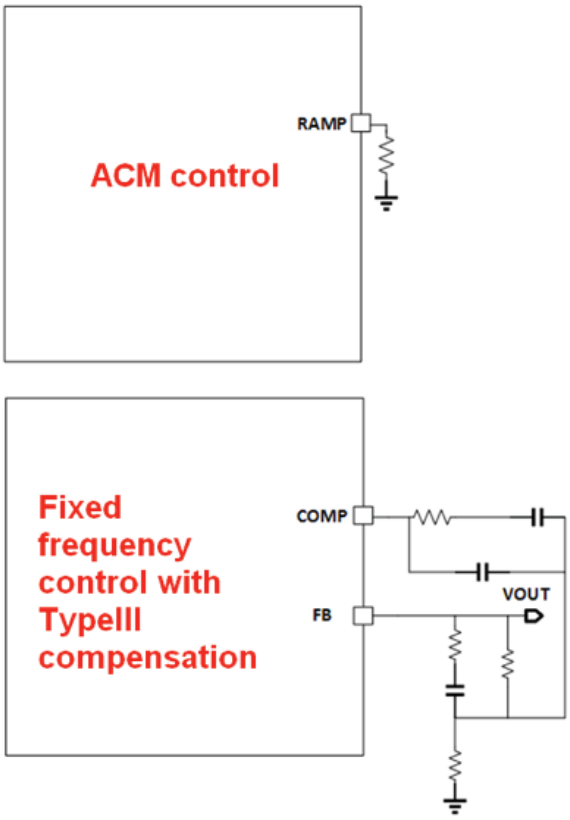


Figure 9. *Compensation example for ACM control and traditional control, which requires Type III compensation.*

ACM only needs a single optimizing resistor to ground to optimize for LC, frequency and design variations, whereas traditional current or voltage modes require more extensive Type II or Type III compensation networks, which increase design complexity and consume more board space. **Figure 9** compares the compensation needed for ACM with a fixed-frequency control scheme.

Most existing true-fixed-frequency/no-external-compensation converters are based on traditional PCM by simply moving the external compensation to inside the circuitry, with the internal compensation designed and optimized to cover a certain application condition (including F_{SW}). If the internal compensation of a traditional PCM needs to cover application cases for a wide-enough stability range, the internal loop and slope compensation will be very difficult to optimize if you need to achieve a fast transient response, especially during large load-current step changes. **Table 1** compares traditional PCM and ACM.

	PCM	ACM
Current sensing	• Difficult high-side FET current sensing in 150ns for megahertz switching-frequency applications. • Direct current resistance sensing needs extra pins.	• Easy DC current information sensing from the low-side FET.
Slope compensation	• Difficult to design/optimize slope compensation with parameter variations: inductor, V_{OUT} and F_{SW}. • Designing a larger slope covers wide application cases, with the penalty of a slower loop response.	• The downslope of the internal ramp is known; the slope compensation is always optimized to be half of the down slope of the ramp.
Noise immunity	• Directly related to the real current ripple and current sensing circuit.	• The ramp amplitude is adjustable to provide enough noise margin and low jitter.
Compensation	• Directly related to the current ripple and DC current information. • Specific system application conditions necessitate redesigning external compensation.	• Ramp amplitude and DC value are controlled separately, and thus easily optimized for different applications. • With DC current information sensed and held, very slow integration is possible for internal compensation.

Table 1. *Comparison of traditional PCM and internal compensated ACM.*

Summary

ACM control is a ramp-based PCM control scheme with an internally generated ramp that achieves true fixed frequency without using external compensation. It provides better transient response than traditional PCM by separately optimizing both the AC and DC portions of the voltage loop and ramp loop.

This control mode provides an optimized solution for applications that require predictable frequency without the need for external compensation. The high-performance 25A TPS543B20 and 40A TPS543C20 step-down converter family is the first to implement ACM. The family features stackability to support up to 80A point of load (POL) and includes internal compensation for ease of use, fixed frequency for low EMI noise and full differential sensing to achieve the best V_{OUT} setpoint accuracy.

References

1. Nowakowski, Richard. "Control-Mode Quick Reference Guide." 2017.

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