Average current mode control

Another approach to current mode control, in which the average current (rather than peak) is controlled to follow a reference. Commercial control chips are available that are intended for average current mode control—originally from Unitrode (TI) for rectifier applications—later from other companies—later used in dc-dc, dc-ac applications

Advantages

- Better noise immunity than peak current control
- Better accuracy (no issues related to ripple or artificial ramp)
- Doesn’t need slope compensation (artificial ramp)
- Can control average currents in any branch—need not control only inductor current

Disadvantage: doesn’t provide immediate transistor current limit so doesn’t mitigate transformer saturation problems in push-pull converter
Basic circuit (buck example)

Gate driver

\[ T_c \]

\[ d \]

\[ \frac{1}{VM} \]

\[ G_{ci} \]

Compensator (current loop)

Average current mode controller

The usual voltage feedback loop

\[ G_{ci} \] is typically a PI compensator
Transfer SW sig model

G Vij, Gij, G(v)j are listed in textbook Tables 12.3 - 12.5

Black diagram
Solution of block diagram

Gains of the average current mode controller

Control-to-output:

\[
\left. \frac{\dot{V}_c}{i_c} \right|_{\dot{v}_g = 0} = \frac{Gvd}{Gid} \cdot \frac{T_c}{1+T_c}
\]

Line-to-output:

\[
\left. \frac{\dot{V}_g}{\dot{v}_g} \right|_{i_c = 0} = G_{vg} - \frac{G_{ig} Gvd}{Gid} \cdot \frac{T_c}{1+T_c}
\]

Current loop gain:

\[
T_c = \frac{G_{ei} Gid R_s}{V_M}
\]
Buck example

From Table 12.3:

\[ G_{vd} = \frac{V}{D} \frac{1}{\text{den}(s)} \]

\[ G_{vg} = D \frac{1}{\text{den}(s)} \]

\[ G_{id} = \frac{V}{DR} \frac{1+sRC}{\text{den}(s)} \]

\[ G_{ig} = \frac{D}{R} \frac{1+sRC}{\text{den}(s)} \]

**denominator polynomial**

\[ \text{den}(s) = 1 + \frac{sL}{R} + s^2LC \]

\[ = 1 + \frac{1}{Q \omega_0} + (\frac{s}{\omega_0})^2 \]

\[ \omega_0 = \frac{1}{\sqrt{LC}} \]

\[ Q = R \sqrt{\frac{C}{L}} \]

Zero in \( G_{id}, G_{ig} \):

\[ \omega_2 = \frac{1}{RC} \]

**Uncompensated current loop gain** (with \( G_{ci} = 1 \)):

\[ T_{cu}(s) = \frac{G_{id} Rs}{V_M} = T_{cu0} \frac{1 + \frac{s}{\omega_2}}{1 + \frac{s}{Q \omega_0} + (\frac{s}{\omega_0})^2} \]

with \( T_{cu0} = \frac{R_s}{R} \frac{V}{DVM} \)

\[ T_{cu} = 0^\circ \]

\[ -90^\circ \]
A typical compensator $G_{ci}$

Compensated loop gain $T_c$

$$||T_{cil}|| - 20\text{dB/dec}$$

$$\frac{T_c}{1+T_{cil}} = \begin{cases} 1 & \omega < \omega_c \\ \frac{T_c}{T_c} & \omega > \omega_c \end{cases}$$

Current crossover frequency $\omega_c$
The control-to-output transfer function is

\[ \frac{\hat{v}}{\hat{i}_c} \bigg|_{\hat{v}_g=0} = \frac{G_{ud}}{G_{id}} \frac{T_c}{1+T_c} \quad \text{from p. 4} \]

and

\[ \frac{G_{ud}}{G_{id}} = \left( \frac{V}{D} \frac{1}{\text{den}(s)} \right) \left( \frac{V}{DR} \frac{1+sRC}{\text{den}(s)} \right) = \frac{R}{1+sRC} \]

which is the control-to-output transfer function predicted by the ideal current controller (simple) model

\[ \frac{T_c}{1+T_c} \leq \frac{1}{\left(1 + \frac{s}{\omega_c}\right)} \]

(may have additional terms caused by poles in T_c above \( \omega_c \)) (dc gain might differ if dc gain \( T_c(0) \) is not large)

So

\[ \frac{\hat{v}}{\hat{i}_c} = \frac{R}{\left(1+\frac{s}{\omega_z}\right)\left(1+\frac{s}{\omega_c}\right)} \]
The line-to-output transfer function is

\[
\left. \frac{v}{v_g} \right|_{i_c = 0} = G_{vg} - \frac{G_{ig} G_{vd}}{G_{id}} \frac{T_c}{1 + T_c} \quad (\text{from p.4})
\]

For the buck converter, \( \frac{G_{ig} G_{vd}}{G_{id}} = G_{vg} \)

(This isn't necessarily true for other converters! It occurs in the buck because the inductor directly drives the output port. The result is different for the boost and buck-boost.)

Then

\[
\left. \frac{v}{v_g} \right|_{i_c = 0} = G_{vg} \left( 1 - \frac{T_c}{1 + T_c} \right) = \frac{G_{vg}}{1 + T_c}
\]

The current feedback loop reduces the line-to-output transfer function by a factor of \( \frac{1}{1 + T_c} \); the \( G_{vg} \) term in the equation above is the \( G_{vg}(s) \) for voltage-mode control.

Summary: for \( T_c \to \infty \), average current mode control reduces to the ideal current control model.
The relationship between
- Voltage mode control
- Average current mode control
- Ideal current controller, with $i_L = i_C$

can be found using the Feedback Theorem.

![Diagram of voltage-mode converter model]
The control-to-output transfer function is

\[ \frac{\hat{v}}{\hat{i}_c} = G_{coo} \frac{T_c}{1+T_c} + G_{co} \frac{1}{1+T_c} \]

from feedback theorem

with

\[ G_{coo} = \left. \frac{\dot{v}}{i_c} \right|_{\dot{i}_c \rightarrow 0, \dot{y} \rightarrow 0} \]

Note that \( \dot{y} \rightarrow 0 \) implies that \( \dot{i}_L = \dot{i}_c \)

So \( G_{coo} \) is the control-to-output gain from the ideal current controller model.

and

\[ G_{co} = \left. \frac{\dot{v}}{i_c} \right|_{\dot{i}_c \rightarrow 0, \dot{y} = 0} = 0 \]

There is no path for direct forward transmission via feedback path in the model.

So in general, for average current mode control,

\[ \frac{\hat{v}}{\hat{i}_c} = G_{coo} \frac{T_c}{1+T_c} \]

with \( T_c = \) current loop gain

\[ G_{coo} = \text{control-to-output transfer function from ideal current control model} \]
The line-to-output transfer function is

\[ \frac{\hat{v}}{\hat{v}_g} = G_{g_{oo}} \frac{T_c}{1+T_c} + G_{go} \frac{1}{1+T_c} \]

from feedback theorem.

\[ G_{g_{oo}} = \left. \frac{\hat{v}}{\hat{v}_g} \right|_{i_x \to 0, i_c \to 0} \]

line-to-output transfer function predicted by the ideal current controller model.

\[ G_{go} = \left. \frac{\hat{v}}{\hat{v}_g} \right|_{i_x = 0, i_c = 0} \]

Note that \( \hat{i}_x = 0 \Rightarrow \hat{i} = 0 \).

under these conditions, \( \frac{\hat{v}}{\hat{v}_g} \) is the \( G_{vg}(s) \) from the voltage-mode control model.

So

\[ \frac{\hat{v}}{\hat{v}_g} = \begin{cases} 
G_{g_{oo}}(s) & \text{for } ||T_c|| \gg 1 \quad \text{- ideal current control} \\
G_{vg}(s) & \text{for } ||T_c|| < 1 \quad \text{- reverts to voltage-mode result at high frequency where } ||T_c|| < 1
\end{cases} \]