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DC-DC Converter with Continuous-Time Feed-Forward Sigma-Delta Modulator Control

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Outline

- Research Background and Objective
- ΔΣ Controller Advantages in DC-DC Converter
- Architecture Comparison of ΔΣ Controllers in DC-DC Converter
- Simulation results
- Conclusion

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Research Background

Power device advances

↓

Fast switching speed

↓

For DC-DC converter controller

PWM → ΔΣ modulator

-Fast transient response

-High efficiency at low load

-Spread spectrum of switching noise

Research Objective

Fast, low ripple, low power
DC-DC converter controller design

Our Approach

Application of ΔΣ modulator to DC-DC converter

Feedback	Feed-forward	Discrete-Time	Continuous-Time
● Slow	● Fast	● Slow	● Fast
● Large ripple	● Low ripple	● Large power	● Low power

CT Feed-forward ΔΣ modulator

(CT: Continuous-Time, RC integrator)
(DT: Discrete-Time, Switched-capacitor)

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Tradeoff of Fast Response and Efficiency

Fast Transient Response

↓

Inductor charged, discharged at high speed

↓

High switching frequency

High Efficiency

↓

Lower switching loss

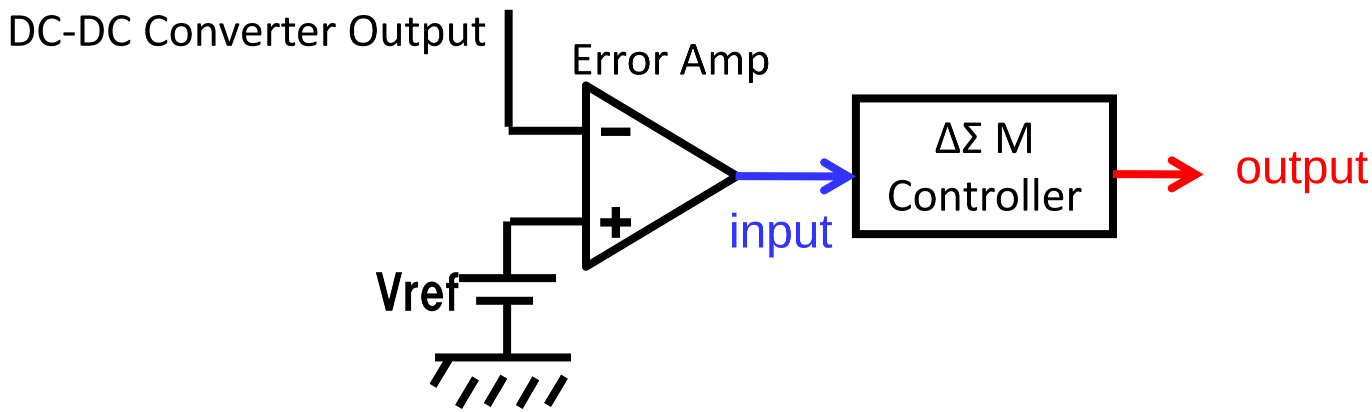
↓

Reduce Number of switching operation

↓

Low switching frequency

ΔΣ Modulator Controller



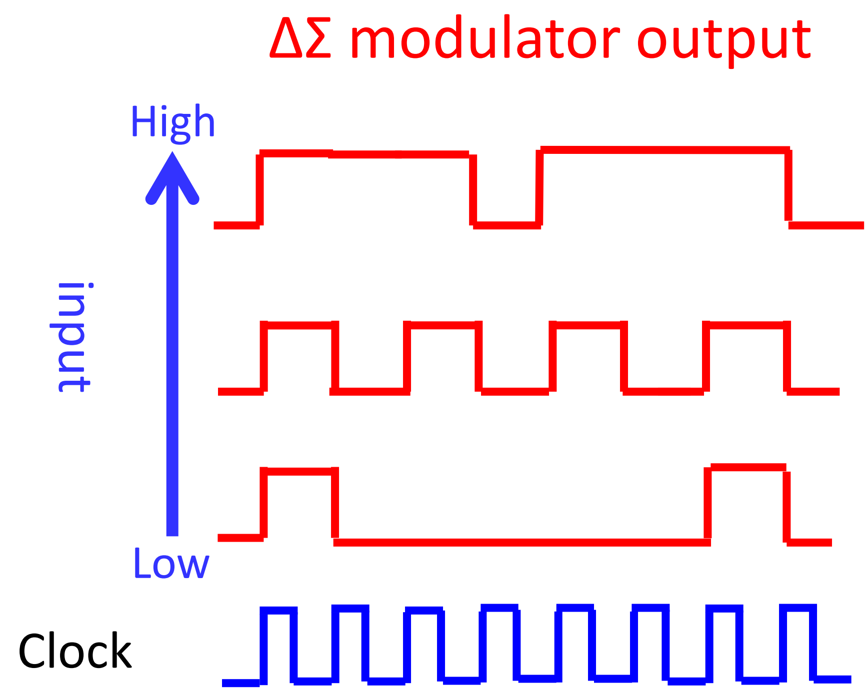
Dense pulse stream

(Fast transient response)

Can satisfy both

Sparse pulse stream

(High efficiency)



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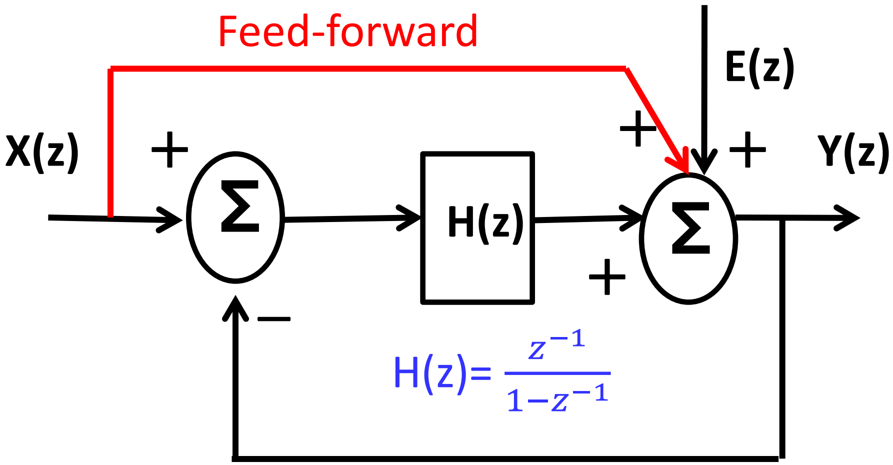
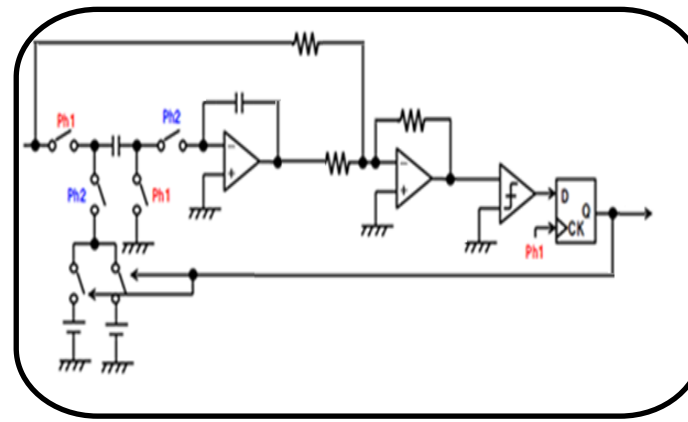
Delta-Sigma Modulator Types

- Feed-forward vs. Feedback ΔΣ modulator
- CT vs. DT ΔΣ modulator
- 1st -order vs. 2nd -order ΔΣ modulator

1^{st}-order Feed-forward ΔΣ Modulator





$$Y(z) = \underline{\underline{1}} \cdot X(z) + \underline{\underline{\frac{1}{1+H(z)}}} \cdot E(z)$$

STF(z)= 1

signal transfer function

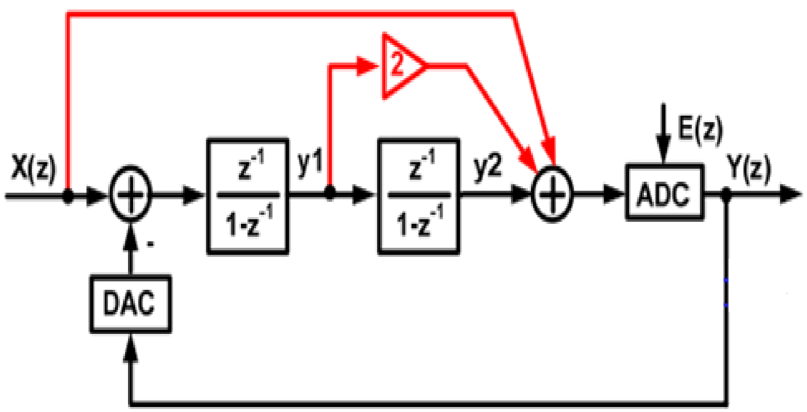
NTF(z)= $1\text{-}z^{-1}$

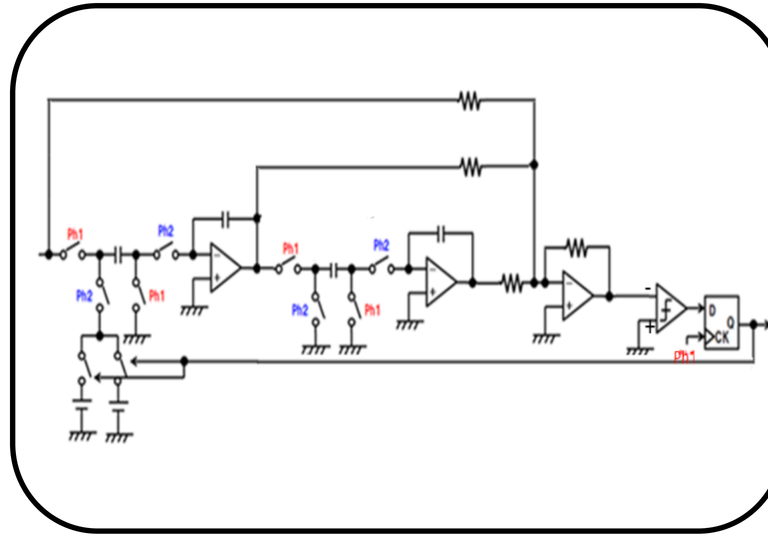
noise transfer function

No Delay

Differentiation=Noise Shaping

2^{nd}-order Feed-forward ΔΣ Modulator





$$Y(z) = 1 \cdot X(z) + (1 - z^{-1})^2 \cdot E(z)$$

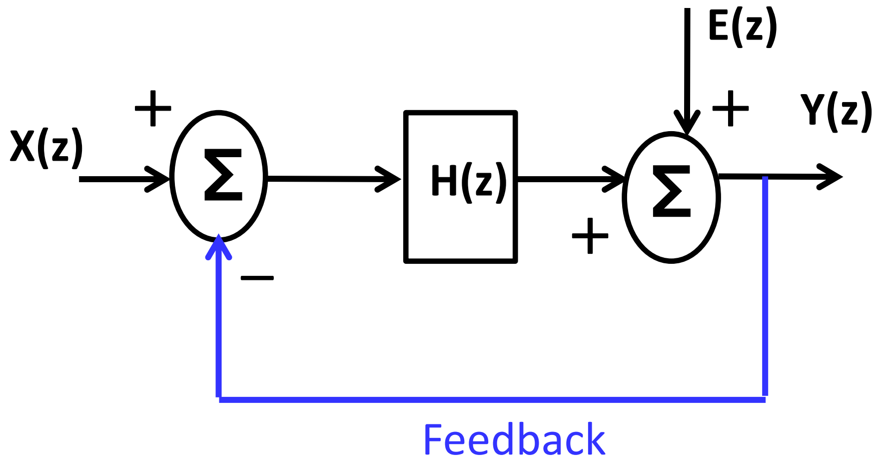
STF= 1

NTF= $(1-z^{-1})^2$

No Delay

2^{nd}-order Differentiation

1^{st} -order Feedback ΔΣ Modulator



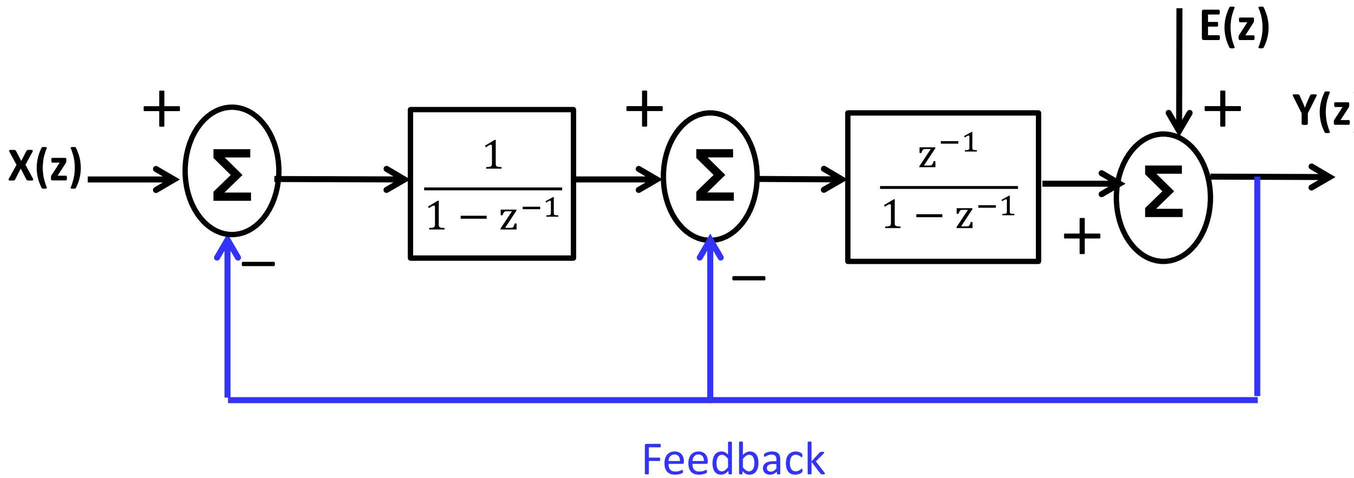
$$Y(z) = \frac{H(z)}{1+H(z)} \cdot X(z) + \frac{1}{1+H(z)} \cdot E(z)$$

$H(z) = \frac{z^{-1}}{1-z^{-1}}$ ⟶ STF(z)= z^{-1} NTF(z)= $1\text{-}z^{-1}$

One-clock delay

Differentiation=Noise Shaping

2^{nd}-order Feedback ΔΣ Modulator



$$Y(z) = z^{-1} \cdot X(z) + (1 - z^{-1})^2 \cdot E(z)$$

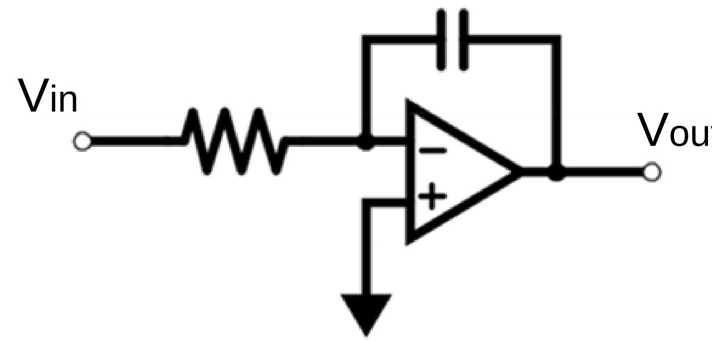
One-clock delay

2^{nd}-order Differentiation

Continuous-Time vs Discrete-Time

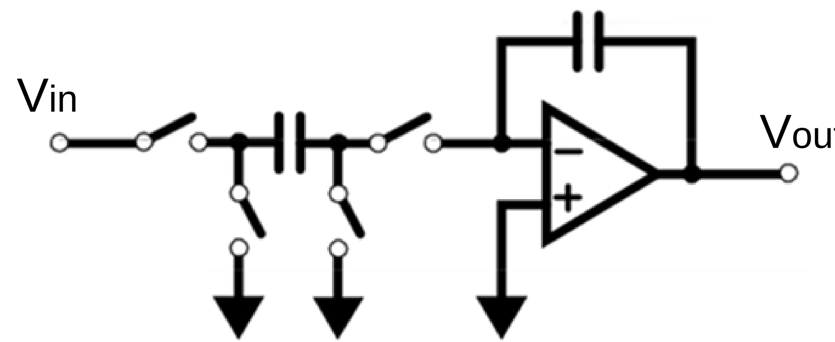
CT ΔΣ modulator

- Low power
- High-speed, high-frequency
- Time constant (RC) variation



DT ΔΣ modulator

- High precision
- High power consumption
- low-speed, low-frequency



CT ΔΣ modulator

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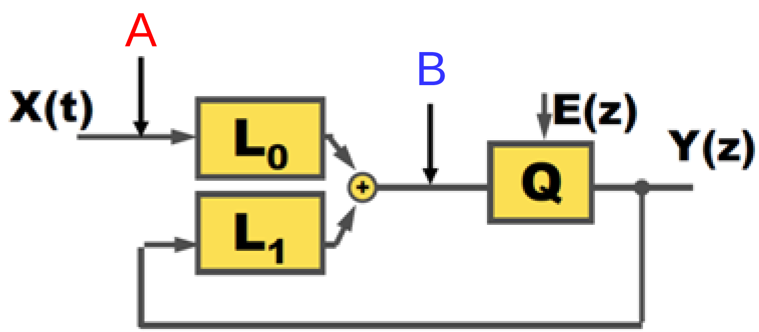
Application to DC-DC converter controller

DT ΔΣ to CT ΔΣ STF Design



$$\text{STF} = \frac{L_0}{1 - L_1}$$

$$\text{NTF} = \frac{1}{1 - L_1}$$

STF: Signal Transfer Function (Y/X)

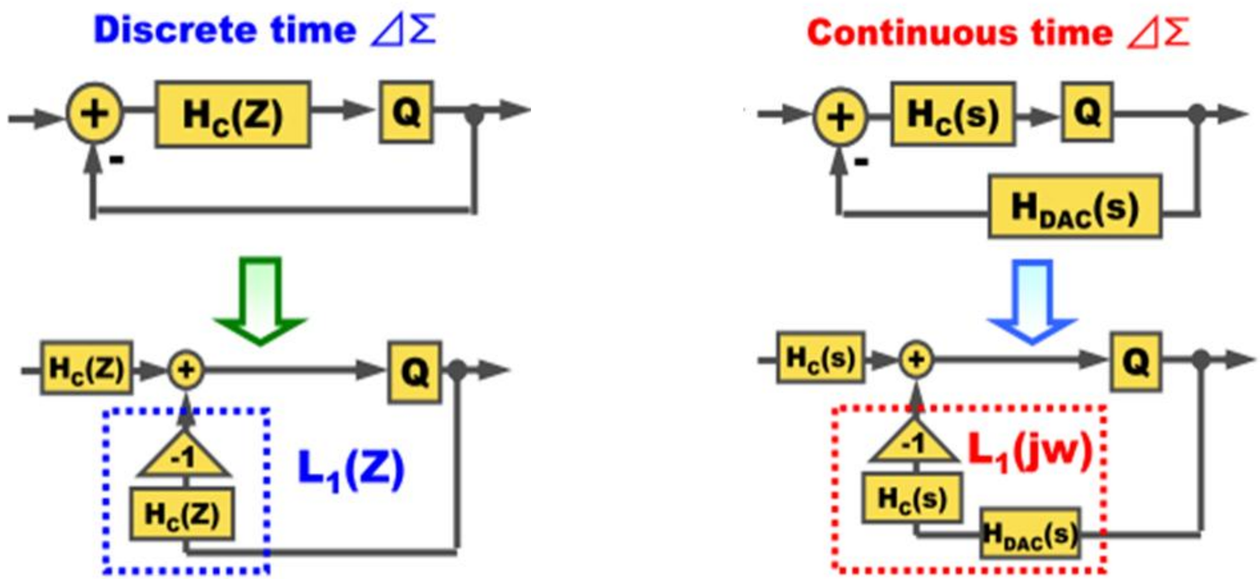
NTF: Noise Transfer Function (Y/E)

Position of the sampling switch

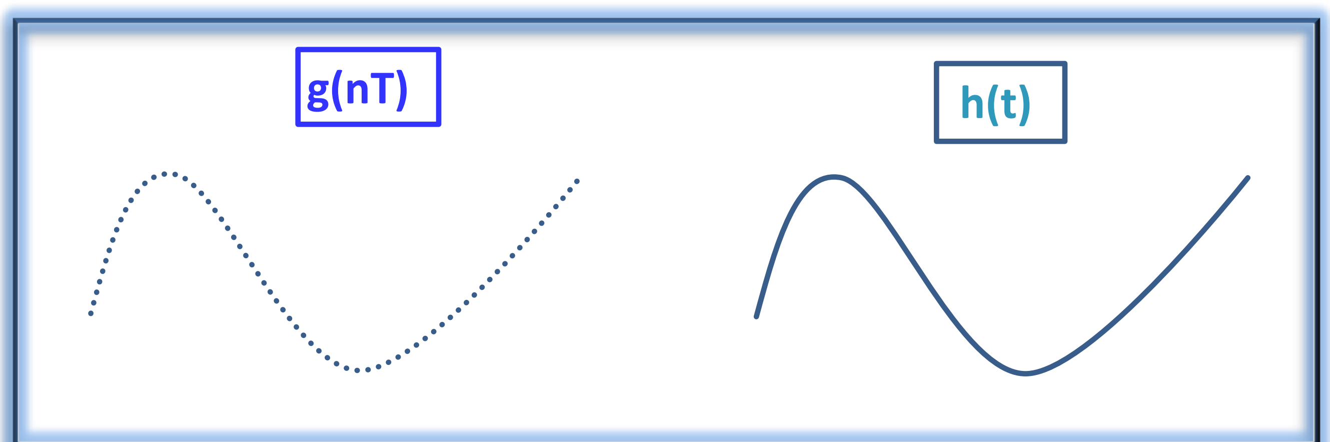
A: Discrete-Time ΔΣ

B: Continuous-Time ΔΣ

Mapping From Discrete-Time To Continuous-Time ΔΣ



Impulse Response Invariant Transformation



Derivation of 1st-order ΔΣ Transfer Function

CT ΔΣ Loop

L1(jω)

Impulse Response

$h(t) = h_c(t) * h_{DAC}(t)$

Laplace Transform

$h_{DAC}(t) = u(t) - u(t-T)$

Laplace Transform

$H_c(s) = \frac{A}{s}$ $\qquad H_{DAC}(s) = \frac{1-e^{-sT}}{s}$

$$H(s) = H_c(s) \cdot H_{DAC}(s) = \frac{A}{s} \cdot \frac{1-e^{-sT}}{s}$$

Inverse Laplace Transform

$$h(t) = \begin{cases} 0 & \text{for } t<=0 \\ A \cdot T & \text{for } t>0 \end{cases}$$

$$h(nT) = \begin{cases} 0 & \text{for } n<=0 \\ A \cdot T & \text{for } n>0 \end{cases}$$

DT ΔΣ Loop

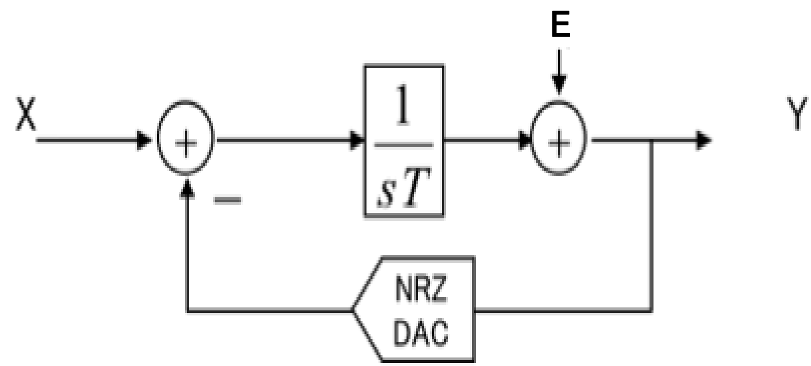
L1(z)

$$g(nT) = \begin{cases} 0 & \text{for } n<0 \\ -1 & \text{for } n>=0 \end{cases}$$

Make h(nT) = g(nT) (n is an integer)

$$H_c(s) = -\frac{1}{sT}$$

1^{st} –order Continuous-Time Feedback ΔΣ STF



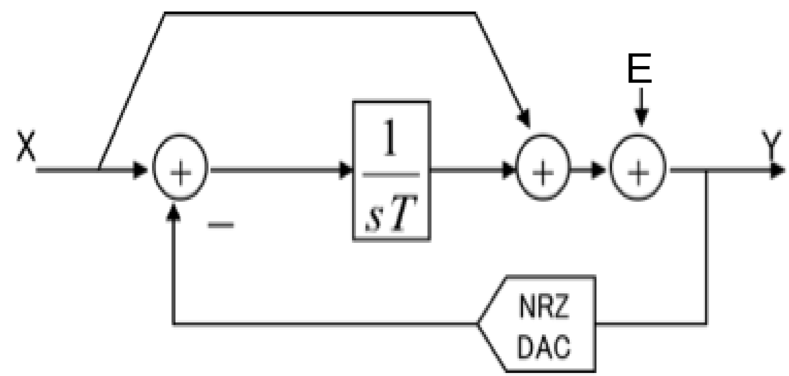
NRZ : Non-Return-to-Zero

$$Hc(s) = -\frac{1}{sT}$$

$$STF(s) = -Hc(s)NTF(s)$$

$$= \frac{1}{1-sT}\,[1-e^{(-sT)}]$$

1st-order Continuous-Time Feed-forward ΔΣ STF



$$Hc(s) = -\frac{1}{sT}$$

$$STF(s) = [1+Hc(s)]NTF(s)$$

$$= [1+\frac{1}{sT}][1-e^{(-sT)}]$$

Derivation of 2nd-order ΔΣ Transfer Function

CT ΔΣ Loop

L1(jω)

DT ΔΣ Loop

L1(z)

Impulse Response

h(t) = hc(t) * hDAC(t)

Laplace Transform

hDAC(t) = u(t) – u(t-T)

Laplace Transform

$$Hc(s) = \frac{A}{s} + \frac{B^2}{s^2} \qquad HDAC(s) = \frac{1-e^{-sT}}{s}$$

$$H(s) = Hc(s) \cdot HDAC(s)$$
$$= [\frac{A}{s} + \frac{B^2}{s^2}] \cdot [\frac{1-e^{-sT}}{s}]$$

Inverse Laplace Transform

$$h(t) = \begin{cases} 0 & \text{for } t<=0 \\ A \cdot T & \text{for } t>0 \end{cases}$$

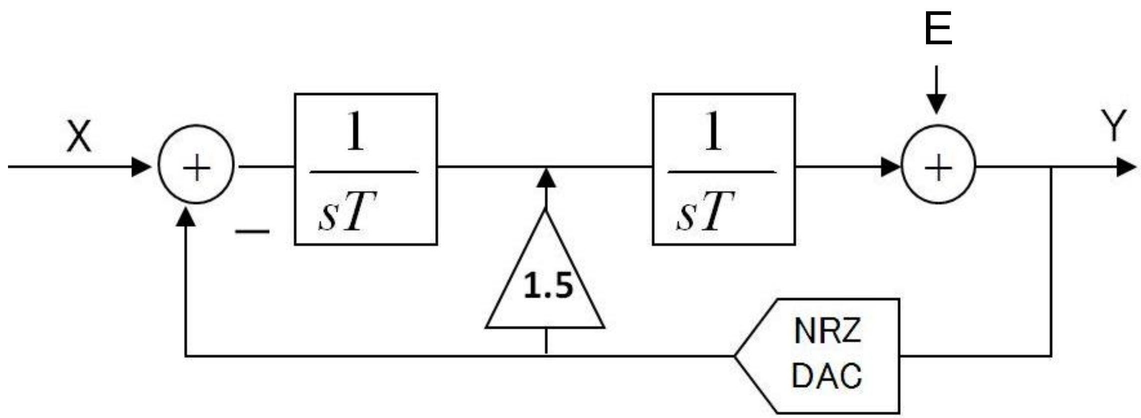
$$g(nT) = \begin{cases} 0 & \text{for } n<=0 \\ -(n+1) & \text{for } n>0 \end{cases}$$

Make h(nT) = g(nT) (n is an integer)

$$Hc(s) = \frac{3}{2sT} + \frac{1}{(sT)^2}$$

$$h(nT) = \begin{cases} 0 & \text{for } n<=0 \\ A \cdot T & \text{for } n>0 \end{cases}$$

2nd -order CT Feedback ΔΣ STF Design

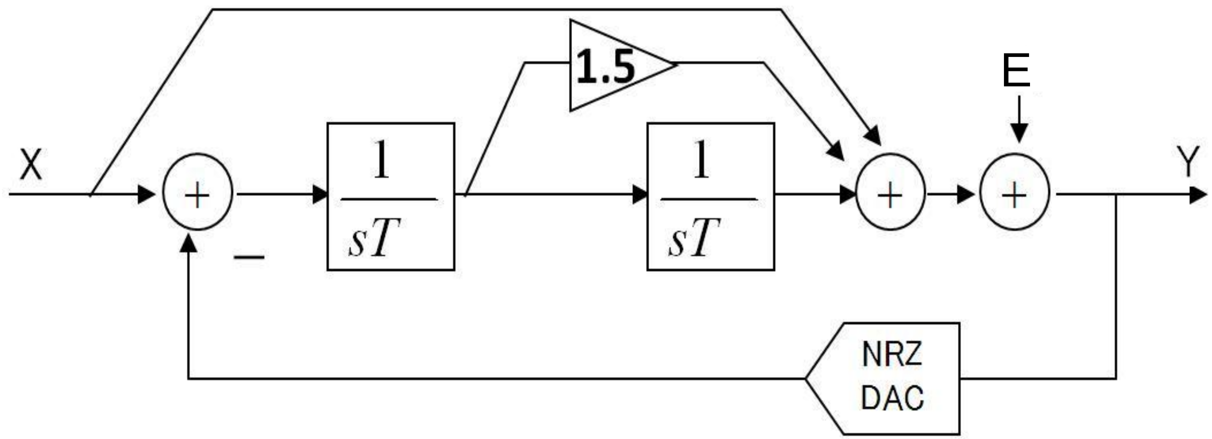


$$Hc(s) = \frac{3}{2sT} + \frac{1}{(sT)^2}$$

$$STF(s) = Hc(s)NTF(s)$$

$$= \left[\frac{2}{sT} + \frac{1}{(sT)^2}\right]\left[1 - e^{(-sT)}\right]$$

2^{nd} CT Feed-forward ΔΣ STF Design

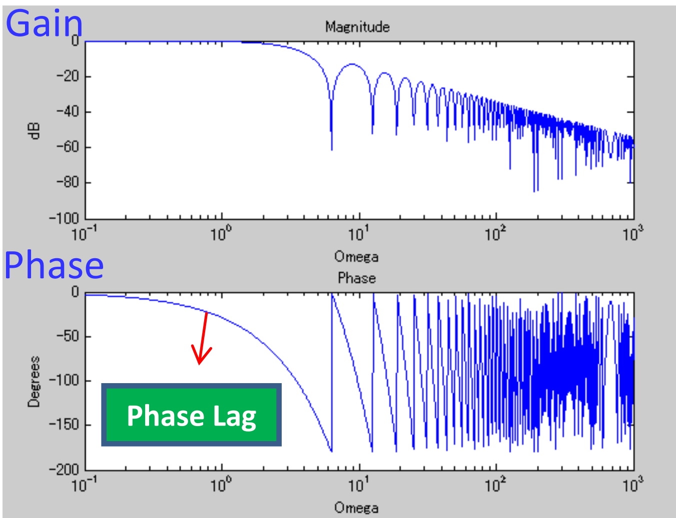


$$Hc(s) = \frac{3}{2sT} + \frac{1}{(sT)^2}$$

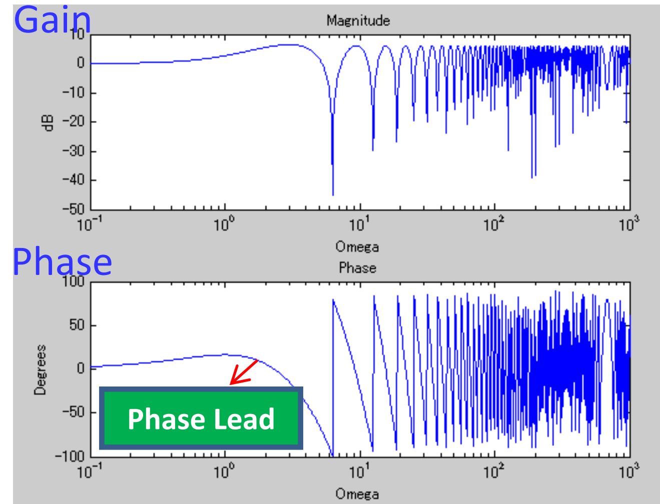
$$STF(s) = [1 + Hc(s)]NTF(s)$$

$$= [1 + \frac{3}{2sT} + \frac{1}{(sT)^2}][1 - e^{(-sT)}]$$

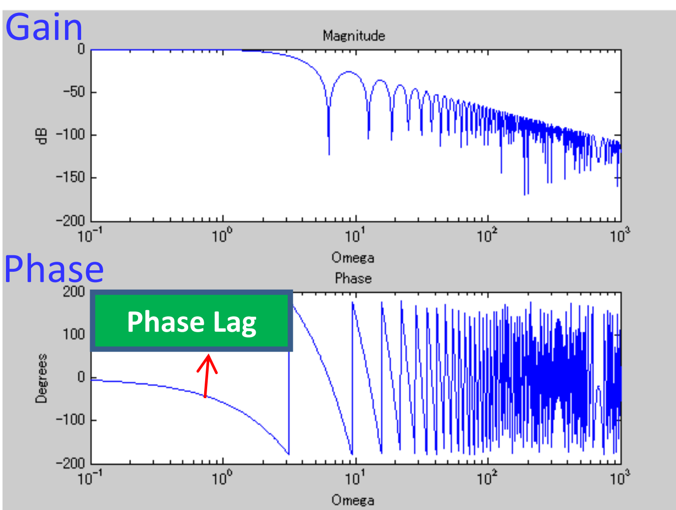
Comparison of STF Bode Plot



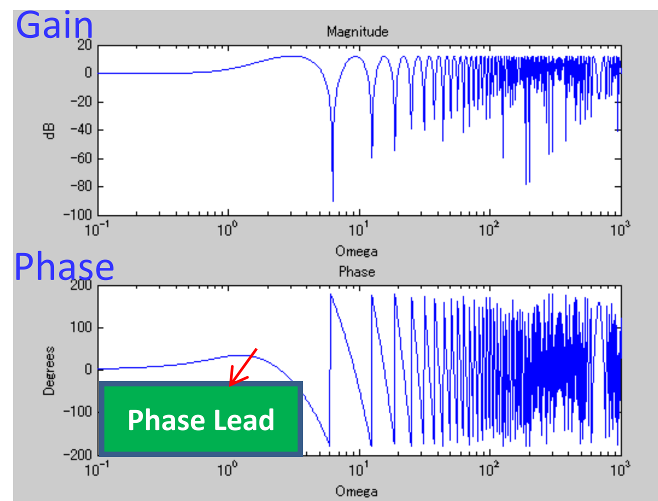
1st -order CT Feedback ΔΣ



1st order CT Feed-forward ΔΣ



2nd -order CT Feedback ΔΣ



2nd -order CT Feed-forward ΔΣ

- Feedback-types have phase lag.
- Feed-forward types have phase lead.

STF Characteristics of CT ΔΣ Modulator

STF Gain

AD Converter
(Anti-aliasing Filtering)

STF Phase

Control applications
(Phase Lead)

New and interesting theoretical issue

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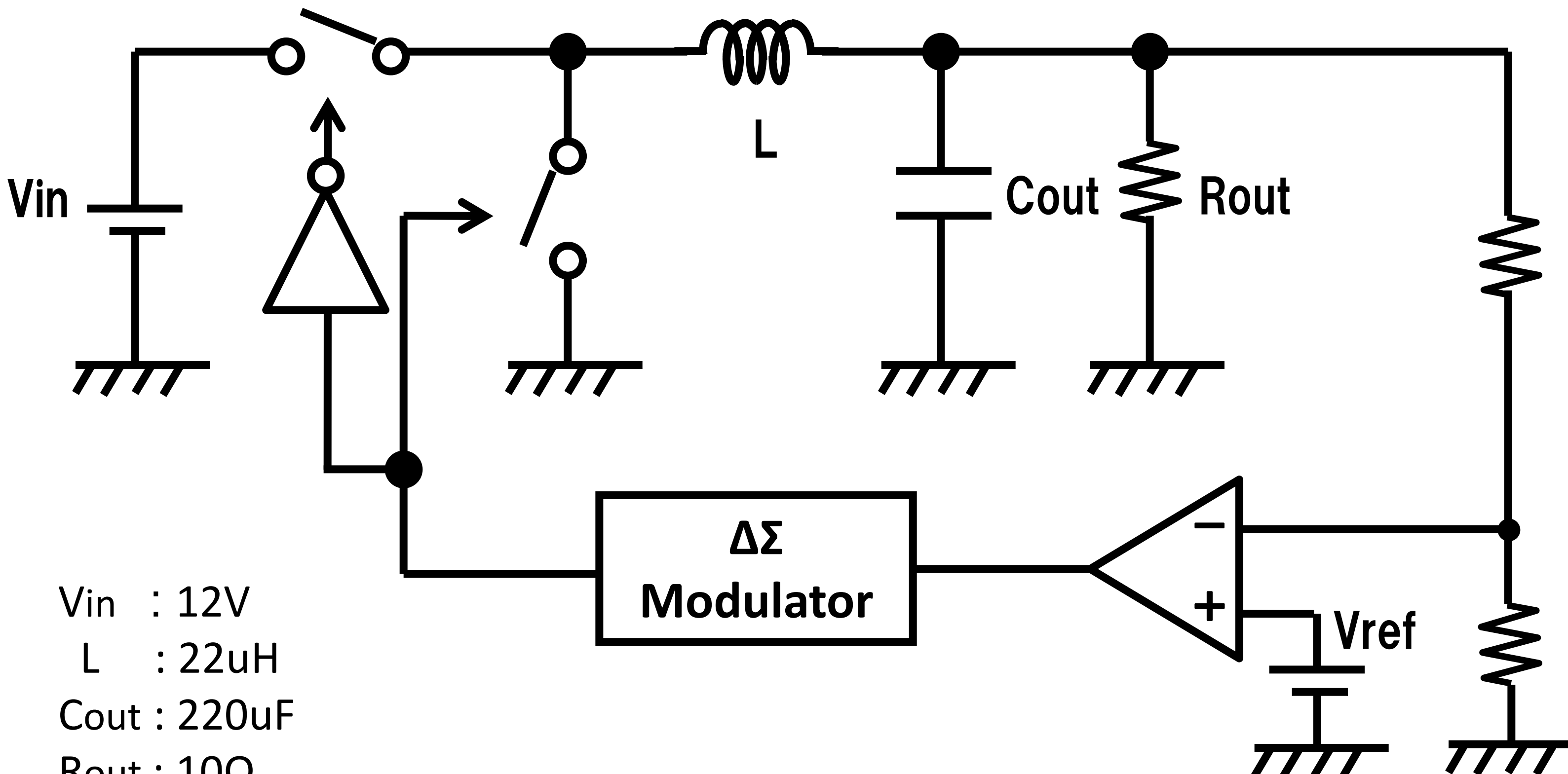
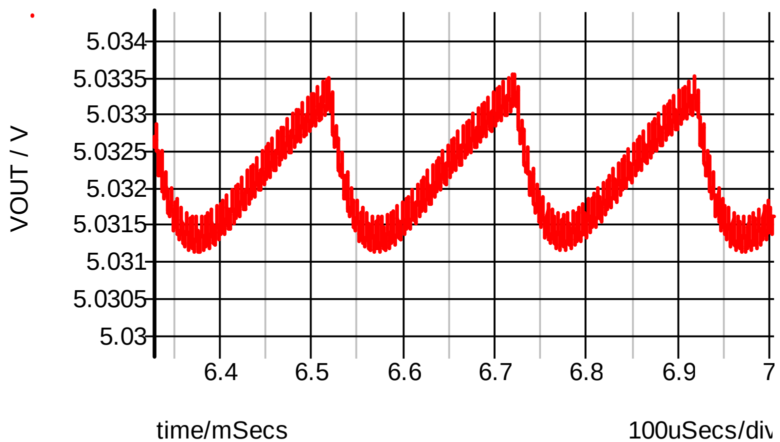
Simulation Conditions



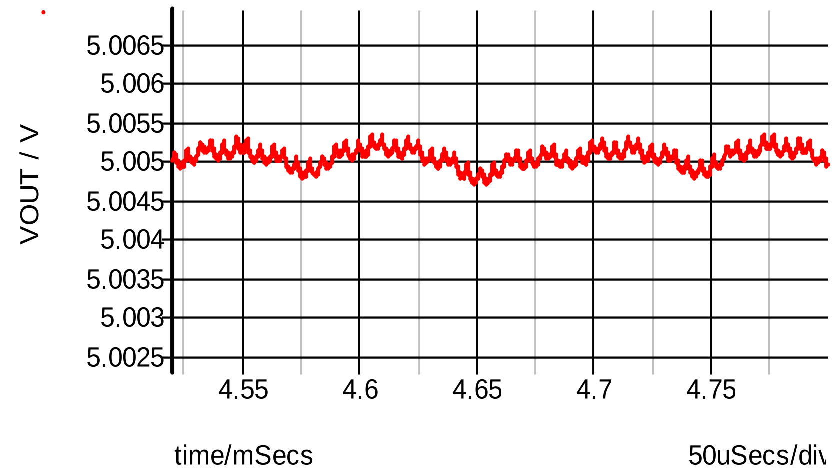
Vin : 12V
L : 22uH
Cout : 220uF
Rout : 10Ω
Fs : 2MHz

Output Voltage Ripple (DT ΔΣ)



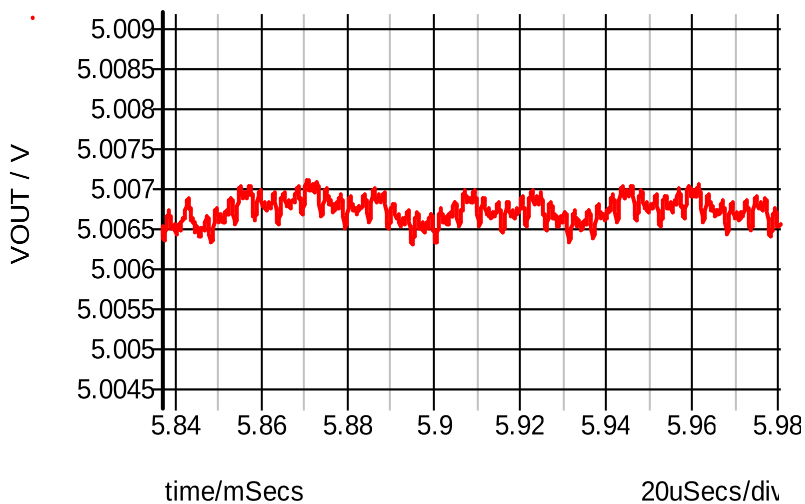
1^{st}-order DT Feedback ΔΣ

ΔV_{pp}=3.2mV



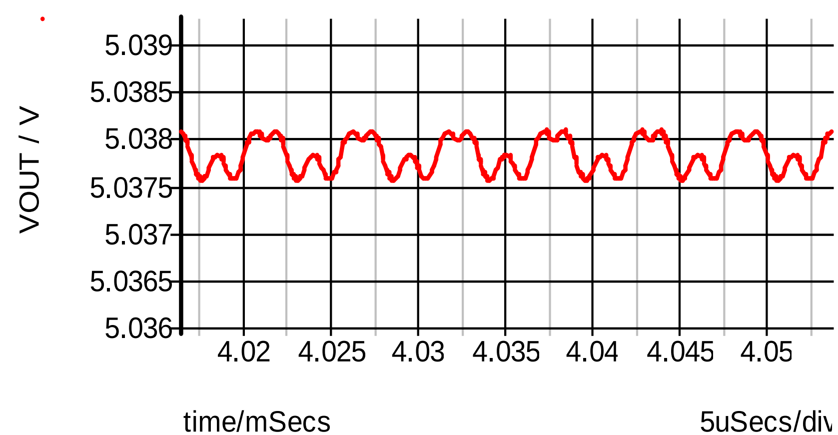
1^{st}-order DT Feed-forward ΔΣ

ΔV_{pp}=0.8mV



2^{st}-order DT Feedback ΔΣ

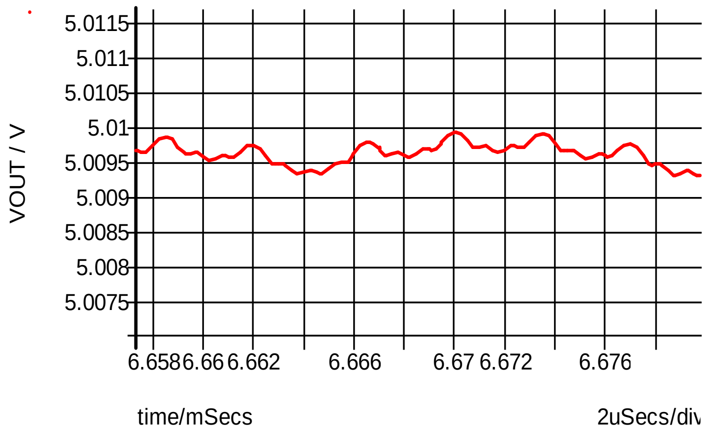
ΔV_{pp}=1.2mV



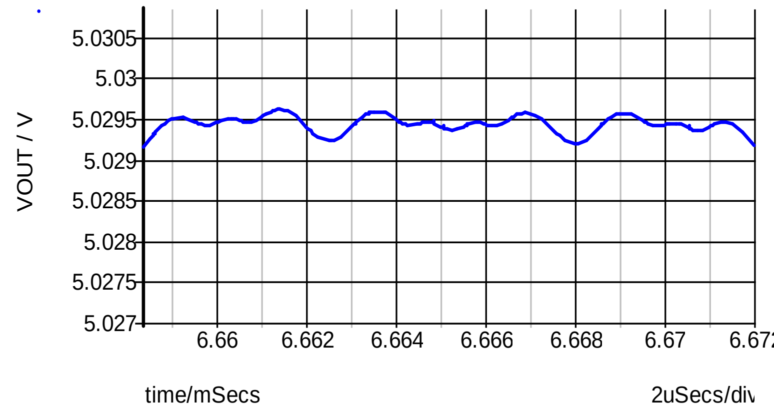
2^{st}-order DT Feed-forward ΔΣ

ΔV_{pp}=0.7mV

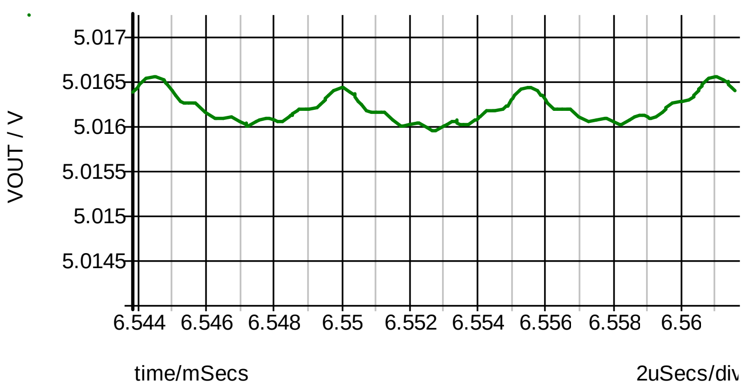
Output Voltage Ripple (CT ΔΣ)



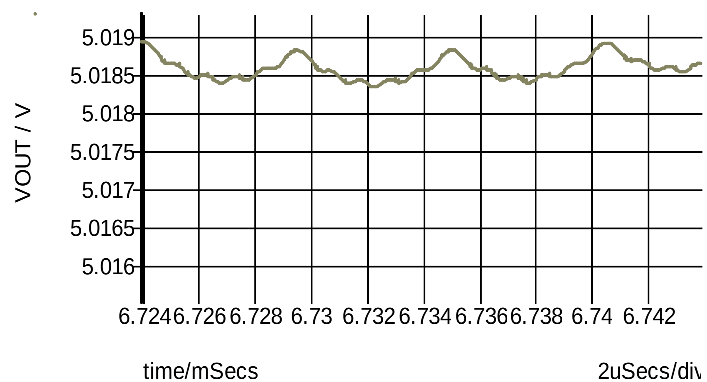
1st-order CT Feedback ΔΣ
ΔVpp=0.5mV



1st-order CT Feed-forward ΔΣ
ΔVpp=0.5mV



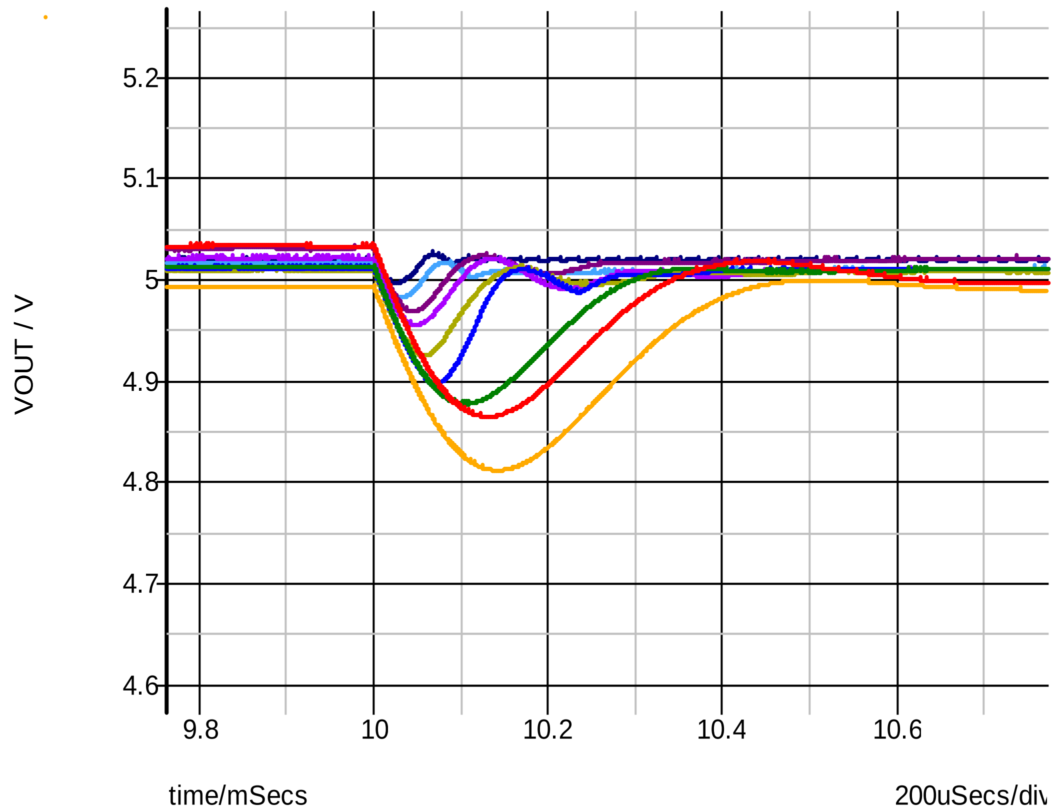
2nd-order CT Feedback ΔΣ
ΔVpp=0.6mV



2nd-order CT Feed-forward ΔΣ
ΔVpp=0.5mV

Transient Response Simulation

(Output Current change from 0.5A to1A)



Slow → Fast

PWM	DT 1st FB	DT 2nd FB	DT 1st FF	DT 2nd FF	CT 1st FB	CT 2nd FB	CT 1st FF	CT 2nd FF

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ΔΣ Controller Comparison

	No Delay	High Frequency	Small Ripple	Low Power	High Precision
1st CT FF ΔΣ	◎	◎		◎	
1st DT FF ΔΣ	◎				◎
1st CT FB ΔΣ		◎		◎	
1st DT FBΔΣ					◎
2nd CT FF ΔΣ	◎	◎	◎	◎	
2nd DT FF ΔΣ	◎		◎		◎
2nd CT FB ΔΣ		◎	◎	◎	
2nd DT FB ΔΣ			◎		◎

Conclusion

2nd-order Continuous-Time, Feed-forward ΔΣ modulator has

- the fastest transient response
- with comparable voltage ripple.

Low power implementation is expected.

Remaining Problem

- Investigation of R,C variation effects