Part II: Converter Dynamics and Control

Fundamentals of Power Electronics   1   *Chapter 7: AC equivalent circuit modeling*

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Chapter 7: AC Equivalent Circuit Modeling

Fundamentals of Power Electronics   2   *Chapter 7: AC equivalent circuit modeling*

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7.1: Introduction

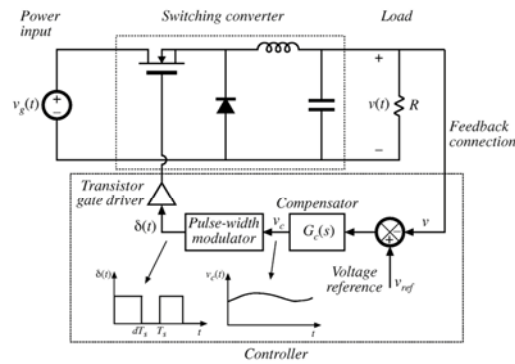Objective: maintain $v(t)$ equal to an accurate, constant value V.

There are disturbances:

- in $v_g(t)$
- in R

There are uncertainties:

- in element values
- in V_g
- in R

A simple dc-dc regulator system, employing a buck converter
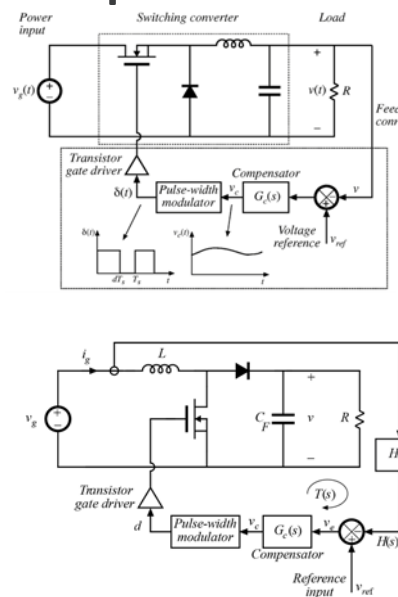

Fundamentals of Power Electronics   3   Chapter 7: AC equivalent circuit modeling

Control Objectives and Inputs

Objectives of Part II

Develop tools for modeling, analysis, and design of converter control systems

Need dynamic models of converters:

How do ac variations in $v_g(t)$, R, or $d(t)$ affect the output voltage $v(t)$?

What are the small-signal transfer functions of the converter?

- Extend the steady-state converter models of Chapters 2 and 3, to include CCM converter dynamics (Chapter 7)
- Construct converter small-signal transfer functions (Chapter 8)
- Design converter control systems (Chapter 9)
- Design input EMI filters that do not disrupt control system operation (Chapter 10)
- Model converters operating in DCM (Chapter 11)
- Current-programmed control of converters (Chapter 12)

Fundamentals of Power Electronics   6   *Chapter 7: AC equivalent circuit modeling*

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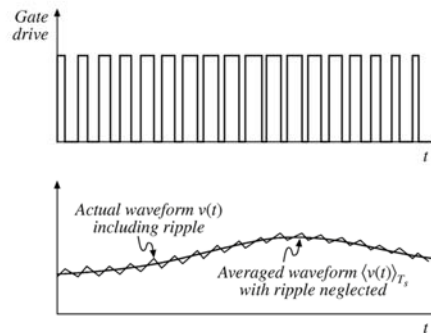## PWM Spectrum

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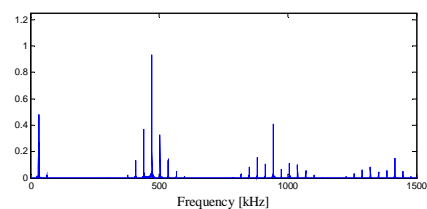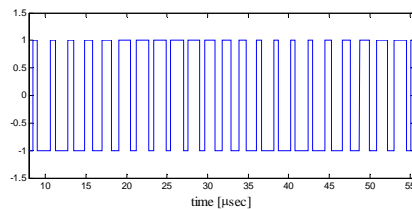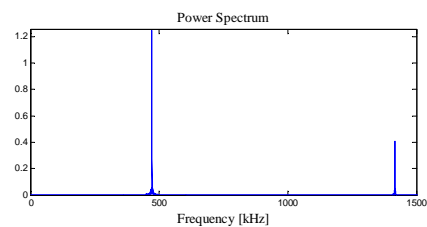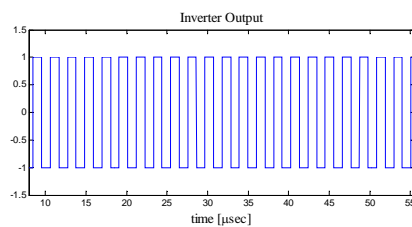
Neglecting The Switching Ripple

Suppose the duty cycle is modulated sinusoidally:

$$d(t) = D + D_m \cos\omega_m t$$

where D and D_m are constants, $\left|D_m\right| \ll D$, and the modulation frequency ω_m is much smaller than the converter switching frequency $\omega_s = 2\pi f_s$.

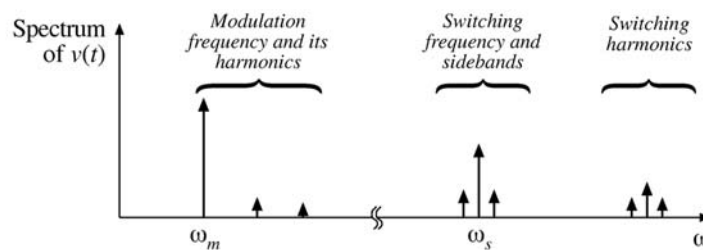The resulting variations in transistor gate drive signal and converter output voltage:

Gate drive

Actual waveform v(t) including ripple

Averaged waveform $\langle v(t)\rangle_{T_s}$ with ripple neglected

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Output Voltage Spectrum

Spectrum of $v(t)$

Modulation frequency and its harmonics

Switching frequency and sidebands

Switching harmonics

ω_m ω_s ω

Contains frequency components at:
- Modulation frequency and its harmonics
- Switching frequency and its harmonics
- Sidebands of switching frequency

With small switching ripple, high-frequency components (switching harmonics and sidebands) are small.

If ripple is neglected, then only low-frequency components (modulation frequency and harmonics) remain.

Fundamentals of Power Electronics   9   Chapter 7: AC equivalent circuit modeling

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Objectives of AC Modeling

- Predict how low-frequency variations in duty cycle induce low-frequency variations in the converter voltages and currents
- Ignore the switching ripple
- Ignore complicated switching harmonics and sidebands

Approach:

- Remove switching harmonics by averaging all waveforms over one switching period

Fundamentals of Power Electronics   10   *Chapter 7: AC equivalent circuit modeling*

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Low-frequency Averaging

Average over one switching period to remove switching ripple:

$$L \frac{d\langle i_L(t)\rangle_{T_s}}{dt} = \langle v_L(t)\rangle_{T_s}$$

$$C \frac{d\langle v_C(t)\rangle_{T_s}}{dt} = \langle i_C(t)\rangle_{T_s}$$

where

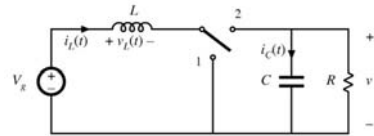$$\langle x(t)\rangle_{T_s} = \frac{1}{T_s} \int_t^{t+T_s} x(\tau)d\tau$$

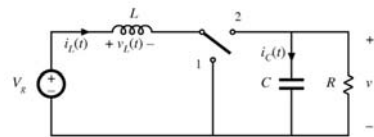Note that, in steady-state,

$$\langle v_L(t)\rangle_{T_s} = 0$$
$$\langle i_C(t)\rangle_{T_s} = 0$$

by inductor volt-second balance and capacitor charge balance.

Fundamentals of Power Electronics   11   *Chapter 7: AC equivalent circuit modeling*

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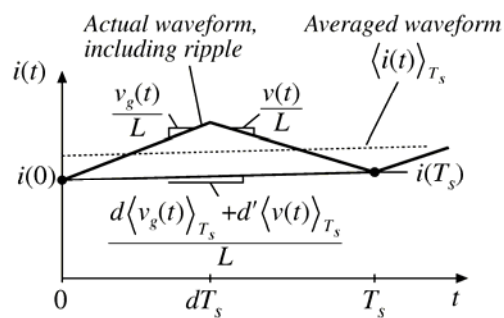
Averaging in Steady-State

Averaging in Transient Operation

Averaging: Correct Prediction

The net change in inductor current over one switching period is exactly equal to the period T_s multiplied by the average slope $\langle v_L \rangle_{T_s} /L$.

Fundamentals of Power Electronics 22 *Chapter 7: AC equivalent circuit modeling*

Averaging: Discussion

Small Signal Modeling: Linearization

Buck Boost AC Modeling

Buck-boost converter example

Fundamentals of Power Electronics   16   Chapter 7: AC equivalent circuit modeling