

Part II: Converter Dynamics and Control

- { 7. AC equivalent circuit modeling
- 8. Converter transfer functions
- 9. Controller design
- ~~10. Input filter design~~
- ~~11. AC and DC equivalent circuit modeling of the discontinuous conduction mode~~
- ~~12. Current programmed control~~

Chapter 7: AC Equivalent Circuit Modeling

- 7.1 Introduction
- 7.2 The basic AC modeling approach → *Equivalent circuit*
- { ~~7.3 State-space averaging~~
- ~~7.4 Circuit averaging and averaged switch modeling~~
- 7.5 The canonical circuit model
- 7.6 Modeling the pulse-width modulator
- 7.7 Summary of key points

7.1: Introduction

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

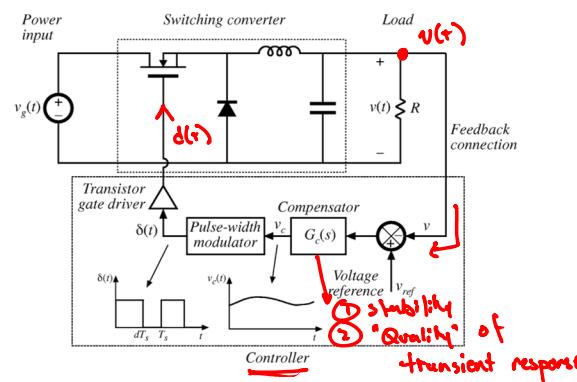
There are disturbances:

- in $v_g(t)$
- in R

There are uncertainties:

- in element values
- in V
- in R

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



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3

Chapter 7: AC equivalent circuit modeling

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Control Objectives and Inputs

V_{out} control:

- Power supply, VRM
- Inverter off-grid

I_{out} control:

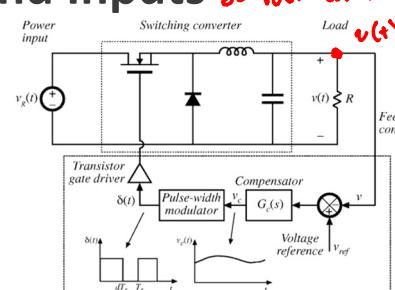
- Grid-tied inverter

V_{in} control:

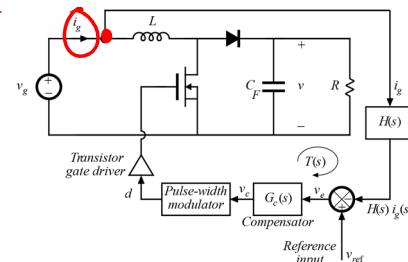
- Solar panel MPPT converter

I_{in} control:

- PFC rectifiers
- Grid tied rectifier



dc i_{in} control



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Objectives of Part II

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

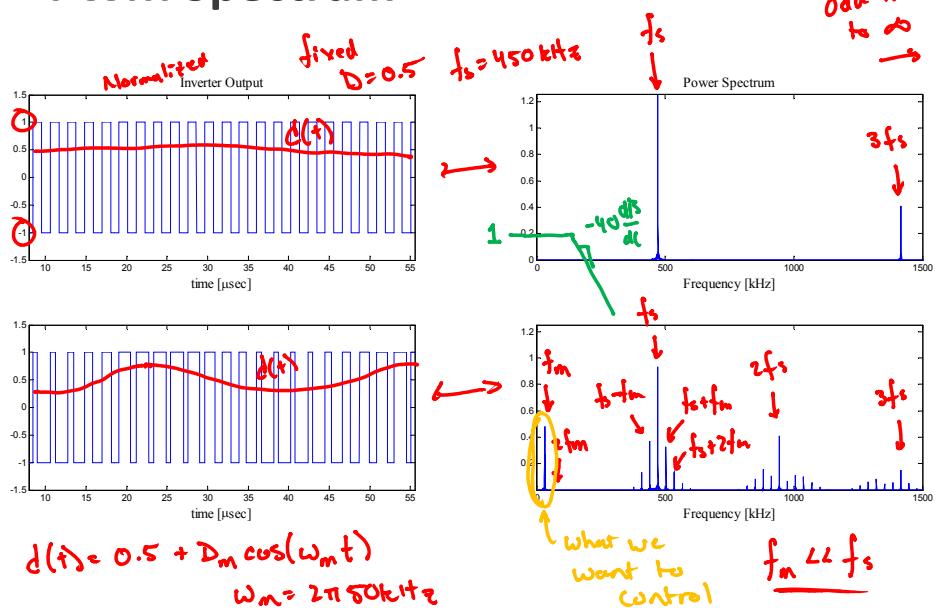
Need dynamic models of converters:

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? LTI transfer function $\frac{v(s)}{d(s)}$

- 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)~~

PWM Spectrum



Neglecting The Switching Ripple

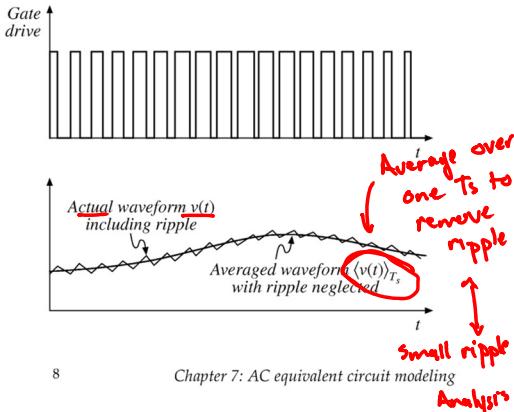
Suppose the duty cycle is modulated sinusoidally:

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

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

$$\omega_m \ll \omega_s$$

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



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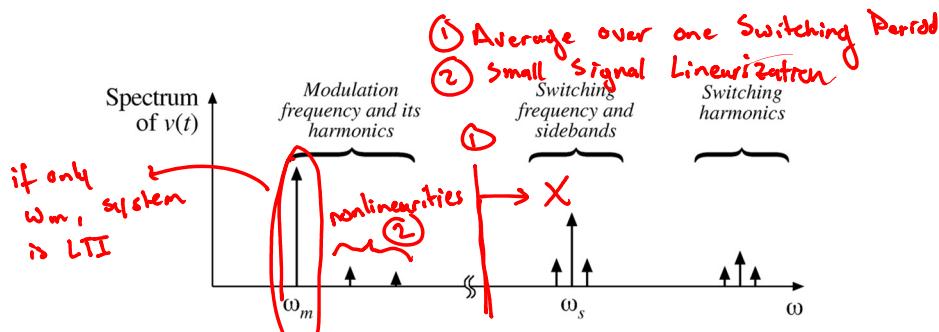
8

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Analyses

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Output Voltage Spectrum



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.

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9

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Objectives of AC Modeling

$$\phi \ll \omega_m \ll \omega_s \quad (\text{typical: } \omega_m \leq \frac{\omega_s}{10})$$

- Predict how low-frequency variations in duty cycle induce low-frequency variations in the converter voltages and currents

Ignore the switching ripple \rightarrow average away

Ignore complicated switching harmonics and sidebands

Approach:

(1)

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

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

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

Note that, in steady-state,

$$\begin{aligned} \rightarrow \langle v_L(t) \rangle_{T_s} &= 0 \\ \langle i_C(t) \rangle_{T_s} &= 0 \end{aligned} \quad \left. \begin{array}{l} \text{No longer} \\ \text{true} \end{array} \right\}$$

by inductor volt-second balance and capacitor charge balance.

L to C will show up in eq. circuit models