

Application Guidelines for the Microchip Constant On-Time Regulators with Internal Ripple Injection

Author: Paolo Nora, Victor Uzum
Microchip Technology Inc.

INTRODUCTION

Buck Switch-Mode Power Supplies are popular solutions for today's customer POL applications. The main control mode architecture types are: voltage-mode, current-mode and Constant On-Time (COT) control mode.

The ripple-based COT control architecture is more and more popular among customers due to its very simple control loop design, fast transient response (due to wide bandwidth), while achieving a relatively constant switching frequency and high efficiency at light loads, and implemented with little additional design effort.

CONSTANT ON-TIME CONTROL ARCHITECTURE

COT is a ripple-based control mode. The output regulation is achieved by comparing the falling slope of the output voltage to a threshold. As illustrated in Figure 1, when the output voltage waveform V_O is crossing the regulation threshold V_{REF} , switch HS is activated (the SR latch is set).

At the same time, an internal I/C timer starts and generates a RESET pulse to the latch after a certain time, T_{ON} . Therefore, the high-side switch will be activated for a fixed time, equal to T_{ON} , which is fixed by the I_T/C_{TON} slope across the timing capacitor C_{TON} , and by the value of threshold V_{TH} . Since all the parameters determining T_{ON} are constant, the ON-time of HS is also constant, which is why the basic form of this type of control is called "Constant ON-Time". It should be noted that the duration of the RESET pulse to the SR latch might be stretched as needed by the "Min. T_{OFF} " one-shot to enforce a minimum duration of the OFF time. This is needed, for example, to replenish the bootstrap capacitor for the high-side driver (if the HS switch is an N-channel MOSFET driven by a bootstrapped driver), or for measuring the current across the $R_{DS(ON)}$ of the low-side switch LS, as in the case of many regulators listed below.

Indeed, if the output voltage waveform is still below the regulation threshold V_{REF} after the minimum T_{OFF} has expired, the COT regulator immediately reacts by triggering another T_{ON} pulse. This fast reaction to a sagging output voltage, a key factor in load transient response, is the main benefit of COT control.

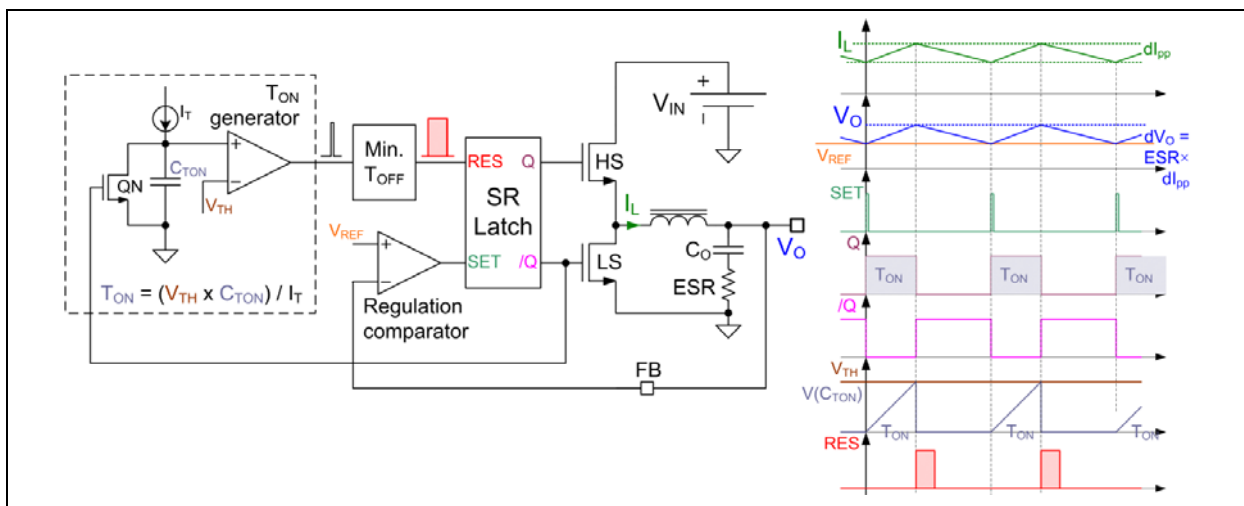


FIGURE 1: Constant On-Time Control Architecture.

Despite its uncontested advantages, this control scheme has an important drawback. The output voltage ripple must be large enough to reliably trigger the comparator and, most importantly, the phase of the output ripple must closely match the inductor current ripple component, meaning that the output voltage capacitor ESR must be quite large.

Many authors have performed a detailed analysis of the stability constraints for COT due to the output capacitor ESR [Redl, Sun, Lee]. They all conclude that the stability constraint is:

EQUATION 1:

$$\frac{T_{ON}}{2} < ESR \times C_O$$

Since large output ripple is not desirable in most customer applications, two main solutions can be implemented to provide a large enough ripple on the feedback path without increasing the output voltage ripple: ripple injection and Emulated Ripple Mode (ERM). For a detailed description of COT architecture and ripple injection techniques, refer to the documents and the tutorial presentations available on the Microchip website.

RIPPLE INJECTION TECHNIQUES

There are various techniques for feedback ripple injection in COT regulators, listed below.

LARGE ESR OUTPUT CAPACITOR (OR A RESISTOR IN SERIES WITH THE OUTPUT CAPACITOR)

This solution is not usually desirable, since low output voltage ripple is one of the most frequent constraints in customer applications. In addition, this method is sensitive to output noise, since it is translated into feedback ripple. Usually, low ESR ceramic output capacitors are recommended for this type of regulator because of their good high-frequency characteristics and output ripple attenuation performance.

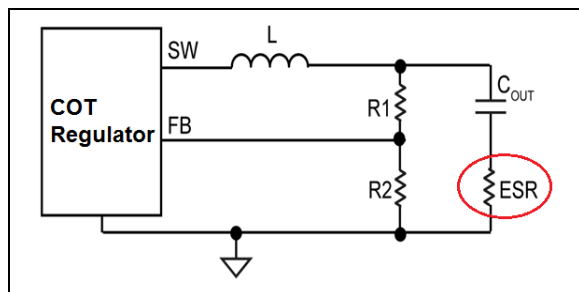


FIGURE 2: Increasing the Feedback Ripple by Increasing the Output Capacitor ESR.

A FEED-FORWARD CAPACITOR IN PARALLEL WITH THE TOP RESISTOR OF THE FEEDBACK DIVIDER

This solution can be applied if the time constant of the output capacitor is still adequate for stable operation, but its amplitude at the FB pin is too shallow for jitter-free operation. In this case the full amplitude of the output ripple can be recovered by feeding it directly to the feedback path. The feed forward capacitor bypasses high-frequency ripple directly to the FB pin and ensures a phase boost around the middle of the relevant bandwidth.

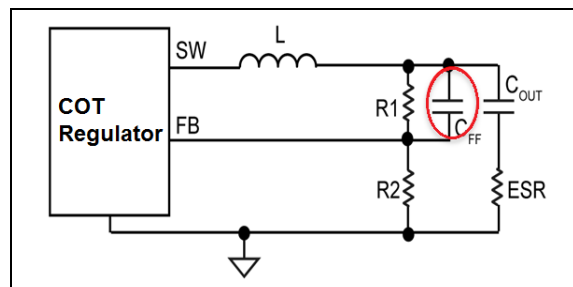


FIGURE 3: Feeding the Output Ripple to the FB Path without Increasing the Output Voltage Ripple.

A SERIES RC CELL ADDED BETWEEN THE SWITCH NODE AND THE FEEDBACK PATH

This solution is necessary if the output capacitor ESR is no longer sufficient to achieve stability. This is the case when ceramic output capacitors are used. In this case, the in-phase ripple must be created using the Ri-Ci network shown in the picture below. The current through Ri is almost a square wave with no DC component (blocked by Ci) and it is integrated across capacitor CFF to generate a triangular wave shape. Care must be taken because CFF also bypasses the entire "out-of-phase" output ripple to the feedback pin, and the self-injected "in-phase" ripple must be large enough to overcome the output ripple.

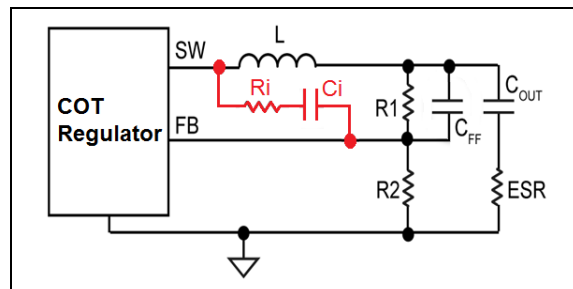


FIGURE 4: Injected Ripple from the SW Node using a Series RC Cell.

INTERNAL RIPPLE INJECTION

In case of low input voltage, low power DC-DC converters using low ESR ceramic output capacitors, the ripple injection components (feed-forward capacitor and the series injection RC cell) are frequently integrated on the regulator die.

This is convenient for customer applications, since the number of external components needed for regulator integration is lower. Additionally, the ripple injection components are already dimensioned for stable loop performance, and for the best compromise between ripple amplitude, the line regulation and the transient response time.

However, to make monolithic integration practical, the value of the DC blocking capacitor is typically limited to some picofarads. Therefore, even if the switching frequency is in the MHz range, the values of R_i and the feedback resistors must be high.

In case of fixed output voltage versions, the feedback resistors are also integrated in the regulator package. That further reduces the number of external components.

Since the switching frequency is internally fixed, a limited range of inductors and a minimum output capacitance are typically suggested for these monolithic regulators to avoid any possible stability issues in customer applications.

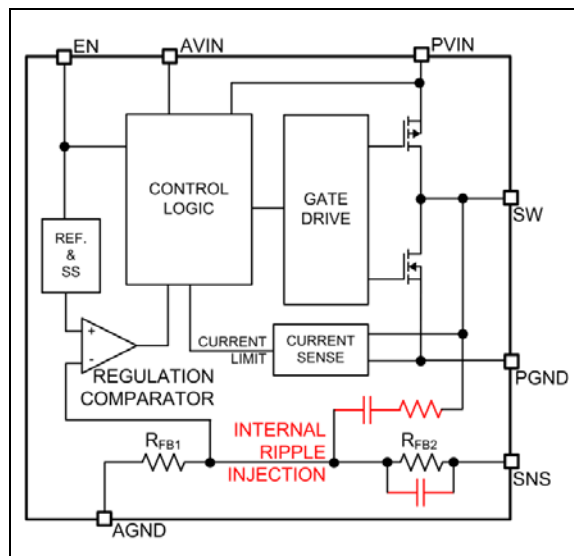


FIGURE 5: Internal Ripple Injection Network Used for Low-power COT Regulators.

MICROCHIP REGULATORS WITH INTERNAL RIPPLE INJECTION

There are many buck hysteretic COT regulators with internal ripple injection in the Microchip portfolio, refer to [Table 1](#)

TABLE 1: MICROCHIP BUCK COT REGULATORS WITH INTERNAL RIPPLE REJECTION

Product	No. of Outputs	Input Min Voltage (V)	Input Max Voltage (V)	Switching Frequency (Hz)	VFB (V) (adj.)
MIC23158	2	2.7	5.5	3000	0.62
MIC23159	2	2.7	5.5	3000	0.62
MIC23250	2	2.7	5.5	4000	0.72
MIC23254	2	2.5	5.5	4000	N.A. ⁽¹⁾
MIC23030	1	2.7	5.5	8000	0.62
MIC23031	1	2.7	5.5	4000	0.62
MIC23050	1	2.7	5.5	4000	N.A. ⁽¹⁾
MIC23051	1	2.7	5.5	4000	N.A. ⁽¹⁾
MIC23150	1	2.7	5.5	4000	N.A. ⁽¹⁾
MIC23153	1	2.7	5.5	4000	0.62
MIC23155	1	2.7	5.5	3000	0.62
MIC23201	1	2.7	5.5	2000	0.62
MIC23303	1	2.9	5.5	4000	0.62
MIC4930	1	2.7	5.5	3300	0.625
MIC4950	1	2.7	5.5	3300	0.625
MIC23603	1	2.9	5.5	4000	0.62
MIC23450	3	2.7	5.5	3000	0.62
MIC23451	3	2.7	5.5	3000	0.62

Note 1: N.A.: adjustable version not available; only fixed output voltage options are offered.

DESIGN CONSTRAINTS FOR MICROCHIP INTERNAL RIPPLE INJECTION REGULATORS

For all COT regulators with internal ripple injection (MIC23XXX and MIC49XX), precise indications related to design application rules are provided in the corresponding data sheets (all documents can be reviewed and downloaded from the Microchip website at <http://www.microchip.com>).

For all adjustable output voltage versions, recommended values for feedback divider resistors are clearly specified (usually hundreds of kilohms for both top and bottom resistors). For the fixed output voltage versions, these feedback resistors are inside the regulator package, so they cannot be changed by the end user.

One common recommendation for feedback voltage resistor divider values show in [Table 2](#).

TABLE 2: TYPICALLY RECOMMENDED FEEDBACK RESISTOR VALUES

V _{OUT}	R ₁	R ₂
1.2V	274 kΩ	294 kΩ
1.5V	316 kΩ	226 kΩ
1.8V	301 kΩ	160 kΩ
2.5V	316 kΩ	105 kΩ
3.3V	309 kΩ	71.5 kΩ

The typically recommended feedback resistor values table is applicable to regulators like MIC4930, MIC4950, MIC23450, MIC23451 and MIC23153.

Some of the data sheets also indicate an optimum range for the external feed-forward capacitors (usually a few tens of picofarads) if they are not already included in the regulator internal circuitry.

The same documents also specify the optimal ranges for the external inductors used in the buck step down topology (usually between 0.47 μH and 4.7 μH), and the recommended input/output capacitor types and values.

Designers must pay attention to all application recommendations and implement them in their designs. Otherwise, they may encounter stability issues, or the ripple fed into the feedback path might not be large enough to ensure optimal functionality of the COT control loop.

The internal ripple injection network is typically sufficient for the desired ripple on the feedback path, if the recommended divider resistors and feed-forward capacitor are used. If significantly lower feedback divider resistors and/or a higher feed-forward capacitor are used, the amount of ripple at the feedback pin might not be sufficient for stable regulator operation. In this case, external ripple injection is needed. This is accomplished by connecting a series RC circuit between the SW and the FB regulator pins and placing a feed-forward capacitor in parallel with the top resistor of the feedback resistive divider (see [Figure 4](#)).

The injected ripple is calculated using [Equation 2](#):

EQUATION 2:

$$\Delta V_{FB(pp)} = V_{IN} \times K_{DIV} \times D \times (1 - D) \times \frac{1}{f_{SW} \times \tau}$$

where:

EQUATION 3:

$$K_{DIV} = (R_1 \parallel R_2) / (R_{INJ} + R_1 \parallel R_2)$$

EQUATION 4:

$$D = V_{OUT} / V_{IN} = DutyCycle$$

V_{IN} = Input Voltage, V_{OUT} = Output Voltage

EQUATION 5:

$$\tau \equiv (R_1 \parallel R_2 \parallel R_{inj}) \times C_{FF}$$

In the derivation of [Equation 2](#), it is assumed that the condition expressed by [Equation 6](#) is satisfied:

EQUATION 6:

$$\frac{1}{f_{SW} \times \tau} \ll 1$$

where f_{SW} = Switching Frequency.

Please note that the external ripple injection network and feedback network impedance levels must be set low enough to override the effects of the internal ripple injection.

PRACTICAL EXAMPLE (MIC4930/50)

The MIC4930/50 are Microchip buck regulators that feature internal ripple injection (see Figure 5). The components used for their internal ripple injection network are $R_{INJ} = 360 \text{ k}\Omega$ and $C_{INJ} = 1.3 \text{ pF}$.

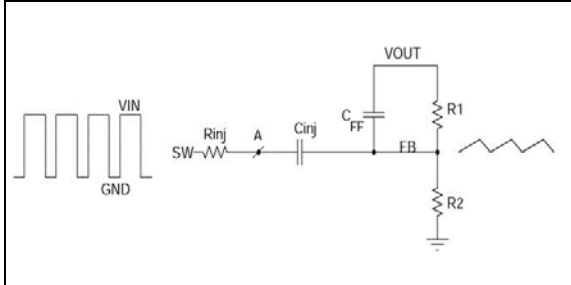


FIGURE 6: MIC4930/50 Internal Injection Path from the SW Node to the FB Pin.

The A node DC voltage is equal to V_{OUT} , because the RC network is the low pass type. This can be better understood by considering that C_{INJ} is a DC blocking capacitor, so no net DC current can flow through R_{INJ} in steady-state. Therefore, the DC (average) values at node SW and at node A must be equal, and the DC value (average) of node SW is $D \times V_{IN} = V_{OUT}$ (assuming a loss-less inductor). So, when SW voltage is equal to V_{IN} , the current injected in the feed-forward capacitor (C_{FF}) is calculated in Equation 7 (neglecting the small amount of current flowing through R_1 and R_2).

EQUATION 7:

$$(V_{IN} - V_{OUT})/R_{INJ}$$

The peak-to-peak amplitude of the voltage ripple injected into the feedback node will then be:

EQUATION 8:

$$\Delta V_{FB(pp)} = (V_{IN} - V_{OUT})/R_{INJ} \times \frac{T_{ON}}{C_{FF}}$$

where T_{ON} is the measured regulator ON time. It can be shown that Equation 2 and Equation 8 yield the same result by using Equations 3, 4 and 5.

Calculating the feedback ripple amplitude for a particular use case ($V_{IN} = 5.0\text{V}$, $V_{OUT} = 1.8\text{V}$, $I_{OUT} = 1\text{A}$, $C_{IN} = C_{OUT} = 10\mu\text{F}$ and $C_{FF} = 22 \text{ pF}$), the result is 48 mV_{PP} , as the measured T_{ON} is 119 ns .

In order to confirm the theoretical expected value, the feedback ripple amplitude can be measured using a differential oscilloscope probe (usually less than 1 pF differential capacitance) to avoid adding a higher capacitance in parallel with the feedback path by using

a normal oscilloscope probe. Nevertheless, the parasitic capacitances on the board will still affect the measured result.

For this particular use case, the measured feedback ripple is 46 mV_{PP} for MIC4930, and 47 mV_{PP} for MIC4950, which is close to the theoretically predicted value.

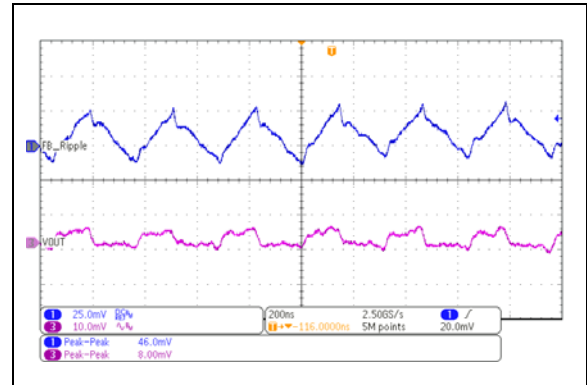


FIGURE 7: MIC4930 Feedback Ripple Amplitude for $V_{IN} = 5.0\text{V}$, $V_{OUT} = 1.8\text{V}$, $I_{OUT} = 1\text{A}$, $C_{FF} = 22 \text{ pF}$.

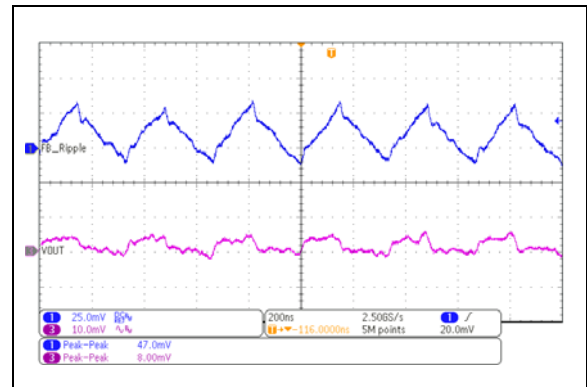


FIGURE 8: MIC4950 Feedback Ripple Amplitude for $V_{IN} = 5.0\text{V}$, $V_{OUT} = 1.8\text{V}$, $I_{OUT} = 1\text{A}$, $C_{FF} = 22 \text{ pF}$.

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