

D-CAP2TM Frequency Response Model based on frequency domain analysis of Fixed On-Time with Bottom Detection having Ripple Injection

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ABSTRACT

Hysteretic control [2], which is basically non-linear control, has become an important control method due to its fast transient response. Normal hysteretic control requires a relatively high-ESR output capacitor. Adding ripple injection to hysteretic control allows the use of low-ESR ceramic output capacitors [3]-[6]. A “Fixed on-time with bottom detection having a ripple injection” control topology is shown in Figure 1. This topology, which is a type of hysteretic control, became popular due to pseudo fixed PWM frequency operation along with compatibility with low-ESR ceramic output capacitors. It is interesting that this control method behaves like linear control, showing similarity to a frequency response (bode-plot) of voltage mode control while keeping wide loop bandwidth, f_{bw} . The frequency domain analysis of the “fixed on-time with bottom detection having ripple injection” is carried out [1] for the optimal DC-DC converter design based on the assumption of (a) Averaged model is applicable to a “small-signal analysis” for frequencies less than the switching frequency and, (b) injected ripple voltage is small compared to reference voltage. As a result, the comparator with ripple injection shows single zero (1st order lead system) characteristics. The open loop transfer function of the converter is expressed as equation (1). Figure 2 shows the approximated curve of the frequency response (bode-plot) based on equation (1). The phase increases up toward +90 degrees due to the single zero, and is a major contributor for the system stability with wide loop bandwidth. This has advantages compared with conventional linear control such as voltage mode control (Figure 3) or a current mode control (Figure 4). For these linear control types, the phase curve is rolling off below 0 degrees in the high frequency range due to the delay of e^{-sT} of the PWM and error amplifier compensation circuit.

The operation of D-CAP2TM control is similar in concept with this “Fixed On-Time with Bottom Detection having Ripple Injection”. The difference is that the ripple injection circuit is integrated on silicon. Therefore, it is stable.

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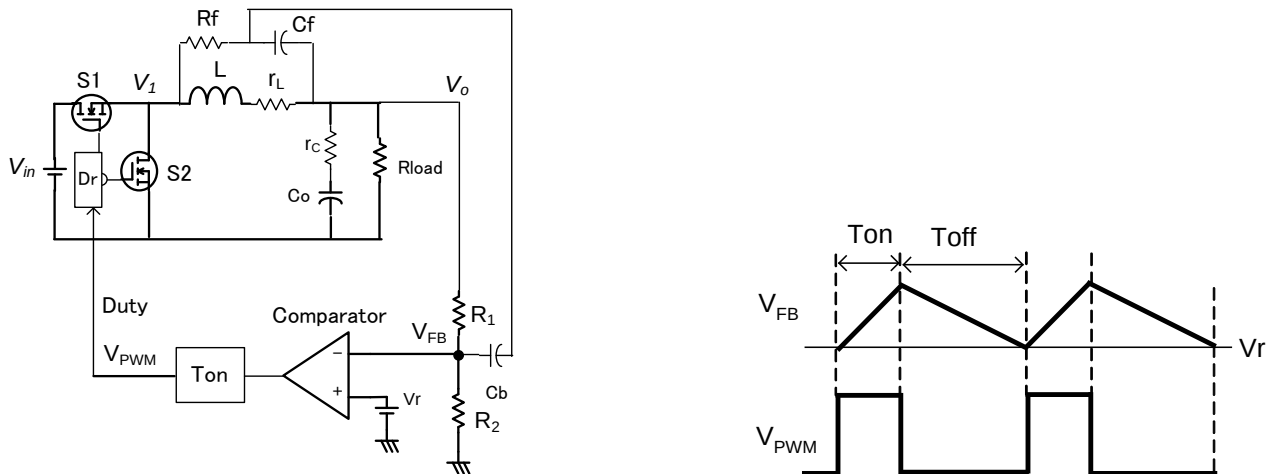


Figure 1. Block diagram of “Fixed On-Time with Bottom Detection having a Ripple Injection [1]

$$G_{open}(s) = G_{dv}(s) \underbrace{\frac{A}{V_{in}}(1 + sT_c)}_{H_{comp}(s)} H_d(s) \quad (1)$$

Where $G_{dv}(s)$ is the transfer function from Duty to V_O , well known using “state-space averaging model”,

$H_{comp}(s)$: Transfer function of the comparator having ripple injection circuit from V_O to Duty.

$A = \frac{R_f}{R_1}$: Voltage gain of ripple injection circuit

$T_c = R_1 C_f$, Time constant of ripple injection circuit

$H_d(s) = e^{-sT_{on}/2}$: Delay factor of fixed on time

See the Appendix A to derive equation (1).

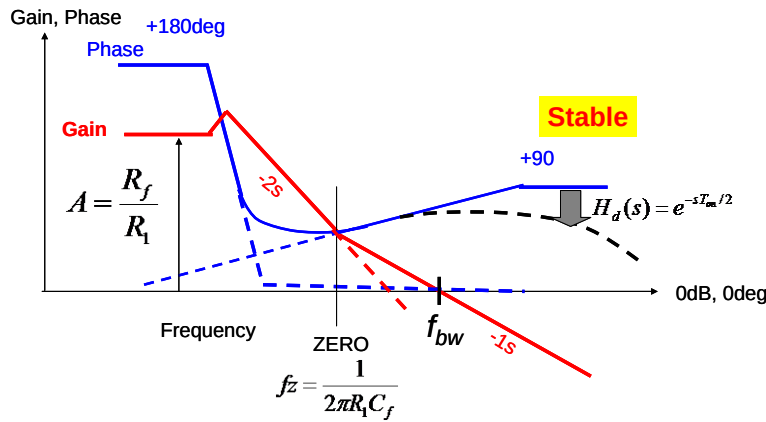


Figure 2. Frequency response (bode-plot) of “Fixed On-Time with Bottom Detection having ripple injection” [1]

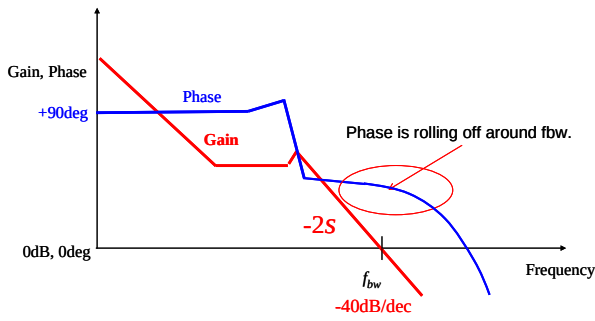


Figure 3. Bode-plot of Voltage mode control

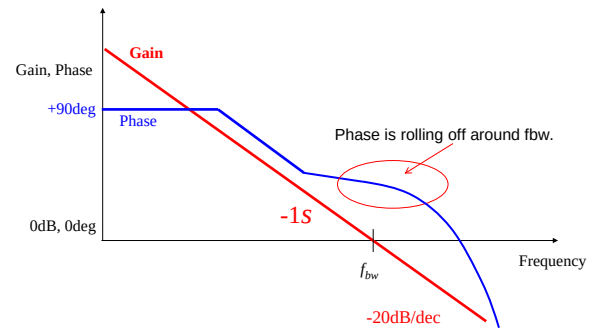


Figure 4. Bode-plot of Current mode control

1 D-CAP2™ open loop transfer function

1.1 Block diagram

Figure 5 shows the block diagram of D-CAP2™ include a comparator having a ripple injection circuit. An open loop transfer function should be expressed in equation (2).

$$G_{open}(s) = G_{dv}(s)H_{FB}(s)H_{COMP}(s)H_d(s) \quad (2)$$

Where, $G_{dv}(s)$ is the transfer function from Duty to V_o using well known “state-space averaging model”.

$H_{FB}(s)$ is the transfer function of the feedback divider network from V_o to V_{FB} .

$H_{COMP}(s)$ is the transfer function of the comparator having ripple injection circuit from V_{FB} to Duty.

$H_d(s) = e^{-sT_{on}/2}$ is the delay due to fixed on time.

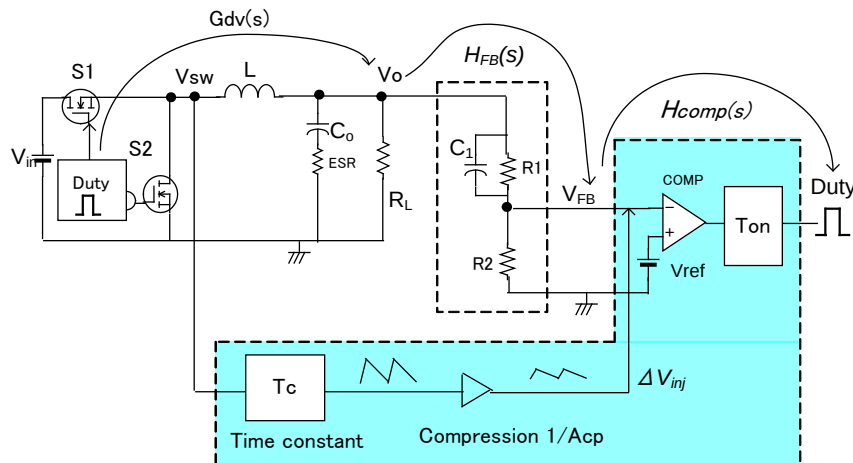


Figure 5. Block diagram of D-CAP2

1.2 $H_{comp}(s)$: The transfer function of comparator with ripple injection

Per the paper of [1], we know that the comparator with the ripple injection circuit has 1-zero (1st order lead system) which the time constant is defined by capacitor and resistor network.

In Figure 5, $H_{comp}(s)$ consists of comparator and the ripple injection circuit. And the ripple injection circuit consists of the time constant block (T_c) and a voltage compression block ($1/A_{cp}$). So, the transfer function $H_{comp}(s)$ is expressed as follows.

$$H_{COMP}(s) = \frac{\Delta D(s)}{\Delta V_{FB}(s)} = \frac{A_{cp}}{V_{in}} (1 + sT_c) \quad (3)$$

1.3 $H_{FB}(s)$: Feedback divider network

The transfer function from V_O to V_{FB} is given as follows.

$$H_{FB}(s) = \frac{R_2}{Z_1(s) + R_2} \quad (4)$$

$$\text{Where, } Z_1(s) = \frac{R_1}{1 + sC_1R_1} \quad (5)$$

DC gain of $H_{FB}(s)$ is

$$H_{FB}(0) = \frac{R_2}{R_1 + R_2} = \frac{V_{ref}}{V_o} \quad (6)$$

1.4 $G_{dv}(s)$: Plant (Power stage transfer function from Duty to V_O)

$G_{dv}(s)$ is given as follows using well known “state-space averaging model”.

$$G_{dv}(s) = \frac{V_{in} \left(1 + \frac{s}{\omega_{esr}} \right)}{1 + 2\delta \frac{s}{\omega_0} + \left(\frac{s}{\omega_0} \right)^2} \quad (7)$$

Where,

$$\delta = \frac{\sqrt{L/C_O} + R_L(r_L + r_C)\sqrt{C_O/L}}{2R_L\sqrt{1 + r_L/R_L}} \quad (8)$$

$$\omega_0 = \sqrt{\frac{1 + r_L/R_L}{LC_O}}$$

1.5 Delay factor of fixed on-time

The duty ratio cannot change while fixed on-time, so it should be considered as delay expressed as follows.

$$H_d(s) = e^{-sT_{on}/2} \quad (9)$$

1.6 Bode-plot shape of D-CAP2™

Now, we derived the open loop transfer function of eq. (2) which the image of the curve is shown in Figure 6. DC gain of open loop transfer function $G_{open}(0)$ is obtained as follows.

$$G_{open}(0) = A_{cp} \times H_{FB}(0) = A_{cp} \times \frac{V_{ref}}{V_O} \quad (10)$$

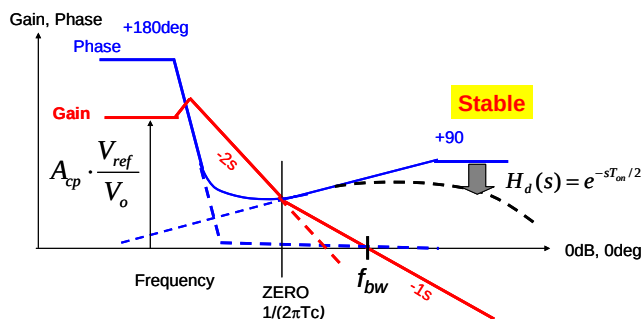


Figure 6. Frequency response (bode-plot) of D-CAP2™

1.7 Measurement block diagram for bode-plot

Figure 7 shows the measurement method using the popular signal injection resistor method in series with feedback network. The injection signal, V_{sig} , from FRA (Frequency Response Analyzer) should be small enough against the amplitude of injected ripple. Usually, V_{sig} is around 1mVpp to 3mVpp. Then, measure the transfer function from V_a to V_b shown in Figure 9.

NOTE: If V_O pin exist, the signal injection resistor (51 ohm) should be connected to R1 and V_O pin as shown in Fig. 7-(a). DO NOT put 51 ohm connect with R1 only as shown in Figure 8 if V_O pin exist. If V_O pin does not exist, put the 51 ohm between R1 and V_o as shown in Figure 7-(b).

Table 1. Applicable Devices as of December 2012

		PKG	Mesurement set up Fig.7	Devices (“/“ denotes devices without or with ECO mode)
Converter	Single		(a)	TPS54225/226, TPS54325/326, TPS54425/426, TPS54429/429E, TPS54525/526, TPS54625/626 ⁽¹⁾
		8SOP	(b)	TPS54227/228, TPS54327/328, TPS54427/428, TPS54527/528, TPS54627/628 ⁽¹⁾ , TPS54229/229E, TPS54329/329E, TPS54339/339E ⁽¹⁾ , TPS54239/239E ⁽¹⁾ , TPS56528/428 ⁽¹⁾ , TPS56228/328 ⁽¹⁾
	Dual	HTSSOP16	(b)	TPS54294/295, TPS54394/395, TPS54494/495, TPS542941/2951
Controller	Single	HTSSOP16	(a)	TPS53114
		VSSOP10	(b)	TPS53014/015
	Dual	TSSOP24	(a)	TPS53125, TPS53126, TPS53127, TPS53128, TPS53129

(1) In development

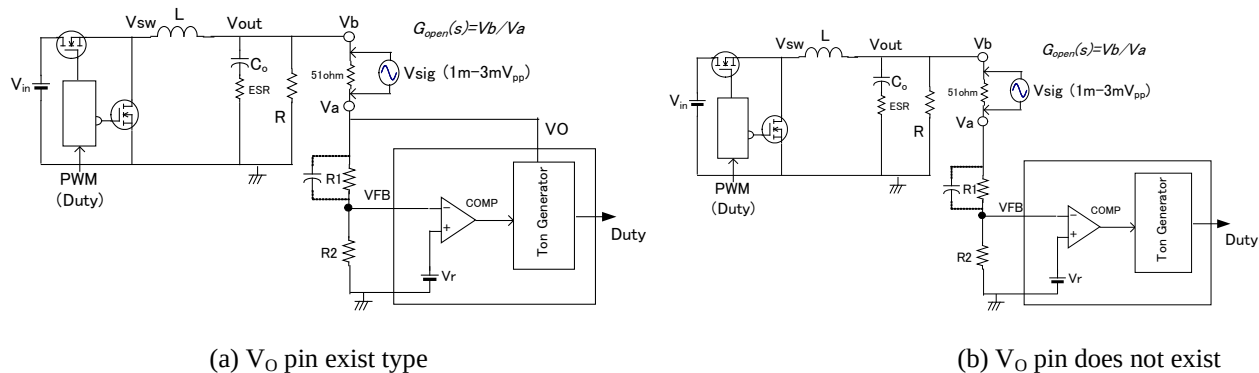


Figure 7. Measurement block diagram for bode-plot

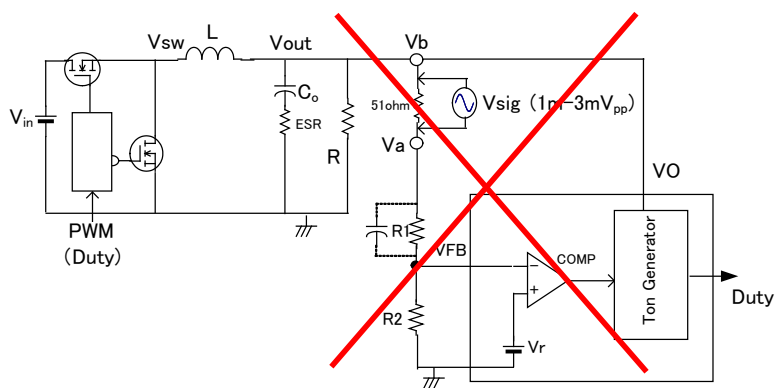


Figure 8. Wrong measurement block diagram of bode-plot for D-CAP2 (if V_O pin exist)

2 Experimental data of bode-plot (Frequency response)

Here are [examples](#) of the TPS54325 (converter) and the TPS53114 (controller). Table 2 and 3 show the value of Acp and Tc of each device with the condition specified in the table.

Table 2.

Device	Condition			Acp	Tc (us)
	Vin(V)	Vo(V)	L(uH)		
TPS54325 (fsw=700kHz)	12.0	1.05	1.5	65	1.06
		1.2	1.5	70	
		1.5	1.5	78	
		1.8	2.2	84	
		2.5	2.2	96	
		3.3	2.2	104	
		5.0	3.3	114	

TPS53114 (Controller):

Table 3.

Device	Condition			Acp	Tc (us)
	Vin(V)	Vo(V)	L(uH)		
TPS53114 (fsw=700kHz)	12.0	1.05	1.5	35	0.95
		1.2	1.5	36	
		1.5	1.5	38	
		1.8	2.2	39	
		2.5	2.2	41	
		3.3	2.2	42	
		5.0	3.3	44	

2.1 TPS54325 (Converter type)

$V_{in} = 12V$, $V_O = 1.05V$, $I_O = 1A$: $L = 1.5\mu H$, $C_{OUT} = 22\mu F \times 2$ (ceramic), $f_{sw} = 700kHz$

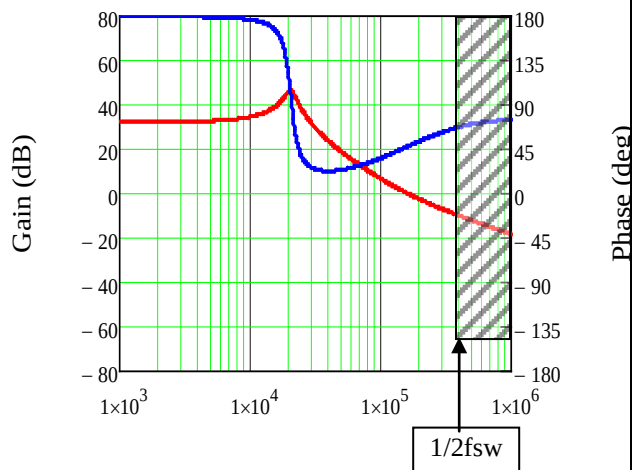


Figure 9. Calculated

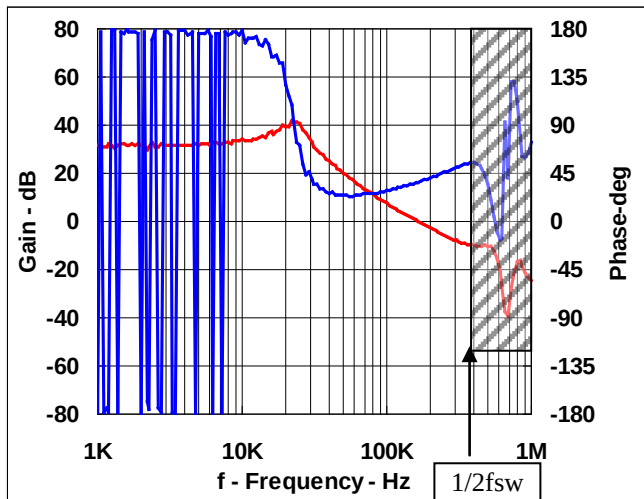


Figure 10. Measured

$V_{in} = 12V$, $V_O = 3.3V$, $I_O = 1A$: $L = 2.2\mu H$, $C_{OUT} = 22\mu F \times 2$ (ceramic), $f_{sw} = 700kHz$

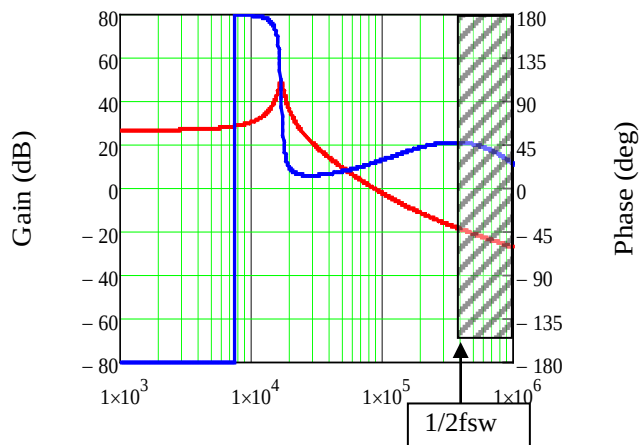


Figure 11. Calculated

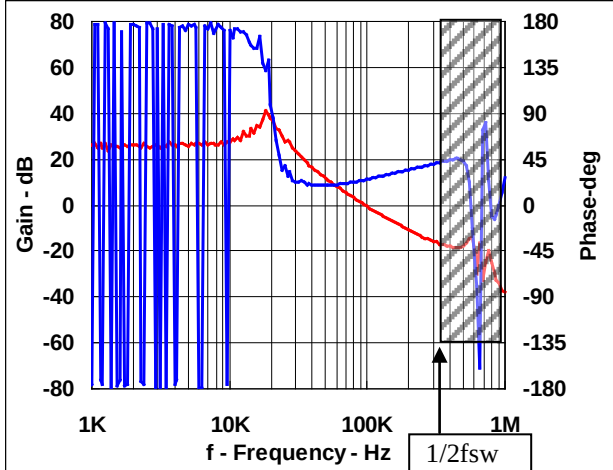


Figure 12. Measured

$V_{in} = 12V$, $V_O = 5V$, $I_O = 1A$: $L = 3.3\mu H$, $C_{OUT} = 22\mu F \times 2$ (ceramic), $f_{sw} = 700kHz$

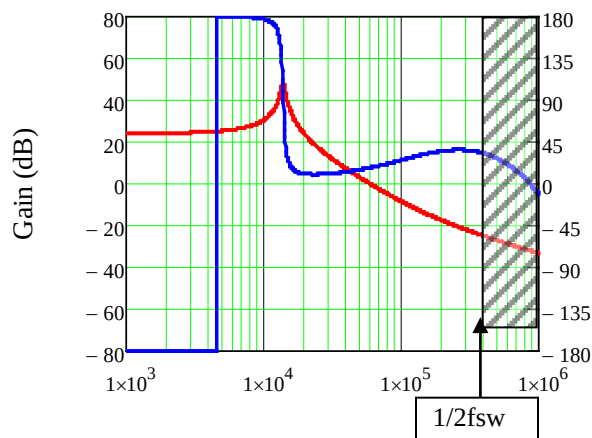


Figure 13. Calculated

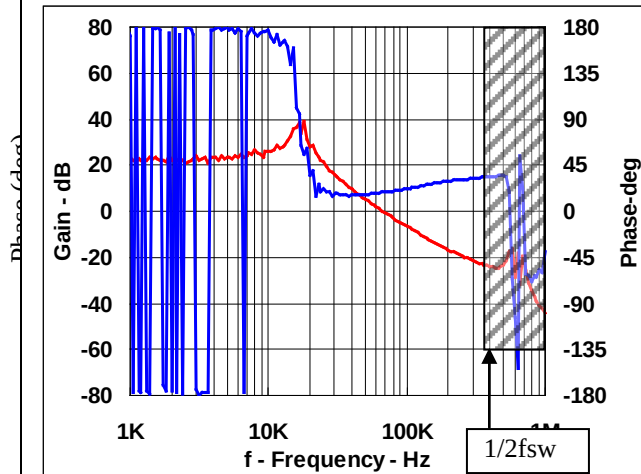


Figure 14. Measured

2.2 TPS53114 (Controller):

$V_{in} = 12V$, $V_O = 1.2V$, $I_O = 2A$, $L = 1.5\mu H$, $C_{OUT} = 22\mu F \times 2$ (ceramic), $f_{sw} = 700kHz$

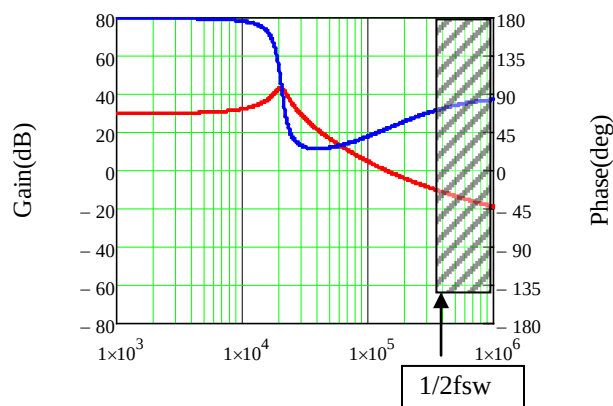


Figure 15. Calculated

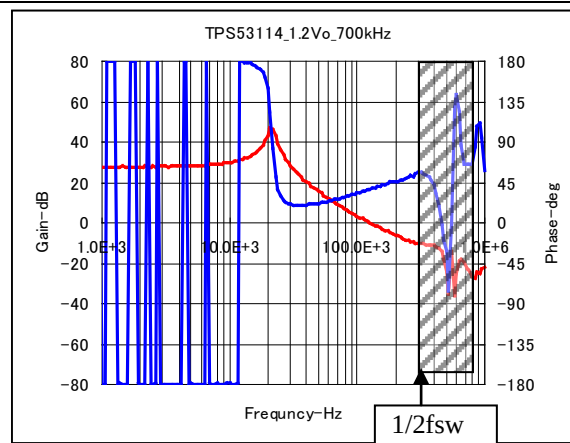


Figure 16. Measured

$V_{in} = 12V$, $V_o = 5V$, $I_o = 2A$, $L = 3.3\mu H$, $C_{OUT} = 22\mu F \times 2$ (ceramic), $f_{sw} = 700kHz$

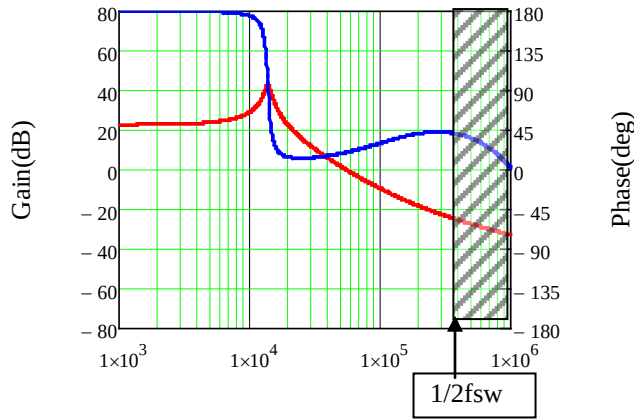


Figure 17. Calculated

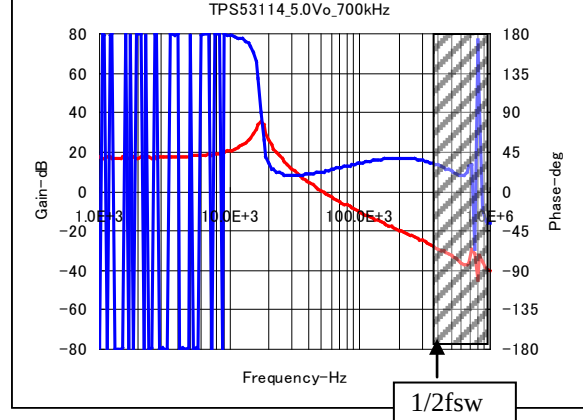


Figure 18. Measured

2.3 Phase compensation technique with Feed Forward capacitor (1pole-1zero of $H_{FB}(s)$)

As shown in equation (2), there exist delay factor $e^{-sT_{on}/2}$ due to fixed on-time. So, for a high duty ratio (such as 12 Vin, 5 Vo, or 5 Vin, 3.3 Vo), the phase curve rolling off by delay factor $e^{-sT_{on}/2}$ becomes obvious.

In this case, feed forward capacitor (C_1 in Figure 5) on $H_{FB}(s)$ circuit can help to get enough phase margin by making 1pole - 1zero in equation below.

$$H_{FB}(s) = \frac{R_2}{Z_1(s) + R_2} = \frac{R_2}{R_1 + R_2} \times \frac{1 + \frac{s}{\omega_z}}{1 + \frac{s}{\omega_p}} \quad (23)$$

Where, Zero (ω_z), pole (ω_p), and center frequency (ω_{center}) of $H_{FB}(s)$ are expressed as follows.

$$\omega_z = \frac{1}{C_1 R_1}, \quad \omega_p = \frac{1}{C_1 (R_1 // R_2)}, \quad \omega_{center} = \sqrt{\omega_z \omega_p} \quad (24)$$

$f_{center} (= \omega_{center}/2\pi)$ is the most phase boosting frequency. Usually, when design $H_{FB}(s)$ with feed forward capacitor, place f_{center} to f_{bw} or $f_z (= \omega_z/2\pi)$ to f_{bw} , or between. It depends on the case.

Figure 19 shows the example of $H_{FB}(s)$ when $V_{in} = 12V$, and $V_{OUT} = 5V$. Figure 19 (a) shows the case of no feed forward capacitor ($C1 = 0pF$). Figure 19 (b) shows the case of $C1 = 47pF$ to make 1pole-1zero of $H_{FB}(s)$. Zero (f_z) is 27.8kHz, and Pole (f_p) is 182kHz. So maximum phase boost is obtained around 71kHz ($=f_{center}$).

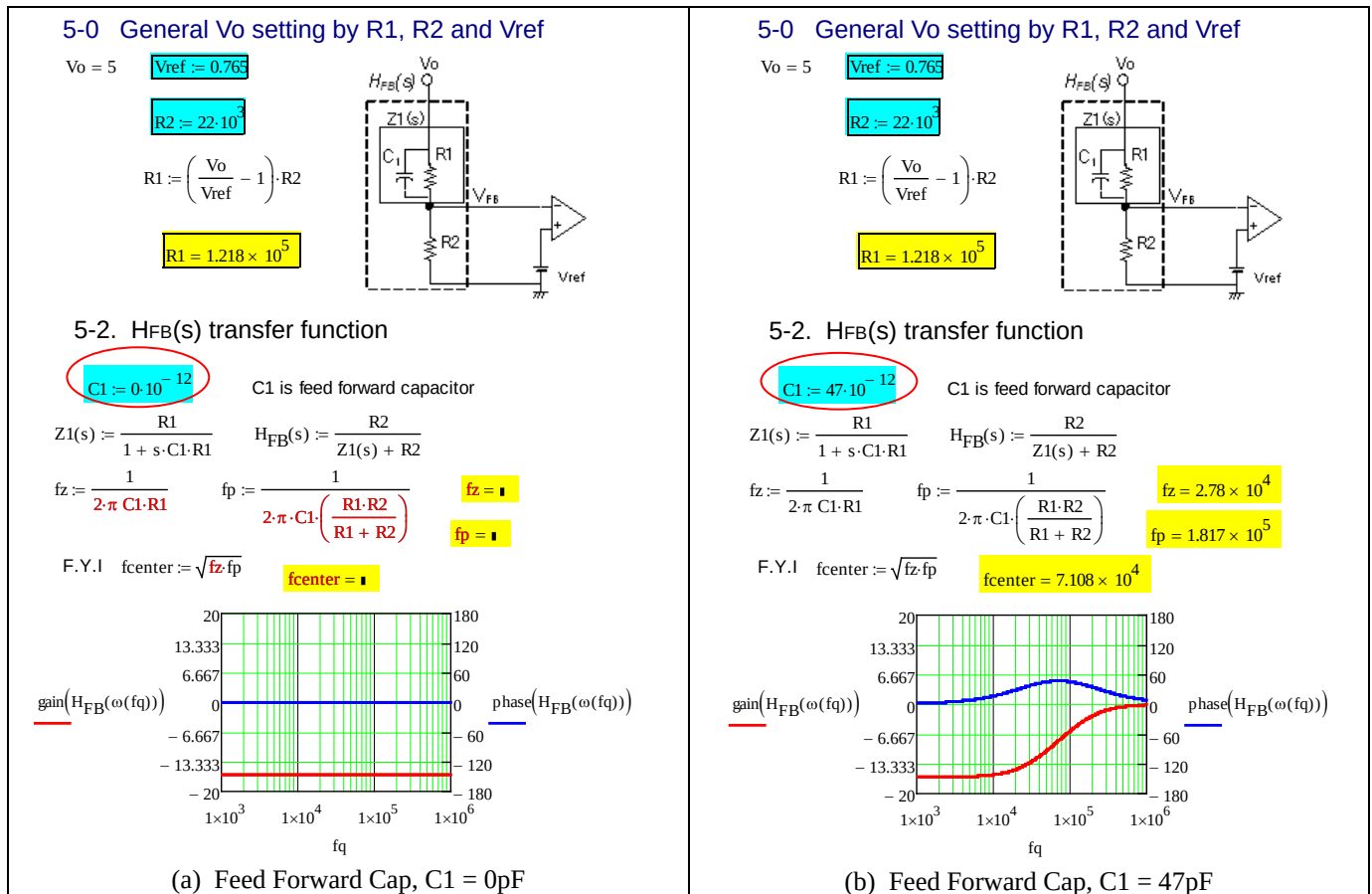


Figure 19. Design of 1pole-1zero using feed forward capacitor (12 Vin, 5 VO)

Figure 20 shows the example of calculated bode-plot (open loop transfer function) of TPS54325 without and with feed forward capacitor, respectively. It is found that the phase margin around loop bandwidth (70kHz) was improved. Here, $L=3.3\mu\text{H}$, $C_o=22\mu\text{F}$, $f_{sw}=700\text{kHz}$.

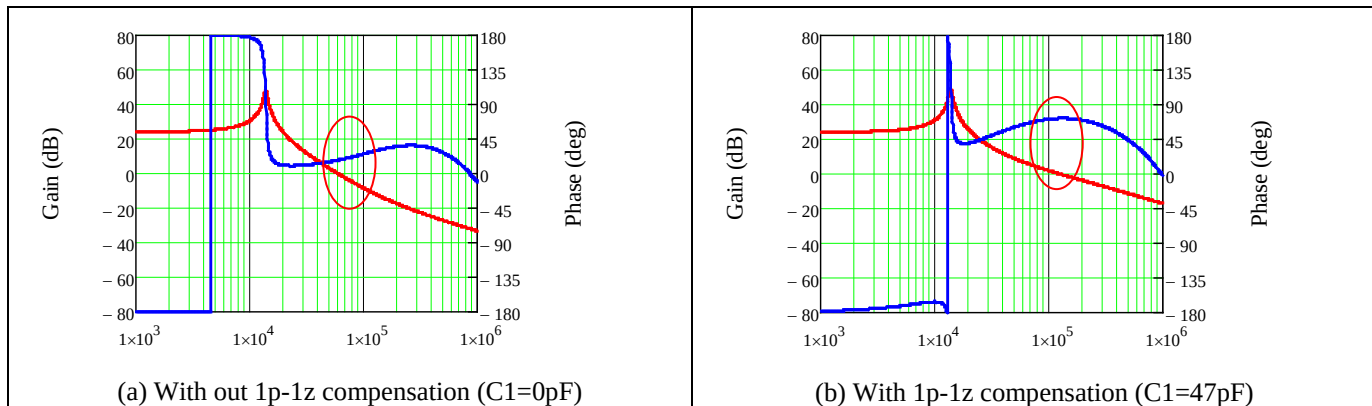


Figure 20. Calculated bode-plot (open loop transfer function) of TPS54325 at 12 Vin, 5 VO.

Figure 21 shows the measured bode-plot with various feed-forward capacitor (C_f means feed-forward capacitor here) to validate the result of Figure 20. It is found that the feed forward capacitor can get enough phase margin as predicted by 1pole-1zero of HFB(s).

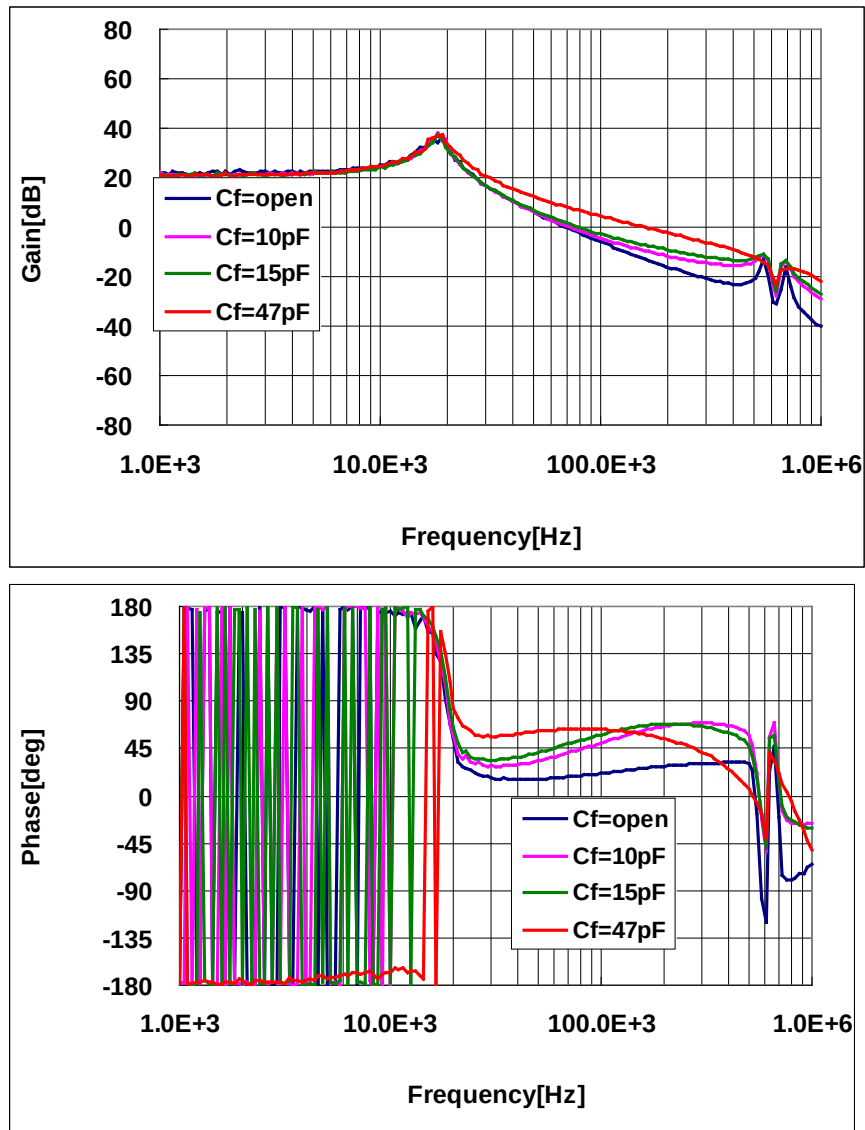


Figure 21. Measured bode-plot (open loop transfer function) of TPS54325 at 12 V_{in} , 5 V_O .

References:

- [1] M. Lin, T. Zaitse, T. Sato, and T. Nabeshima, "Frequency Domain Analysis of Fixed On-Time with Bottom Detection Control for Buck Converter," IEEE IECON2010, pp.475-479
- [2] B.P. Schweizer and A.B. Rosenstein, "Free Running – Switching Mode Regulator: Analysis and Design," IEEE Transactions on Aerospace, vol. AS-2, Oct. 1964, pp.1171-1180.
- [3] R. Miftakhutdinov, "An Analytical Comparison of Alternative Control technique for powering Next-Generation Microprocessors," Texas Instruments Seminar 2002.
- [4] Kisun Lee, Fred C. Lee and Ming Xu, "Novel Hysteretic Control Method for Multiphase Voltage Regulators," APEC2008.
- [5] T. Nabeshima, T. Sato, S. Yoshida, S. Chiba and K. Onda, "Analysis and design consideration of a buck converter with a hysteretic PWM controller," IEEE PESC Records, pp.1711-1716, 2004
- [6] K. Taniguchi, T. Sato, T. Nabeshima, and K. Nishijima, "Constant Frequency Hysteretic PWM Controlled Buck Converter", Proceedings of IEEE PEDS 2009, Paper No.476, CD-ROM, 2009

Appendix A.

A.1 How to derive the transfer function of hysteretic comparator having ripple injection in the hysteretic control

This is the appendix for the paper [1].

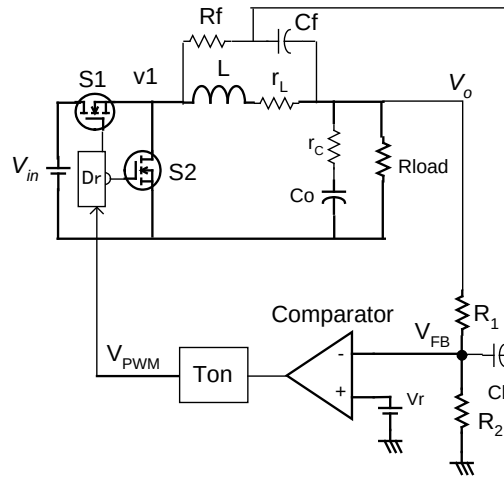


Figure A-1. Block diagram of hysteretic control (Fixed on-time with Bottom detection) having ripple injection

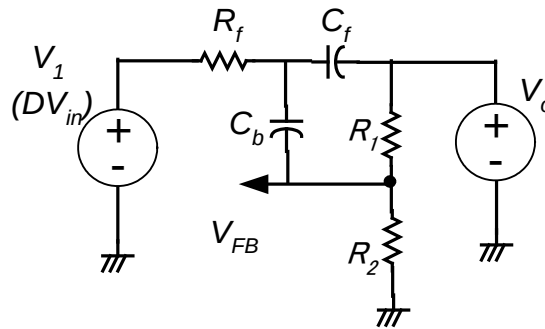


Figure A-2. Equivalent circuit of Figure A-1

There are two voltages of $V_1 (=DV_{in})$ and V_O in Figure A-2. Principle of superposition is used to get the transfer function.

A.2 When $V_O = 0$ (V_O short)

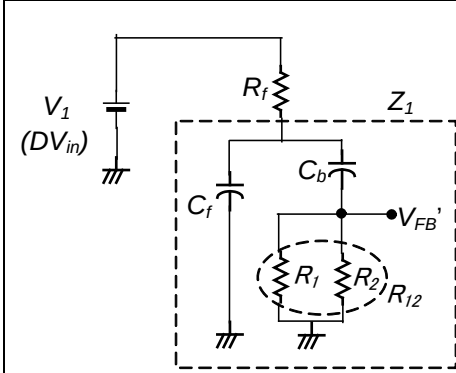


Figure A-3 Equivalent Circuit of Fig. A-2 when $V_O = 0$

The impedance of Z_1 is expressed as follows.

$$Z_1 = \frac{1}{sC_f} \parallel \left(\frac{1}{sC_b} + R_{12} \right) \quad (A-1)$$

$$= \frac{1 + sR_{12}C_b}{s(C_f + C_b) + s^2C_fC_bR_{12}}$$

Where, $R_{12} = \frac{R_1R_2}{R_1 + R_2}$

Using equation (A-1), V_{FB}' is expressed as follows with $D \times V_{in}$.

$$V_{FB}' = DV_{in} \times \frac{Z_1}{R_f + Z_1} \times \frac{R_{12}}{\frac{1}{sC_b} + R_{12}} = \frac{sC_bR_{12}}{s^2T_cC_bR_{12} + sC_bR_{12} + sR_f(C_f + C_b) + 1} \times DV_{in} \quad (A-2)$$

Where, $T_c = C_fR_f$

A.3 When $V_1 = 0$ (V_1 short)

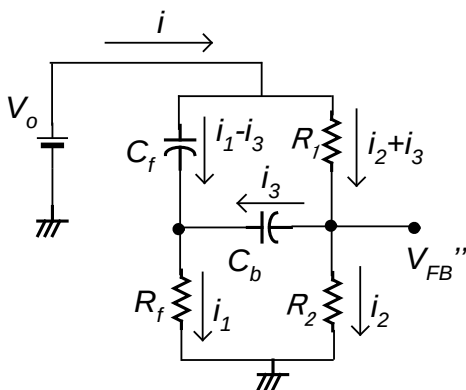


Figure A-4 Equivalent Circuit of Fig. A-2 when $V_1 = 0$

By Kirchhoff's laws, equations were obtained as follows.

$$V_O = \frac{1}{sC_f}(i_1 - i_3) + R_f i_1 \quad (A-3)$$

$$V_O = R_1(i_2 + i_3) + R_2 i_2 \quad (A-4)$$

$$R_f i_1 = R_2 i_2 - \frac{1}{sC_b} i_3 \quad (A-5)$$

i_3 is obtained by eliminating i_1 from equations (A-3) and (A-5).

$$i_3 = \frac{1}{\frac{R_f}{1 + sC_f R_f} + \frac{1}{sC_b}} \times \left(R_2 i_2 - \frac{R_f}{R_f + \frac{1}{sC_f}} \times V_O \right) \quad (A-6)$$

i_2 is obtained by eliminating i_3 from equations (A-4) and (A-6).

$$i_2 = \frac{\left(\frac{R_f}{1 + sC_f R_f} + \frac{1}{sC_b} \right) \times \frac{1}{R_1} + \frac{sC_f R_f}{1 + sC_f R_f}}{R_2 + \frac{R_1 + R_2}{R_1} \times \left(\frac{R_f}{1 + sC_f R_f} + \frac{1}{sC_b} \right)} V_O \quad (A-7)$$

So, we can get V_{FB}'' as follows.

$$V_{FB}'' = R_2 i_2 = \frac{\left(\frac{R_f}{1 + sC_f R_f} + \frac{1}{sC_b} \right) \cdot \frac{1}{R_1} + \frac{sC_f R_f}{1 + sC_f R_f}}{1 + \frac{R_1 + R_2}{R_1 R_2} \cdot \left(\frac{R_f}{1 + sC_f R_f} + \frac{1}{sC_b} \right)} V_O = \frac{s^2 \cdot T_C C_b R_1 R_2 + s \cdot R_2 (T_C + R_f C_b) + R_2}{s^2 \cdot T_C C_b R_1 R_2 + s \{ C_b R_1 R_2 + (R_1 + R_2) (T_C + R_f C_b) \} + (R_1 + R_2)} \cdot V_O \quad (A-8)$$

From the principle of superposition,

$$V_{FB} = V_{FB}' + V_{FB}'' = \frac{sC_b R_{12}}{s^2 T_C C_b R_{12} + sC_b R_{12} + sR_f (C_f + C_b) + 1} \times DV_{in} \quad (A-9)$$

$$+ \frac{s^2 \times T_C C_b R_1 R_2 + s \times R_2 (T_C + R_f C_b) + R_2}{s^2 \times T_C C_b R_1 R_2 + s \{ C_b R_1 R_2 + (R_1 + R_2) (T_C + R_f C_b) \} + (R_1 + R_2)} \times V_O$$

Here we can assume below because the ripple voltage ΔV_{FB} is small enough compared to V_{FB} .

$$V_{FB} = V_r \quad (A-10)$$

Equation (A-9) is simply expressed as follows. This is a steady-state solution.

$$V_{FB} = V_r = G_1(s)DV_{in} + G_2(s)V_O \quad (A-11)$$

$$\text{Where, } G_1(s) = \frac{sC_b R_{12}}{s^2 T_C C_b R_{12} + sC_b R_{12} + sR_f(C_f + C_b) + 1}$$

$$G_2(s) = \frac{s^2 \times T_C C_b R_1 R_2 + s \times R_2 (T_C + R_f C_b) + R_2}{s^2 \times T_C C_b R_1 R_2 + s \left\{ C_b R_1 R_2 + (R_1 + R_2) (T_C + R_f C_b) \right\} + (R_1 + R_2)}$$

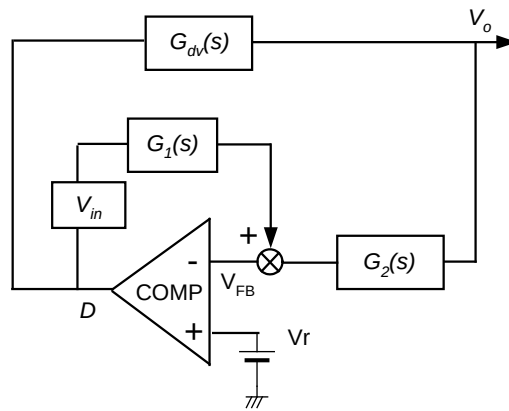


Figure. A-5. Control Block Diagram of equation (A-11)
($G_{dv}(s)$ is the known plant transfer function from D to V_o)

A.4 Transfer function from ΔV_O to ΔD (Small-signal dynamic characteristic analysis)

Through a well-known “small-signal dynamic characteristic analysis”, assuming $D \rightarrow D + \Delta D$, $V_O \rightarrow V_O + \Delta V_O$ to see the transfer function from ΔV_O to ΔD . Equation (A-11) is expressed as follows.

$$V_r = G_1(s)(D + \Delta D)V_{in} + G_2(s)(V_O + \Delta V_O) \quad (A-12)$$

Substituting equation (A-11) as steady-state solution to equation (A-12), equation (A-13) was obtained.

$$\begin{aligned} \frac{\Delta D}{\Delta V_O} &= - \frac{G_2(s)}{G_1(s)} \times \frac{1}{V_{in}} = - \frac{s^2 \times T_C C_b R_1 R_2 + s \times R_2 (T_C + R_f C_b) + R_2}{\frac{s^2 \times T_C C_b R_1 R_2 + s \{C_b R_1 R_2 + (R_1 + R_2)(T_C + R_f C_b)\} + (R_1 + R_2)}{s C_b R_{12}}} \times \frac{1}{V_{in}} \\ &= - \frac{s^2 T_C C_b R_1 + s(T_C + R_f C_b) + 1}{s R_1 C_b} \times \frac{1}{V_{in}} \end{aligned} \quad (A-13)$$

Finally, putting $C_b = \infty$, the simplified equation of the comparator transfer function was obtained as follows.

$$\frac{\Delta D}{\Delta V_O} = - \frac{R_f}{R_1 V_{in}} (1 + s R_1 C_f) \quad (A-14)$$

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