**D-CAP2™ 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-CAP2™ 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.
D-CAP2™ open loop transfer function

1.1 Block diagram .......................................................................................................................... 4
1.2 $H_{\text{comp}}(s)$: The transfer function of comparator with ripple injection ............................. 5
1.3 $H_{\text{FB}}(s)$: Feedback divider network .................................................................................. 5
1.4 $G_{\text{dv}}(s)$: Plant (Power stage transfer function from Duty to $V_O$) ................................. 6
1.5 Delay factor of fixed on-time .................................................................................................. 6
1.6 Bode-plot shape of D-CAP2™ ............................................................................................. 6
1.7 Measurement block diagram for bode-plot .......................................................................... 7

2 Experimental data of bode-plot (Frequency response) ............................................................ 9
2.1 TPS54325 (Converter type) ................................................................................................. 10
2.2 TPS53114 (Controller): ....................................................................................................... 11
2.3 Phase compensation technique with Feed Forward capacitor (1pole-1zero of $H_{\text{FB}}(s)$) .... 12

References: .................................................................................................................................... 16
Appendix A. .................................................................................................................................... 17
A.1 How to derive the transfer function of hysteretic comparator having ripple injection in the hysteretic control ........................................................................................................................................ 17
A.2 When $V_O = 0$ ($V_O$ short) ............................................................................................... 18
A.3 When $V_1 = 0$ ($V_1$ short) ................................................................................................. 18
A.4 Transfer function from $\Delta V_O$ to $\Delta D$ (Small-signal dynamic characteristic analysis) .... 21

Figure 1. Block diagram of “Fixed On-Time with Bottom Detection having a Ripple Injection [1]
\[ G_{\text{open}}(s) = G_{dv}(s) \frac{A}{V_{\text{in}}} \left( 1 + sT_c \right) H_d(s) \]

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

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

\[ A = \frac{R_f}{R_1} : \text{Voltage gain of ripple injection circuit} \]

\[ T_c = R_1 C_f , \text{ Time constant of ripple injection circuit} \]

\[ H_d(s) = e^{-sT_0/2} : \text{Delay factor of fixed on time} \]

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]
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).

\[ G_{open}(s) = G_d(s)H_{FB}(s)H_{COMP}(s)H_d(s) \]  

(2)

Where, \(G_d(s)\) is the transfer function from Duty to Vo using well known “state-space averaging model”.

\(H_{FB}(s)\) is the transfer function of the feedback divider network from Vo 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.
1.2 $H_{\text{comp}}(s)$: 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 ($1^{\text{st}}$ order lead system) which the time constant is defined by capacitor and resister network.

In Figure 5, $H_{\text{comp}}(s)$ 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 $H_{\text{comp}}(s)$ is expressed as follows.

$$H_{\text{comp}}(s) = \frac{\Delta D(s)}{\Delta V_{FB}(s)} = \frac{A_{cp}}{V_{in}} (1 + sT_c)$$  \hspace{1cm} (3)

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

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

$$H_{\text{FB}}(s) = \frac{R_2}{Z_1(s) + R_2}$$  \hspace{1cm} (4)

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

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

$$H_{\text{FB}}(0) = \frac{R_2}{R_1 + R_2} = \frac{V_{\text{ref}}}{V_o}$$  \hspace{1cm} (6)
1.4 **Gdv(s): Plant (Power stage transfer function from Duty to \( V_o \))**

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

(7)

Where,

\[
\delta = \sqrt{\frac{L}{C_o}} + R_L (r_L + r_C) \sqrt{C_o/L} \quad \left(\frac{1 + r_L/R_L}{2R_L}\right) \sqrt{1 + r_L/R_L}
\]

(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.

\[
H_d(s) = e^{-sTon/2}
\]

(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.

\[
G_{open}(0) = A_{cp} x H_{FB}(0) = A_{cp} \times \frac{V_{ref}}{V_o}
\]

(10)
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, Vsig, from FRA (Frequency Response Analyzer) should be small enough against the amplitude of injected ripple. Usually, Vsig is around 1mVpp to 3mVpp. Then, measure the transfer function from Va to Vb 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 Vo as shown in Figure 7-(b).

Table 1. Applicable Devices as of December 2012

<table>
<thead>
<tr>
<th></th>
<th>PKG</th>
<th>Mesurement set up Fig.7</th>
<th>Devices (“/“ denotes devices without or with ECO mode)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8SOP</td>
<td>HTSSOP16</td>
<td>TPS54294/295, TPS54294/295, TPS54494/495, TPS542941/2951</td>
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<tr>
<td>Controller</td>
<td>Single</td>
<td>HTSSOP16</td>
<td>TPS53114</td>
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<td>VSSOP10</td>
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<td>TPS53125, TPS53126, TPS53127, TPS53128, TPS53129</td>
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</tbody>
</table>

(1) In development
D-CAP2™ Frequency Response Model based on frequency domain analysis of Fixed On-Time with Bottom Detection having Ripple Injection

\[
G_{\text{open}}(s) = \frac{V_b}{V_a}
\]

Figure 7. Measurement block diagram for bode-plot

Figure 8. Wrong measurement block diagram of bode-plot for D-CAP2 (if VO 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.**

<table>
<thead>
<tr>
<th>Device</th>
<th>Condition</th>
<th>Acp</th>
<th>Tc (us)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPS54325</td>
<td>Vin(V)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(fsw=700kHz)</td>
<td>12.0</td>
<td>1.05</td>
<td>65</td>
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<tr>
<td></td>
<td></td>
<td>1.2</td>
<td>70</td>
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<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>78</td>
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<td></td>
<td>1.8</td>
<td>84</td>
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<td>96</td>
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<td>3.3</td>
<td>104</td>
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<tr>
<td></td>
<td></td>
<td>5.0</td>
<td>114</td>
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<tr>
<td></td>
<td>Vo(V)</td>
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TPS53114 (Controller):

**Table 3.**

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<th>Condition</th>
<th>Acp</th>
<th>Tc (us)</th>
</tr>
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<td>Vin(V)</td>
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<tr>
<td>(fsw=700kHz)</td>
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<td>1.05</td>
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<td>Vo(V)</td>
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</table>

D-CAP2TM Frequency Response Model based on frequency domain analysis of Fixed On-Time with Bottom Detection having Ripple Injection
2.1 TPS54325 (Converter type)

\[ \text{Vin} = 12V, \ V_O = 1.05V, \ I_O = 1A; \ L = 1.5uH, \ C_{OUT} = 22uFx2 \text{ (ceramic), } 700kHz \]

![Figure 9. Calculated](image1)

![Figure 10. Measured](image2)

\[ \text{Vin} = 12V, \ V_O = 3.3V, \ I_O = 1A; \ L = 2.2uH, \ C_{OUT} = 22uFx2 \text{ (ceramic), } f_{sw} = 700kHz \]

![Figure 11. Calculated](image3)

![Figure 12. Measured](image4)
Vin = 12V, \( V_o = 5V \), \( I_o = 1A \); \( L = 3.3uH \), \( C_{OUT} = 22uF \) (ceramic), \( f_{sw} = 700kHz \)

2.2 TPS53114 (Controller):
Vin = 12V, \( V_o = 1.2V \), \( I_o = 2A \), \( L = 1.5uH \), \( C_{OUT} = 22uF \) (ceramic), \( f_{sw} = 700kHz \)
Vin = 12V, Vo=5V, Io=2A, L = 3.3uH, COUT = 22uFx2 (ceramic), fsw=700kHz

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

As shown in equation (2), there exist delay factor $e^{-\frac{2\pi}{sT_{on}}}$ 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 $e^{-\frac{2\pi}{sT_{on}}}$ becomes obvious.

In this case, feed forward capacitor (C1 in Figure 5) on HFB(s) circuit can help to get enough phase margin by making 1pole - 1zero in equation below.

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

(23)

Where, Zero ($\omega_z$), pole ($\omega_p$), and center frequency ($\omega_{center}$) of $H_{FB}(s)$ are expressed as follows.

$$\omega_z = \frac{1}{C_1R_1}, \quad \omega_p = \frac{1}{C_1(R_1//R_2)}, \quad \omega_{center} = \sqrt{\omega_z\omega_p}$$

(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 ($C_1 = 0\, \mu F$). Figure 19 (b) shows the case of $C_1 = 47\, \mu F$ 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=3.3uH, Co=22uFx2, fsw=700kHz.

(a) Without 1p-1z compensation (C1=0pF)
(b) With 1p-1z compensation (C1=47pF)

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 (Cf 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 Vin, 5 VO.
References:


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)

The impedance of $Z_1$ is expressed as follows.

$$Z_1 = \frac{1}{sC_f} // \left( \frac{1}{sC_b} + R_{12} \right)$$

(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 $D x Vin$.

$$V_{FB}' = DV_{in} \frac{Z_1}{R_f + Z_1} \left( \frac{1}{sC_f} + R_{12} \right)$$

$$sC_bR_{12}$$

$$s^2T_cC_bR_{12} + sC_bR_{12} + sR_f(C_f+C_b) + 1$$

$DV_{in}$  (A-2)

Where, $T_c = C_fR_f$

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

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

$$V_O = \frac{1}{sC_i}(i_1 - i_3) + R_1i_1$$  (A-3)

$$V_O = R_1(i_2 + i_3) + R_2i_2$$  (A-4)

$$R_1i_1 = R_2i_2 - \frac{1}{sC_b}i_3$$  (A-5)
\( i_3 \) is obtained by eliminating \( i_1 \) from equations (A-3) and (A-5).

\[
i_3 = \frac{1}{R_f} \times \left( R_2 i_2 - \frac{R_f}{R_f + \frac{1}{sC_f}} \times V_O \right)
\]  \hspace{1cm} (A-6)

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

\[
i_2 = \frac{R_f}{1 + sC_f R_f} \times \frac{1}{R_f} + \frac{sC_f R_f}{1 + sC_f R_f} \times \frac{1}{R_f} + \frac{1}{sC_f} \times V_O
\]  \hspace{1cm} (A-7)

So, we can get \( V_{FB} \) as follows.

\[
V_{FB} = \frac{R_f}{R_f + \frac{1}{sC_f}} \times \left( \frac{1}{R_f} + \frac{sC_f R_f}{1 + sC_f R_f} \right) \times \frac{1}{1 + sC_f R_f} \times \frac{1}{sC_f} \times V_O
\]  \hspace{1cm} (A-8)

From the principle of superposition,

\[
V_{FB} = V_{FB}' + V_{FB}'' = \frac{sC_b R_{12}}{s^2 T_C b R_{12} + s C_b R_{12} + s R_f (C_f + C_b) + 1} \times DV_{in}
\]  \hspace{1cm} (A-9)

\[
+ \frac{s^2 \times T_C b R_{12} R_f + s \times R_2 (T_C + R_f C_b) + R_2}{s^2 \times T_C b R_{12} R_f + s \left( C_b R_{12} + (R_1 + R_2) (T_C + R_f C_b) \right) + (R_1 + R_2)} \times V_O
\]

Here we can assume below because the ripple voltage \( \Delta V_{FB} \) is small enough compared to \( V_{FB} \).

\[
V_{FB} = V_r
\]  \hspace{1cm} (A-10)
Equation (A-9) is simply expressed as follows. This is a steady-state solution.

\[ V_{FB} = V_r = G_1(s)DV_{in} + G_2(s)V_O \]  

(A-11)

Where,

\[ G_1(s) = \frac{sC_bR_{12}}{s^2T_CbR_{12} + sC_bR_{12} + sR_f(C_f + C_b) + 1} \]

\[ G_2(s) = \frac{s^2 \times T_CbR_1R_2 + s \times R_2(T_C + R_fC_b) + R_2}{s^2 \times T_CbR_1R_2 + s \left( C_bR_1R_2 + (R_1 + R_2)(T_C + R_fC_b) \right) + (R_1+R_2)} \]

Figure. A-5. Control Block Diagram of equation (A-11)  
(Gdv(s) is the known plant transfer function from D to Vo)
A.4 Transfer function from $\Delta V_o$ to $\Delta D$ (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 $\Delta V_O$ to $\Delta D$. 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.

$$\frac{\Delta D}{\Delta V_O} = -\frac{G_2(s)}{G_1(s)} \times \frac{1}{V_{in}} = -\frac{s^2 \times T_c C_b R_1 R_2 + s \times R_2(T_c + R_1 C_b) + R_2}{s^2 T_c C_b R_{12} + s C_b R_{12} + s R_f (C_f + C_b) + 1} \times \frac{1}{V_{in}}$$

(A-13)

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

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