Transient Response versus Ripple – An Analysis of Ripple Injection Techniques Used in Hysteretic Controllers

Dilip Mohol, Gitesh Bhagwat, Akshat Garg SVA Power - SPD

ABSTRACT

In this application note we highlight the implications of ripple injection techniques, aimed at minimizing output ripple voltage, on the transient response of a supply. The results help choose a suitable ripple injection technique after striking a balance between the output ripple voltage and the transient response required by the load.

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1 Introduction

Power supply applications that expect ultra-fast transient response along with lower ripple are growing today. So, there is an eminent need to use supplies that offer very fast transient responses, at the same time maintaining the required output voltage ripple. Hysteretic-based feedback in the design of a Buck switch mode supply is popular among customers especially for its simple control scheme. Many modifications have been done by various IC manufactures in the hysteretic control scheme, for example, the Constant On Time (COT) scheme used by TI.

Many techniques aim at injecting ripple in the feedback loop while minimizing the same in the final output voltage as delivered to the load with a good degree of success.

However, this does adversely affect the transient response of the supply, an aspect often neglected by amateur power supply designers.

2 Hysteretic Controllers

Of all the voltage regulator control strategies ever devised, the hysteretic regulator is probably the simplest. This control methodology simply turns a switch on when the output voltage is below the lower reference and turns the switch off when the output rises to a slightly higher reference. The output ripple is, therefore, a direct function of the difference between the upper and lower reference threshold, that is, the hysteresis amplitude.

In Figure 1, the switch is turned on when the feedback voltage falls below the lower threshold and is turned off when the feeback voltage crosses the upper threshold.

This is a simple hysteretic control scheme which only uses the variation or ripple on the output voltage for control. This results in variable frequency operation which is undesirable because of variable frequency of radiated noise resulting in difficult filter design.

2.1 Constant On Time Control Scheme

A solution to this is the COT control scheme.

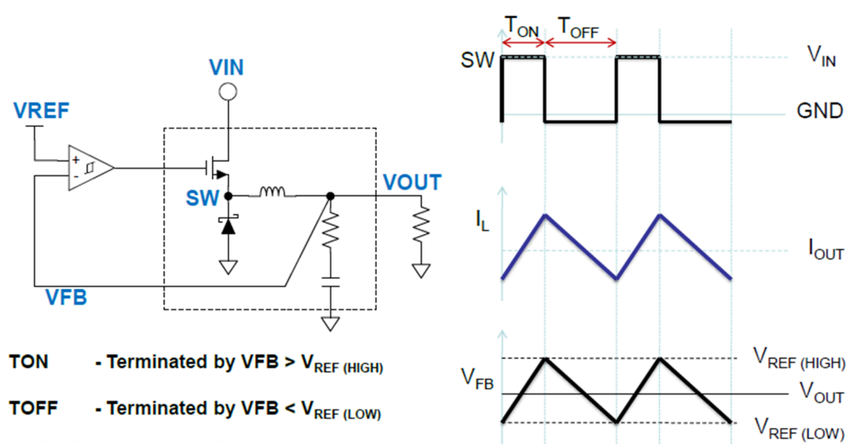


Figure 1. Hysteretic Control Scheme

In the COT scheme, as the name suggests, the ON time of the switch is made fixed (set by an external resistor). Only the off time is determined by when the feedback voltage falls below the lower threshold.

The ON time is given as:

$$T_{ON} = \frac{K \times R_{ON}}{V_{IN}} \quad (1)$$

Since this varies as $1/V_{IN}$, this ensures fixed frequency operation in CCM operation.

This frequency is given as:

$$FSW = \frac{V_{OUT}}{2(K \times R_{ON})} \quad (2)$$

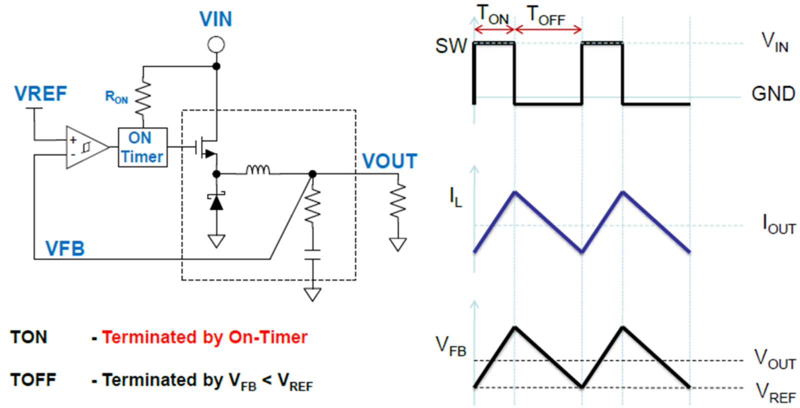


Figure 2. Constant on Time (COT) scheme

COT offers several advantages:

1. Simple design
2. No compensation required
3. Excellent transient response as there is no error amplifier or compensation components in the feedback loop to limit the bandwidth

2.2 Ripple Injection Techniques

The major disadvantage with this simple scheme is its dependence on the output ripple voltage. This can be resolved by filtering out the ripple from the output but not the feedback path or generating a ripple from the inductor itself.

A detailed discussion of the different ripple injection techniques that can be used in hysteric converters follows:

1. Adding a series resistance Rc with the output capacitor. This, in effect, increases the ESR of the output Capacitor.

   Figure 3 shows a circuit with the Rc connected. Equation 3 is used to calculate the value of Rc:

$$RC\ min = \frac{Vripple \times V_{OUT}}{IL\,min \times V_{REF}} \quad (3)$$

   Where Vripple is the minimum ripple voltage required on the feedback pin.

   This derives from the simple fact that the ripple voltage generated across the Rc is the inductor ripple current times the resistance value. This gets scaled down by a factor of Vref/Vout due to the feedback resistor divider.

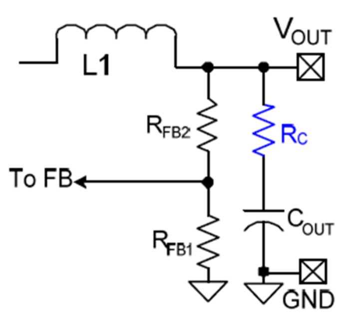


Figure 3. Increasing Output Capacitor ESR to Increase the Feedback Ripple

2. Adding a feed forward capacitor across the upper feedback resistor reduces the output ripple by bypassing it directly to the FB pin.

   Figure 4 shows a circuit with the Cff connected. Use Equation 4 to calculate the values of Cff:

$$\text{Cff min} = \frac{5}{\left[\text{Fsw} \times \left(R_{FB1} / /R_{FB2}\right)\right]} \tag{4}$$

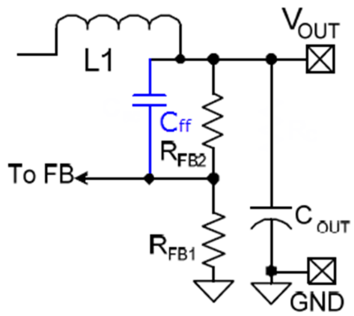


Figure 4. Bypassing the Output Ripple Directly to the Feedback Pin - Reducing the Output Ripple

3. Adding an integrator circuit across the inductor.

   Figure 5 shows a circuit with the components connected.

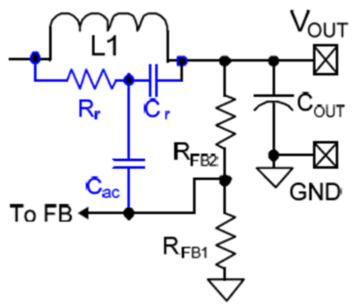


Figure 5. Ripple Injection Using the Inductor Current Ripple

The Rr and Cr form a triangular wave generator that provides desired information to the FB pin. It does this by integrating the voltage across the inductor and coupling the resulting ac signal to the FB pin through capacitor Cac.

The calculation of the values of Rr, Cr, and Cac are understood as:

Cr: The impedance of the integrator capacitor should be small compared to the feedback divider impedance at the desired switching frequency. The impedance of the feedback network is the parallel combination of Rfb1||Rfb2. The impedance of Cr at the switching frequency can be taken to be about one tenth of this value.

$$Cr = \frac{5 \times (Rfb1 + Rfb2)}{\pi \times (Fsw \times Rfb1 \times Rfb2)} \quad (5)$$

Rr: Since $V_{IN} - V_{OUT}$ is very large compared to the ripple voltage being produced, think of the resistor Rr as being a current source. The current is simply $(V_{IN} - V_{OUT})/Rr$.

A charging capacitor obeys the following: I/C = dV/dt. For V_{IN}, based on the operation frequency and duty cycle, the on time can be calculated, this is the dt. The dV term is the minimum required ripple, and Cr is as calculated previously.

Solving for I and then equating it to $(V_{IN} - V_{OUT})/Rr$, gives the value of Rr.

$$Rr = \frac{(Vin - Vout)}{Cr \times Vripple \times Fsw} \quad (6)$$

Cac: The AC coupling cap should be 3 to 4 times larger than the integrator capacitor (Cr).

Cac = 4 × Cr

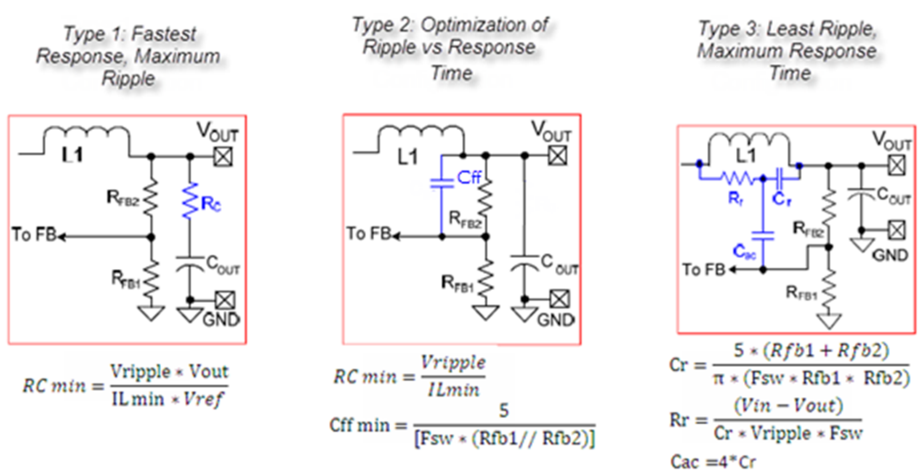


Figure 6. Summary of the Different Ripple Injection Techniques

3 Test Results

3.1 Impact of Ripple Injection Techniques on the Transient Response of the System

As we have seen earlier in this document, one of the primary advantages of hysteretic controllers is the excellent transient response as there are no compensation components in the feedback loop to limit the bandwidth.

However, using ripple injection techniques introduces additional reactive components. This helps to reduce the ripple, but has an impact on the transient response of the system.

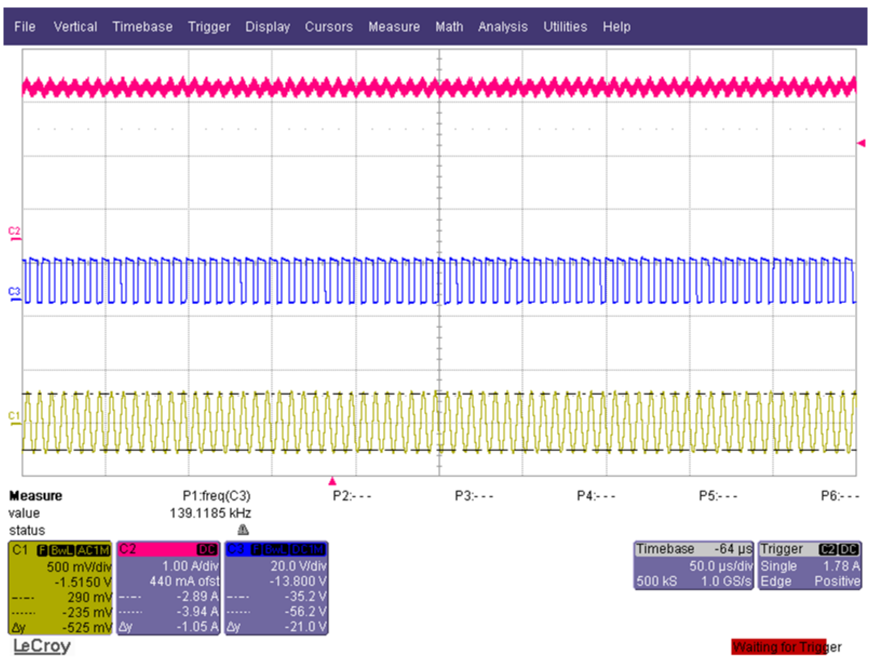
To get a comparative overview, we use a hysteretic controller, LM5085, to measure the response of the same system to the same load changes but with different injection techniques.

Figure 7 to Figure 20 give an idea of the settling time, output ripple, overshoot and undershoot for various ripple injection configurations.

The test parameters used are:

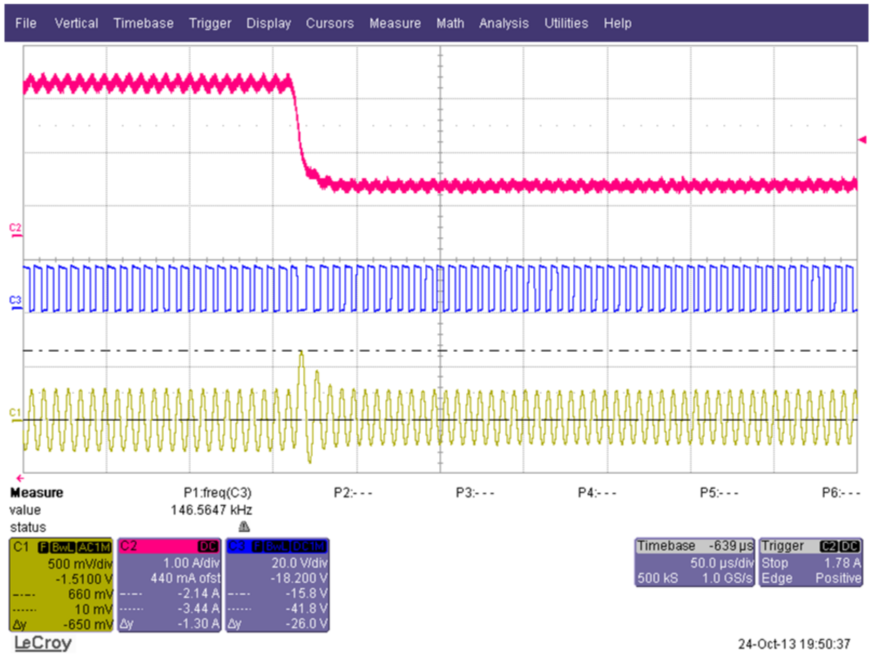
V_{IN} = 16 V
V_{OUT} = 9 V
Load = 3 A to 1 A and 1 A to 3 A

3.2 Case 1 : Resistance in Series with the Output Capacitor (ESR of output cap):



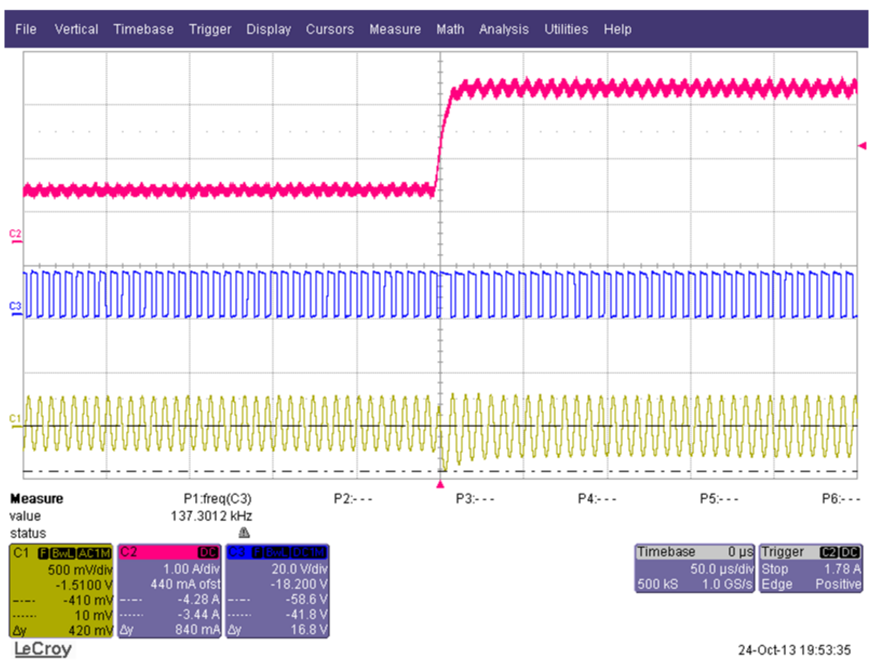
Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

Figure 7. Output Ripple (3-A Load Current) = 525 mV



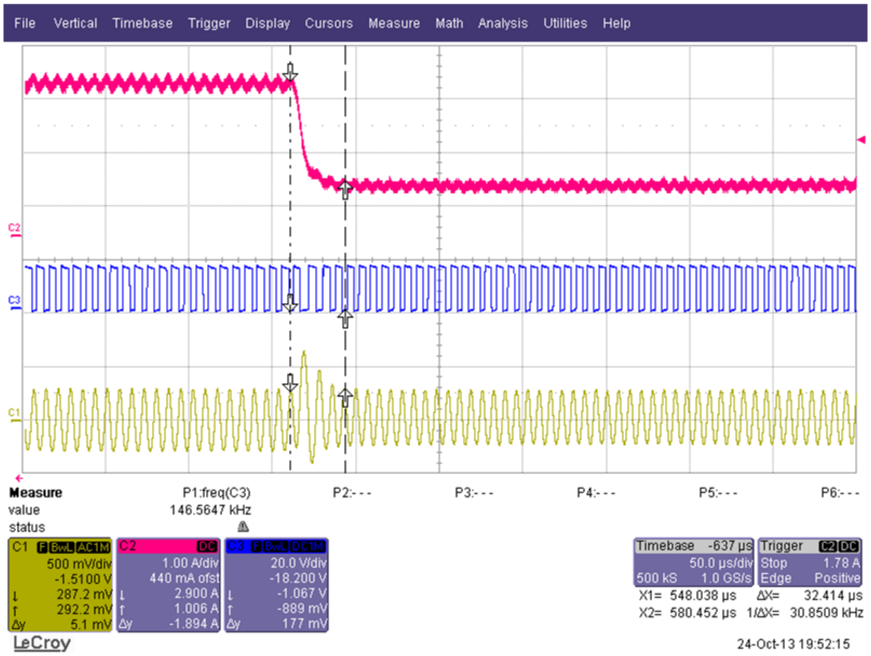
Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

Figure 8. Load Transition (3 A to 1 A) – Overshoot = 650 mV



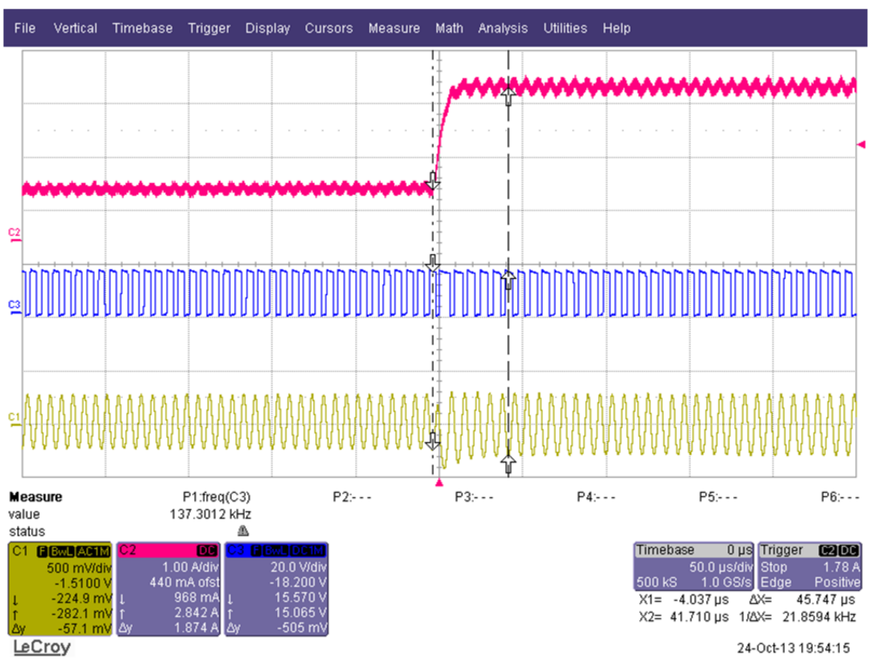
Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

Figure 9. Load Transition (1 A to 3 A) – Undershoot = 420 mV



Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

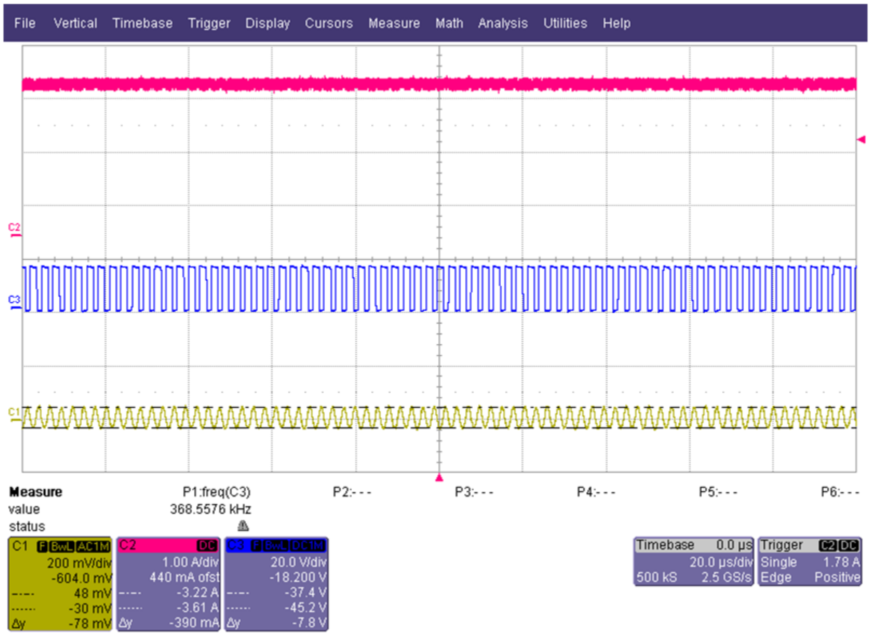
Figure 10. Settling Time (Falling Current) = 32 µs



Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

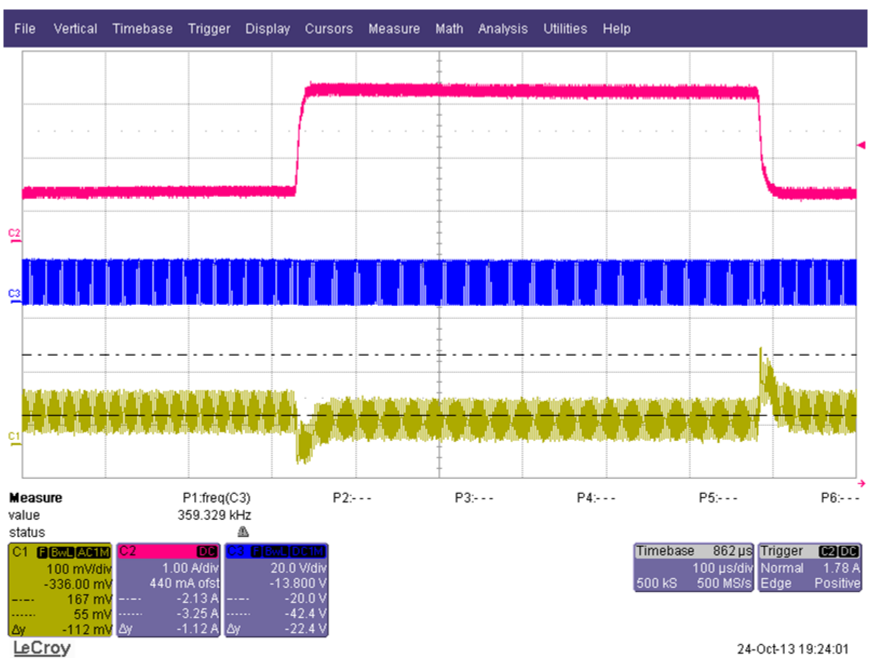
Figure 11. Settling Time (Rising Current) = 45 µs

3.3 Case 2 : Feedforward Capacitor Connected Across Feedback Resistor



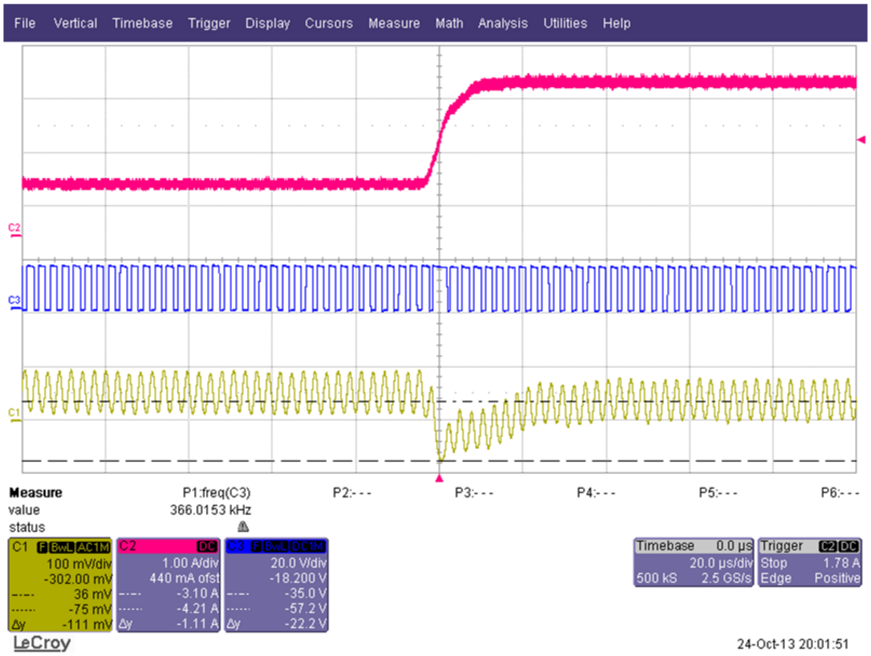
Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

Figure 12. Ripple Voltage (3-A Load) = 78 mV



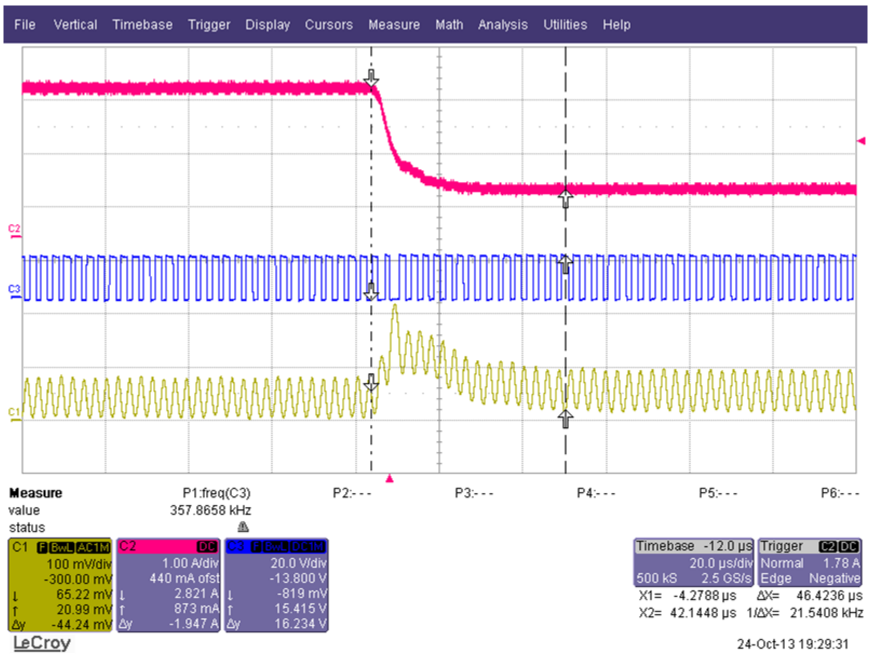
Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

Figure 13. Load Transition (3 A to 1 A) – Overshoot = 112 mV



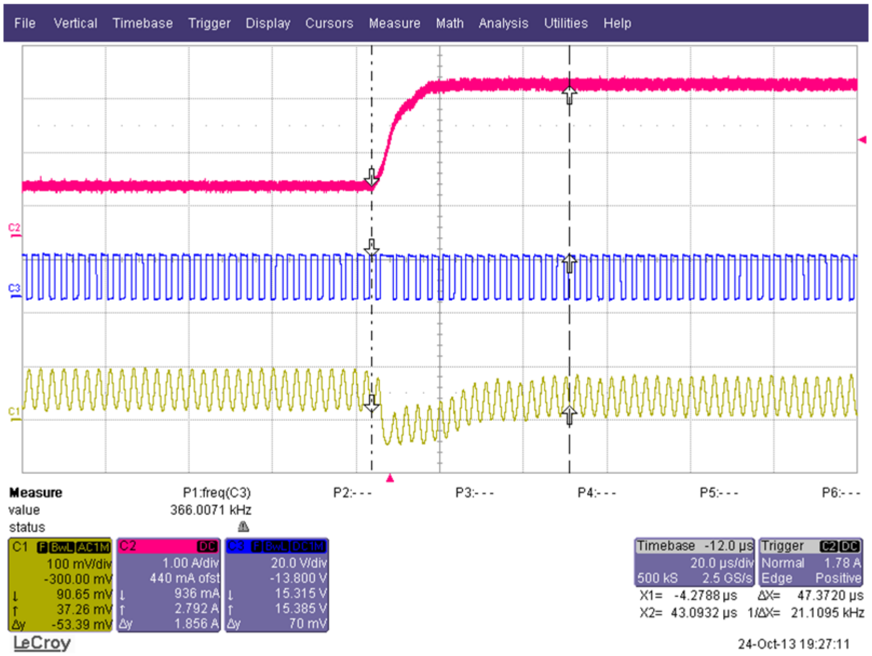
Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

Figure 14. Load Transition (1 A to 3 A) – Undershoot = 111 mV



Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

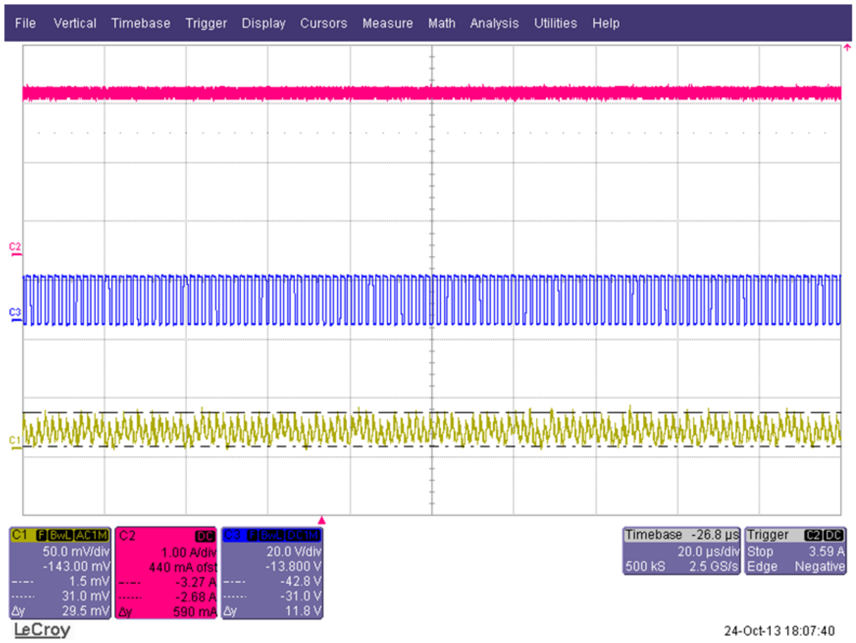
Figure 15. Settling Time (Falling Current) = 46 µs



Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

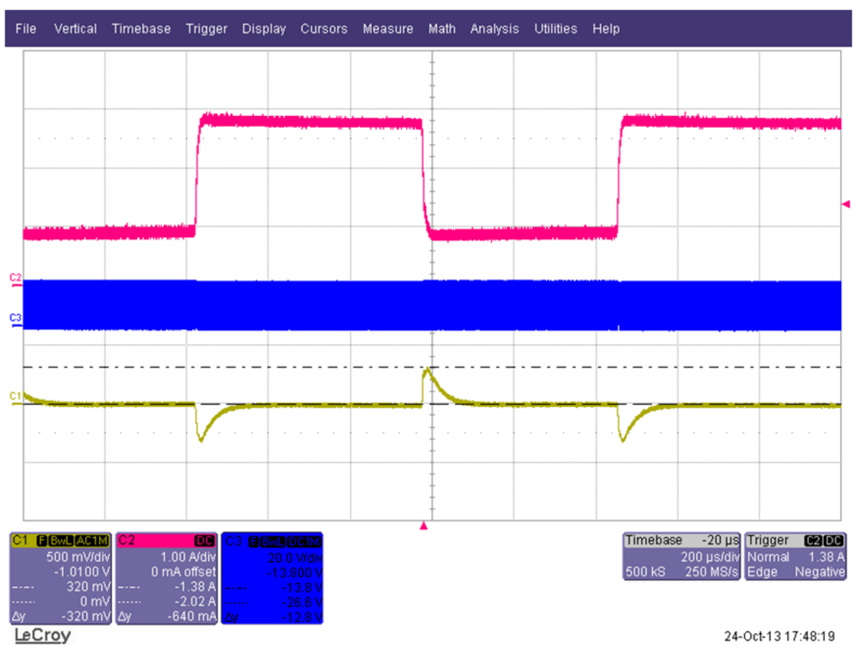
Figure 16. Settling Time (Rising Current) = 47 µs

3.4 Case 3: Inductor Current Ripple Injection



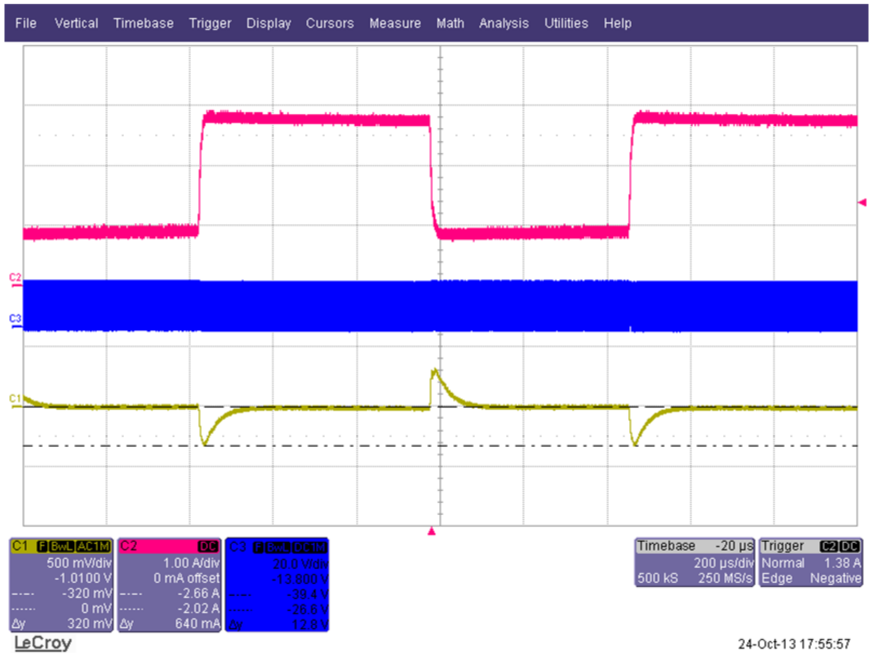
Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

Figure 17. Ripple Voltage (3-A Load Current) = 30 mV



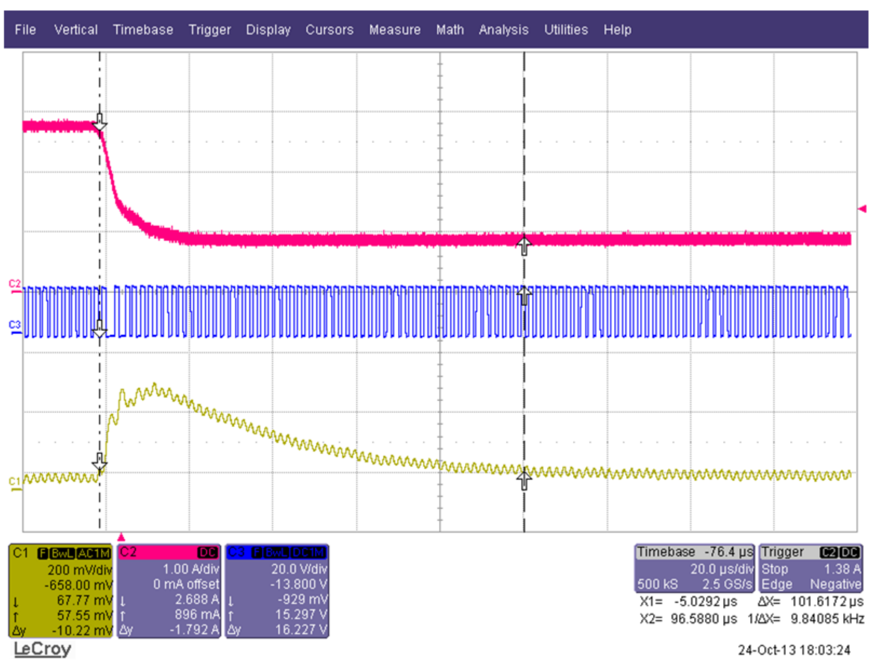
Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

Figure 18. Load Current Rising (3 A to 1 A) – Overshoot = 320 mV



Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

Figure 19. Falling Current (1 A to 3 A) – Undershoot = 320 mV



Ch1: Output Ripple Ch2: Load Current Ch3: Switch Node

Figure 20. Settling time (Falling Edge): 102 µs

From these test waveforms, we can conclude that the response of the system is fastest with just ESR of the output capacitor. The use of a feed forward capacitor helps to optimize the transient response and ripple. Whereas the inductor current ripple injection technique reduces the output ripple by the largest value but also slows the transient response by the largest value.

4 Conclusion

Hysteretic control scheme is one the simplest buck control schemes. However its operation depends on the output ripple. This requirement can be relaxed by introducing different ripple injection techniques aimed at increasing the ripple voltage seen by the feedback pin.

However, these techniques have an impact on the transient response of the system.

From the test results we can conclude that the inductor-current ripple injection technique gives minimum output ripple. But, it also leads to a slow transient response.

Whereas the feed forward Capacitor Cff technique strikes a balance between transient response and output ripple voltage.

Adding ESR in series with Output Capacitor results in high Output ripple but fast transient response.

The conclusion is summarized in the below table:

Method	Output Ripple	Transient Response
Increasing ESR of O/P Capacitor.	High	Fast
Bypassing O/P ripple to the FB pin.	Medium	Medium
Inductor Current ripple Injection.	Low	Slow

These findings can be utilized for other COT Hysteretic controllers such as LM25085, LM3485, LM3489, and so forth.

5 References

1. LM5085 datasheet (SNVS565)
2. *Controlling Output Ripple & Achiev ESR Indep Constant On-Time Reg Designs* Application Report (SNVA166)

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