Construction of $T/(1+T)$

Closed-loop reference-to-output response $\|v/v_{ref}\| = T/(1+T)$

Closed-loop BW $\approx f_c$

$= 1$ for $NTK > 1$

$\Phi_m = 50^\circ$

$Q_u = 4$

Closed-Loop Reference-to-Output
Reference Step Response

- $v_o(t)$
- $i_L(t)$
- $d(t)$

10 mV step
(1.79 V to 1.8 V)
in $v_{ref}$

Note: duty-cycle command does not saturate, response correlates very well with theory based on linear small-signal models.
Output Impedance

Synchronous buck open-loop output impedance

\[ Z_{out}(s) = \left( R_{esr} + \frac{1}{sC} \right) \parallel (R_L + sL) \]

- \( L = 1 \mu\text{H} \)
- \( R_L = 30 \text{ m}\Omega \rightarrow -30\text{dB} \Omega \)
- \( C = 200 \mu\text{F} \)
- \( R_{esr} = 0.8 \text{ m}\Omega \rightarrow -62 \text{dB} \)

\[ Q = \frac{R_0}{R_L + R_{esr}} = \frac{140}{30 \mu\text{H}} = \frac{70\text{m}\Omega}{30\text{m}\Omega} = 2.3 = 7.2\text{dB} \]

\[ R_0 = 70\text{m}\Omega = -23\text{dB} \]

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Reactance Paper

\[ |Z_{out}| \text{ (open loop)} \]
Construction of $1/(1+T)$

$Z_{out, CL} = \frac{Z_{out}}{1 + T}$

Closed-Loop $Z_{out}$

$Z_{out, CL} = \frac{Z_{out}}{1 + T}$
Exact $Z_{out}$

Load Step Response

2.5-5 A step-load transient
Chapter 9: Summary

1. Negative feedback causes the system output to closely follow the reference input, according to the gain $1/H(s)$. The influence on the output of disturbances and variation of gains in the forward path is reduced.

2. The loop gain $T_H$ is equal to the products of the gains in the forward and feedback paths. The loop gain is a measure of how well the feedback system works: a large loop gain leads to better regulation of the output. The crossover frequency $f_c$ is the frequency at which the loop gain $T$ has unity magnitude, and is a measure of the bandwidth of the control system.

$$f_c \approx \left( \frac{\omega}{\omega_o} \right)_{\omega_c}$$
Chapter 9: Summary

3. The introduction of feedback causes the transfer functions from disturbances to the output to be multiplied by the factor \(1/(1+Ts)\). At frequencies where \(T\) is large in magnitude (i.e., below the crossover frequency), this factor is approximately equal to \(1/Ts\). Hence, the influence of low-frequency disturbances on the output is reduced by a factor of \(1/Ts\). At frequencies where \(T\) is small in magnitude (i.e., above the crossover frequency), the factor is approximately equal to 1. The feedback loop then has no effect. Closed-loop disturbance-to-output transfer functions, such as the line-to-output transfer function or the output impedance, can easily be constructed using the algebra-on-the-graph method.

4. Stability can be assessed using the phase margin test. The phase of \(T\) is evaluated at the crossover frequency, and the stability of the important closed-loop quantities \(FT(1+D)\) and \(1/(1+D)\) is then deduced. Inadequate phase margin leads to ringing and overshoot in the system transient response, and peaking in the closed-loop transfer functions.

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Chapter 9: Summary

5. Compensators are added in the forward paths of feedback loops to shape the loop gain, such that desired performance is obtained. Lead compensators, or PD controllers, are added to improve the phase margin and extend the control system bandwidth. PI controllers are used to increase the low-frequency loop gain, to improve the rejection of low-frequency disturbances and reduce the steady-state error.

6. Loop gains can be experimentally measured by use of voltage or current injection. This approach avoids the problem of establishing the correct quiescent operating conditions in the system, a common difficulty in systems having a large dc loop gain. An injection point must be found where interstage loading is not significant. Unstable loop gains can also be measured.
Summary: Effect of Phase Margin

Step Response

$f_c = \text{constant}$

$f_c = (\omega_n)_{cl}$

Speed is about equal for each.
Effect of High/Low Frequency Dynamics

Effect of Bandwidth
Part III: Magnetics

- Ch 13 Basic Magnetics Theory
- Ch 14 Inductor Design
- Ch 15 Transformer Design

Some Inductor Examples
Chapter 13: Basic Magnetics Theory

13.1 Review of Basic Magnetics
   13.1.1 Basic relationships
   13.1.2 Magnetic circuits

13.2 Transformer Modeling
   13.2.1 The ideal transformer
   13.2.2 The magnetizing inductance
   13.2.3 Leakage inductances

13.3 Loss Mechanisms in Magnetic Devices
   13.3.1 Core loss
   13.3.2 Low-frequency copper loss

13.4 Eddy Currents in Winding Conductors
   13.4.1 Skin and proximity effects
   13.4.2 Leakage flux in windings
   13.4.3 Foil windings and layers
   13.4.4 Power loss in a layer
   13.4.5 Example: power loss in a transformer winding
   13.4.6 Interleaving the windings
   13.4.7 PWM waveform harmonics