University of Central Florida

EEL 5245 POWER ELECTRONICS I

Lecture #11: Chapter 4

DC-DC and Review of Ch 2-3

Objectives

- Review of Ch2-3 topics
- Overview of DC-DC Conversion
  - Linear Regulators: Regulated vs. Unregulated
  - Overview of Pulse Width Modulation Converters
- PWM Converter Analysis Principles/Tools
  - Duty Ratio
  - Steady-State
  - Inductor Volt-Second Balance
  - Capacitor charge balance
  - Small Ripple Approximation
  - Conservation of Power

Key Topics from Chapter 2

- Significance of Switching in Power Electronics
- Ideal Switch Characteristics
- Practical Switch Limitations
- Power Loss in Practical Switch
  - Switching Losses
  - Conduction Loss
- Calculation of Switch Loss from V&I Waveforms
- Calculation P_{max} (instantaneous maximum power) from V&I Waveforms
- Semiconductor Devices
  - Device types, function, and current/voltage carry/block.

Key Topics from Chapter 2- Cont

- Figures of Merit (Definitions/Lingo)
  - On state resistance, forward voltage drop, reverse blocking capability, switching time, etc.
- Qualitative Relationships
  - Family to family comparisons (which device is best for a particular application)
    - e.g. MOSFETs faster than BJT
  - Figures of merit comparison within family
    - e.g. Higher reverse blocking, higher on-state resistance

Key Topics from Chapter 3

- Solution of First and Second Order Diff Eq.s by Laplace and Method of Undetermined Coefficients
- Be able to solve any class example and focus on:
  - Mode by mode analysis
  - Energy Transfer from Input to Output
  - Energy exchange from/to reactive elements
  - Initial and final conditions of state variables
  - Continuity of state variables
  - Energy conservation
  - Current commutation
  - Current Freewheeling

Key Topics from Chapter 3

- Output Voltage Ripple
- Inductor Current Ripple
- Load and Line Regulation
- Small Ripple Approximation
- Steady-state definition
- Inductor Volt-Sec Balance
- Capacitor Charge Balance
- Use of Diodes/Switches to control flow of energy and regulate output voltage
- Integration Tips and Tricks (Time shift to simplify)

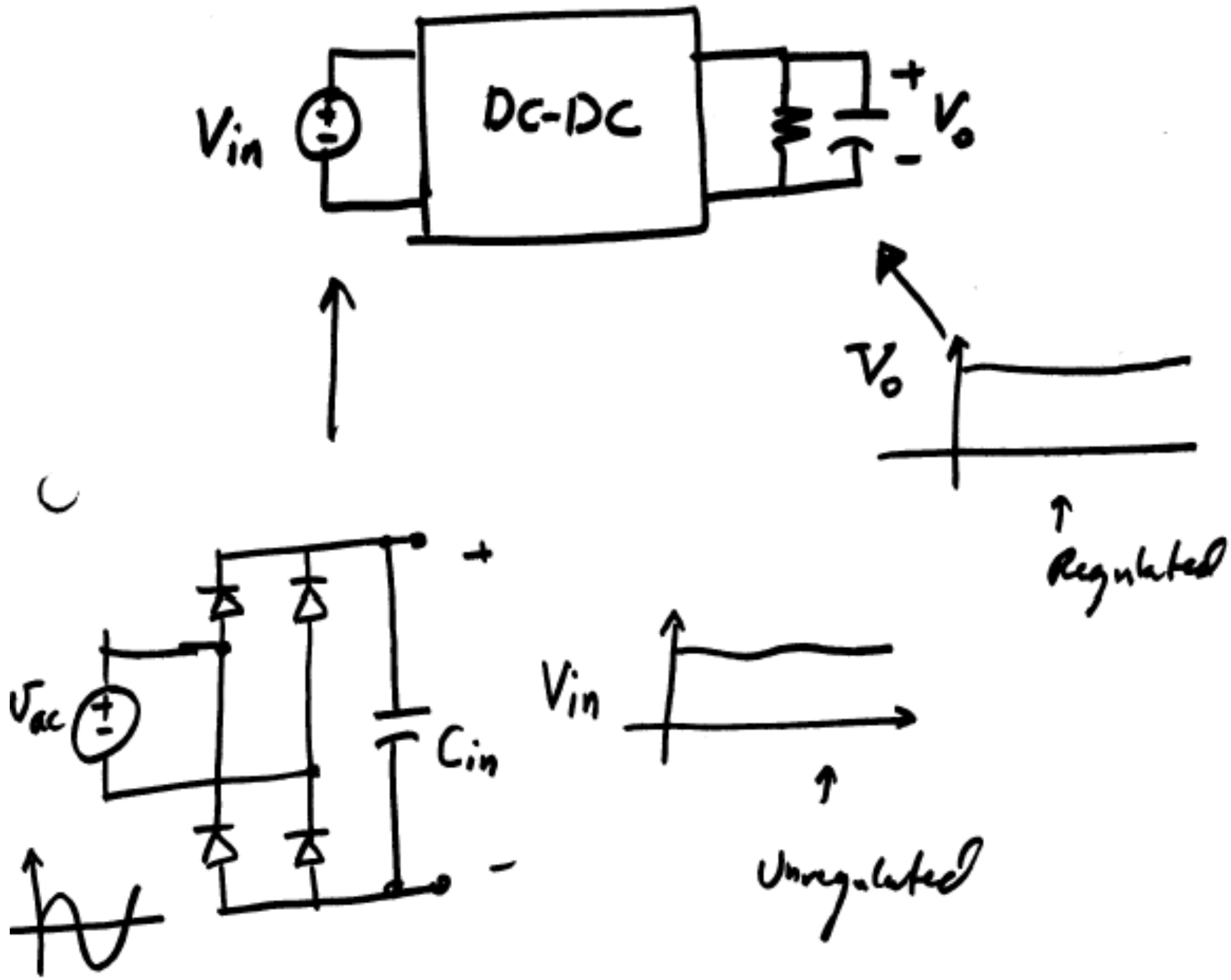
Key Topics from Chapter 3- Cont

- Sinusoidal Systems and Basic Power Concepts
  - Understand and be able to apply basic power concepts to solution of problems involving sinusoidal systems and to some extent non-sinusoidal systems
    - Basic Definitions of average, instantaneous power
    - RMS definition
    - Application of basic integral formulas to commonly observed Power Electronics Waveforms
    - Power Factor Concepts and Correction

Key Topics from Chapter 3- Cont

- Non-Sinusoidal Systems, Harmonics and Fourier Analysis
  - Understand and be able to apply Fourier Analysis to obtain harmonic content of any periodic waveform
    - Both forms of Fourier Series from class
  - Real, Apparent, and Reactive Power in the Nonsinusoidal system
  - Power Factor, distortion factor, displacement factor
  - THD
  - RMS calculation with nonsinusoidal waveforms
  - Understand the effects of Harmonics
    - Neutral currents, I^2*R heating, measurement error, etc.

Overview of DC to DC Conversion



Overview of Linear Regulator

Block diagram for a linear-regulator

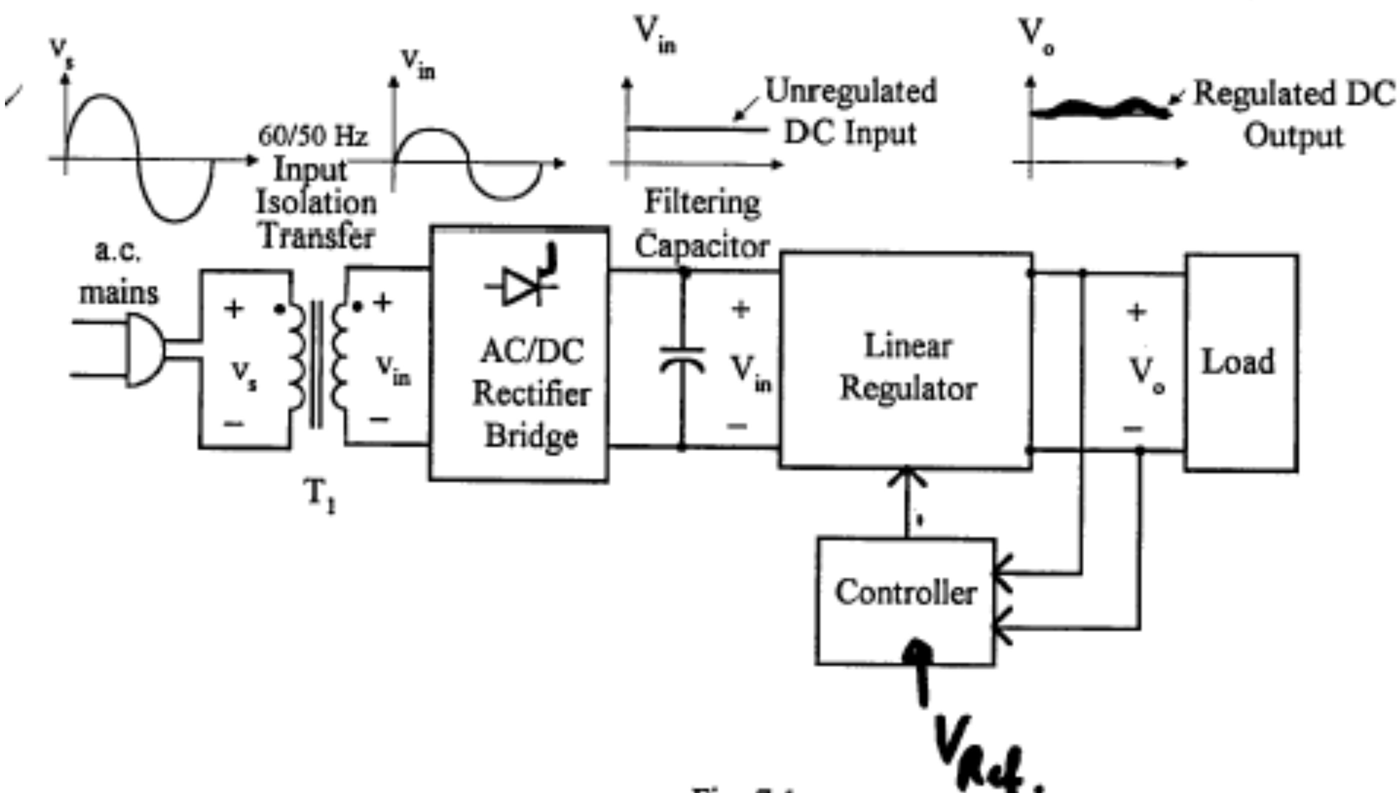
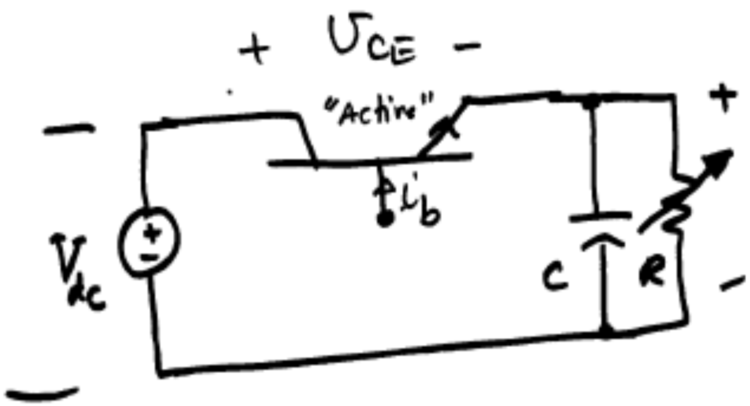
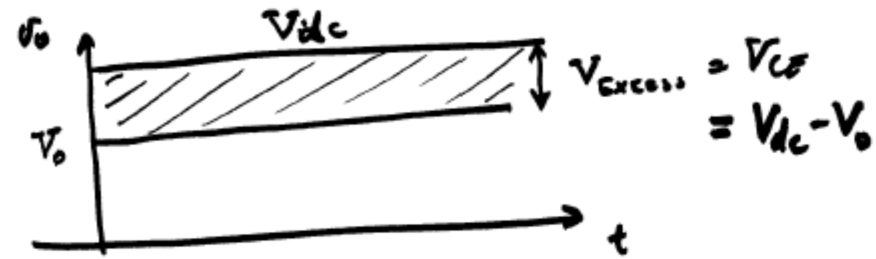


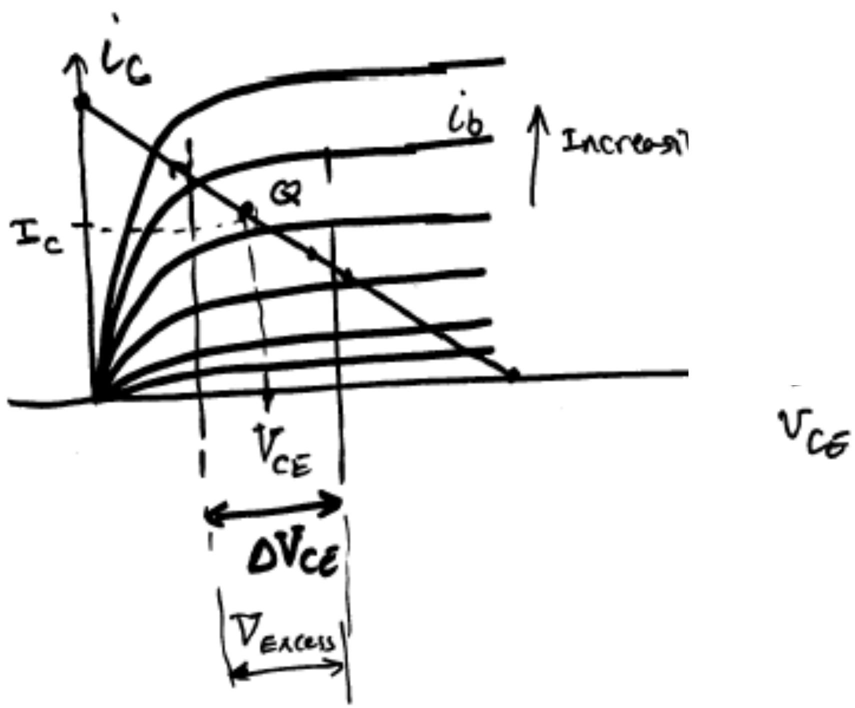
Fig. 7.1

Efficiency of Linear Regulator





$V_{CE} = V_{excess}$ ≑ The wasted voltage across the linear element (transistor).



$V_o = V_{dc} - V_{excess}$

↑

Controlled by varying i_b.

Comments on Linear Regulator

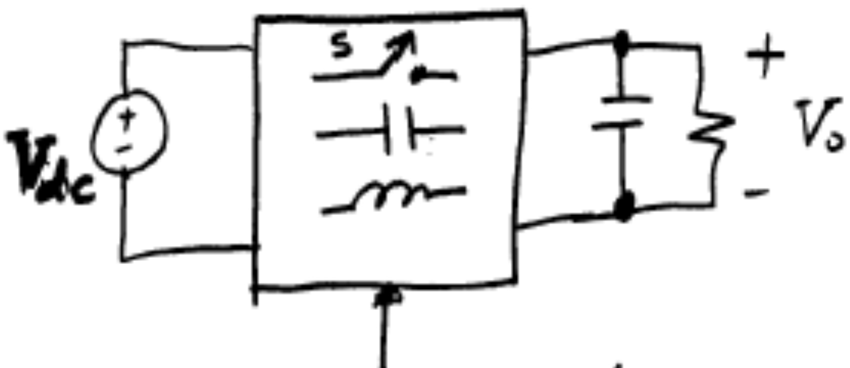
Features:

- Simple Topology (No switching) + Low EMI + reliable!
- Easy to understand (active mode) (simple loop)
- Linear operation for the active device.
- Very high power dissipation. (Low efficiency $\eta = 50\%$)
- Low power applications.

PWM Converter Overview

PWM Switch-Mode Converters

Pulse Width Modulation (PWM)



- Control signal for the switch

- S : operating as switch

mod·u·late

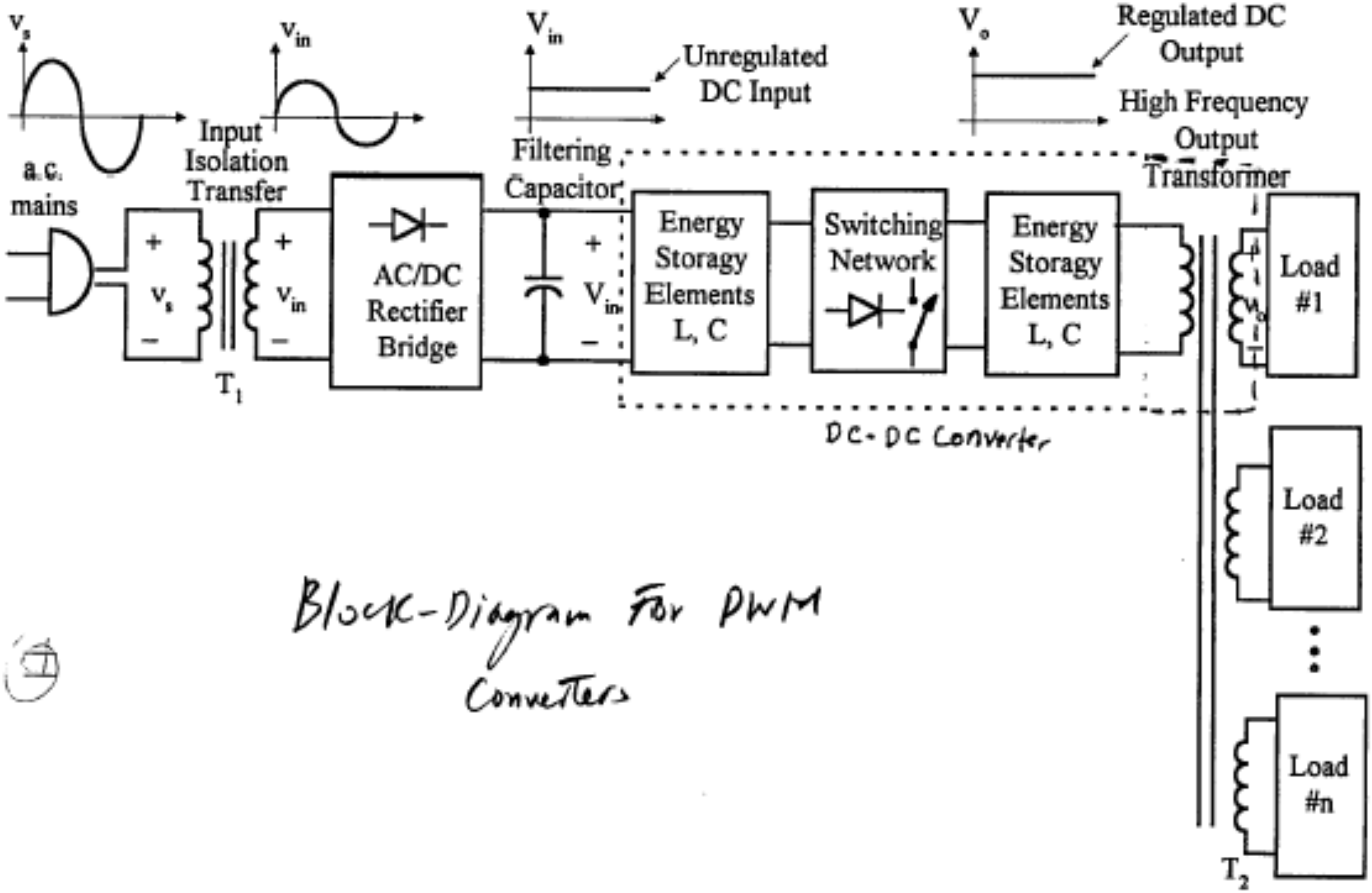
v. **mod·u·lat·ed, mod·u·lat·ing, mod·u·lates**

v. tr.

1.<u>Electronics.</u>

a.To vary the frequency, amplitude, phase, or other characteristic of (electromagnetic waves).

PWM Converter Overview



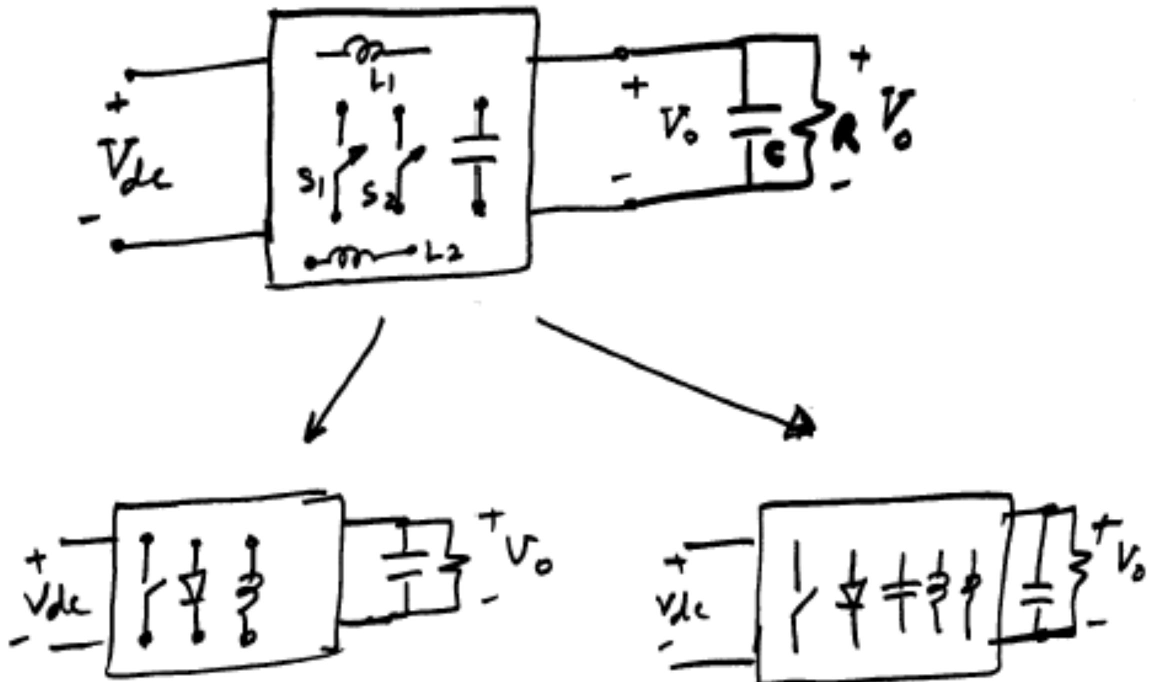
PWM Converter Overview

Features of PWM converters:

- Simple Topologies (one switch)
- Well understood operation/control.
- Simple Control Circuit.
- Wide power applications
- High Efficiency converter (90%).
- Fixed switching frequency (filtering is easy) [low Harmonics]

Applications:

PWM Converter Overview



2nd Order Converters

4th Order Converters

Example:

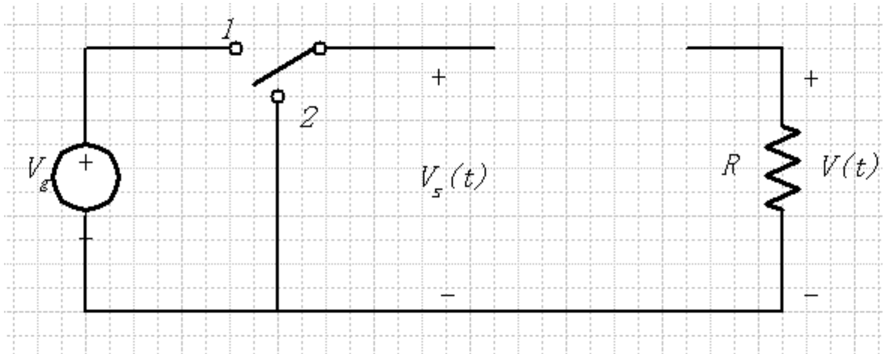
- Buck Converter (step down)
- Boost Converter (step up)
- Buck-Boost Converter
  (step up/down)

Example:

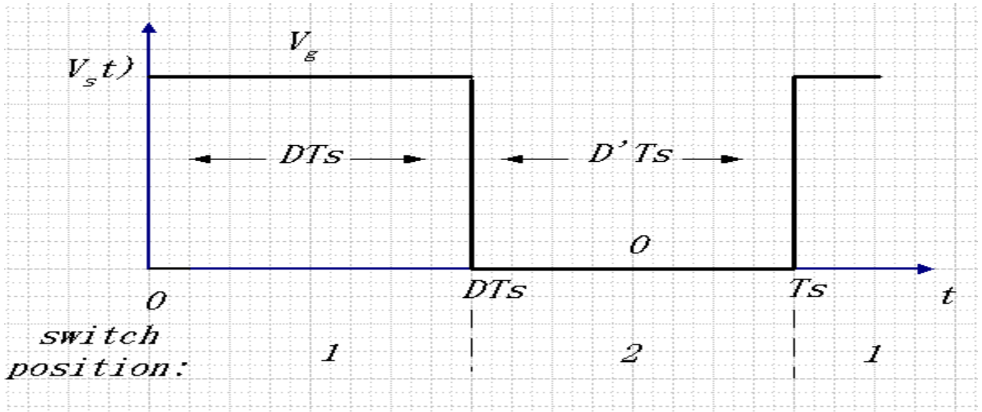
- Ćuk →
- Zeta
- SEPIC

PWM Switching

SPDT switch changes dc component



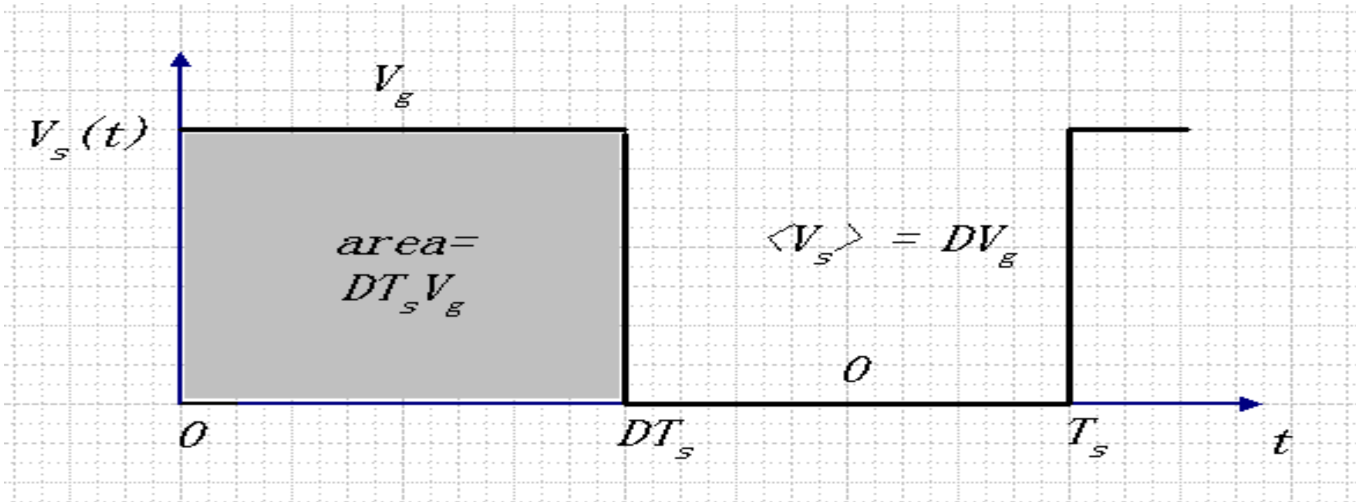
Switch output voltage waveform



Duty cycle *D*:
$0 \le D \le 1$

complement *D'*:
$D' = 1 - D$

Output Voltage Average Value (Buck)

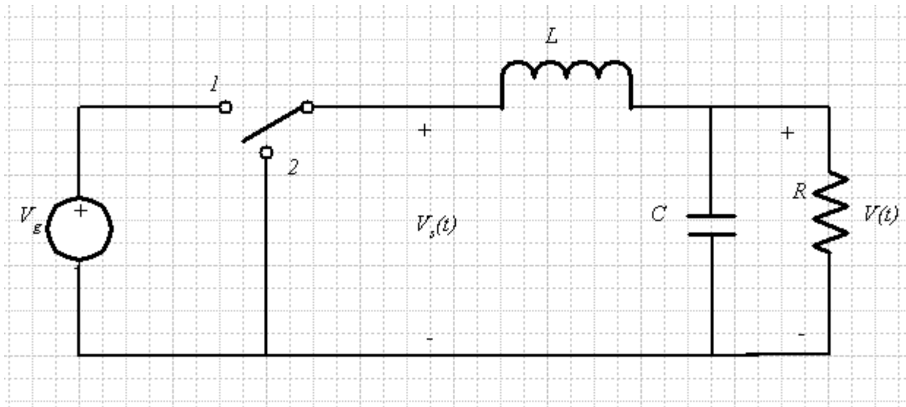


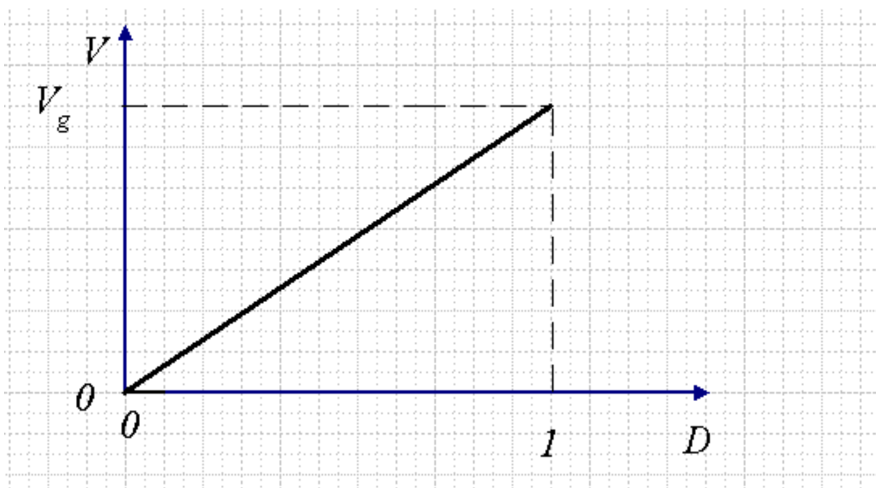
Fourier analysis: Dc component = average value

$$\langle v_s \rangle = \frac{1}{T_s}\int_0^{T_s} v_s(t)\,dt$$

$$\langle v_s \rangle = \frac{1}{T_s}(DT_sV_g) = DV_g$$

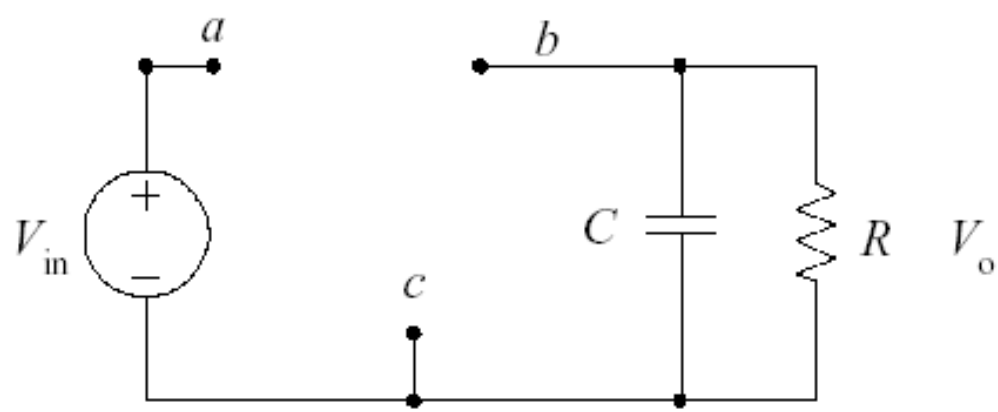
Buck Converter





- Switch Position 2 for allow for uninterrupted inductor current flow
- LPF for smoothing of pulse for constant DC output
- Capacitor hold a DC value for the load when switch in position 1 (Inductor current charge)
- 2^{nd} Order-1 L, 1 C

Derivation of Classic Converter Topologies (2^{nd} Order)



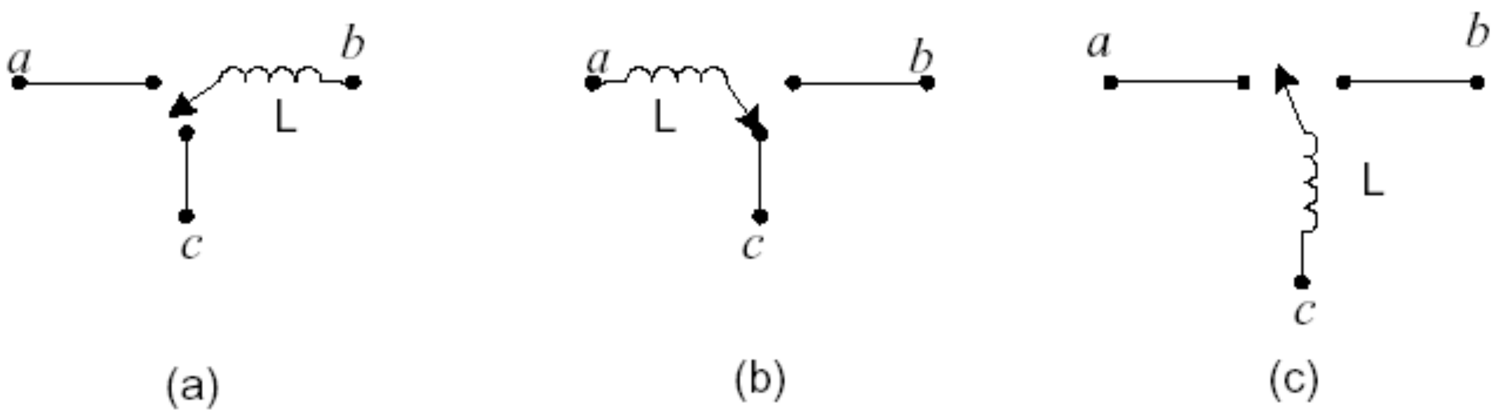
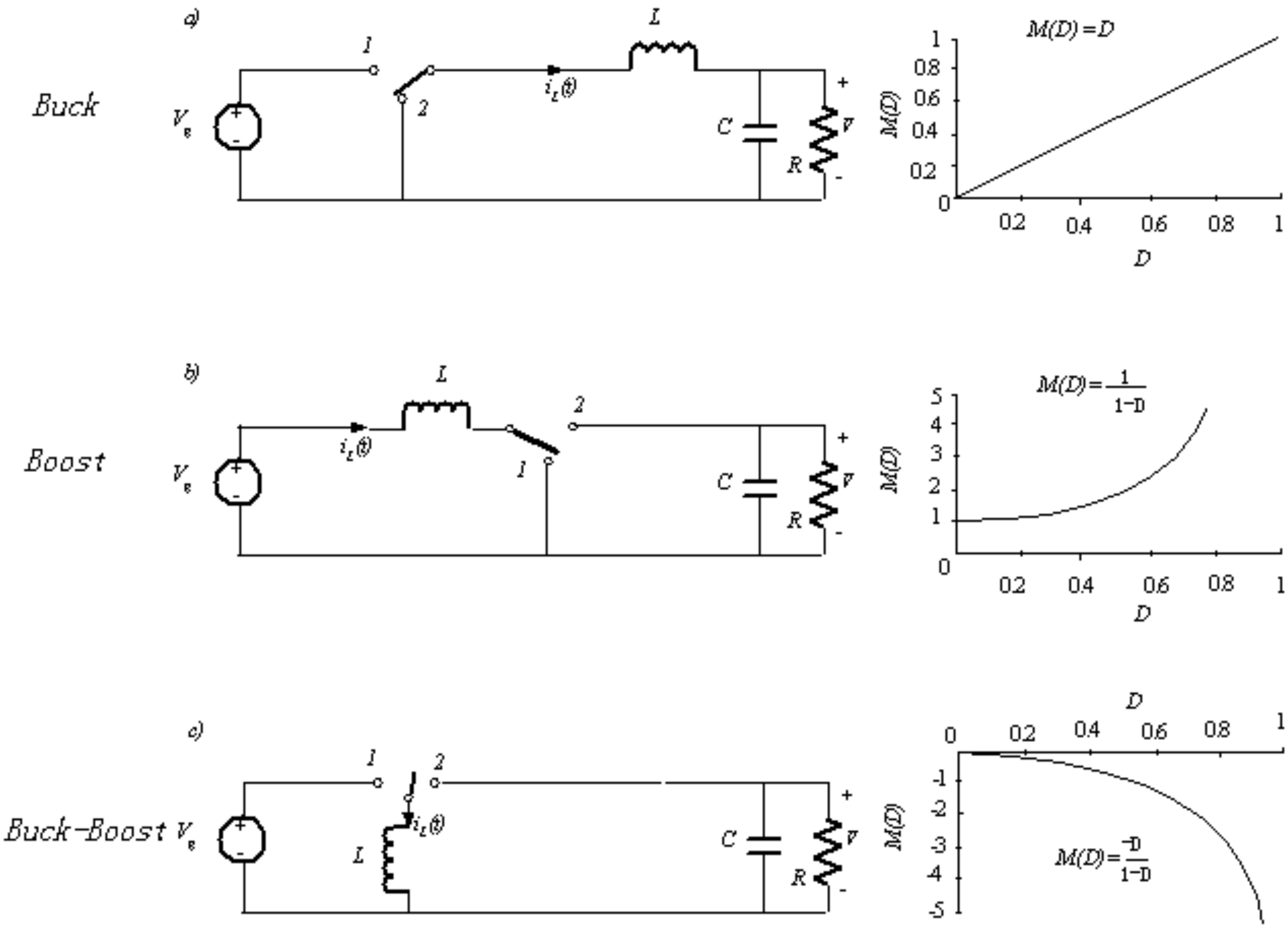


Figure 4.8: Low-pass LC filter (a) buck (b) boost (c) buck boost converter

Classic Converter Topologies



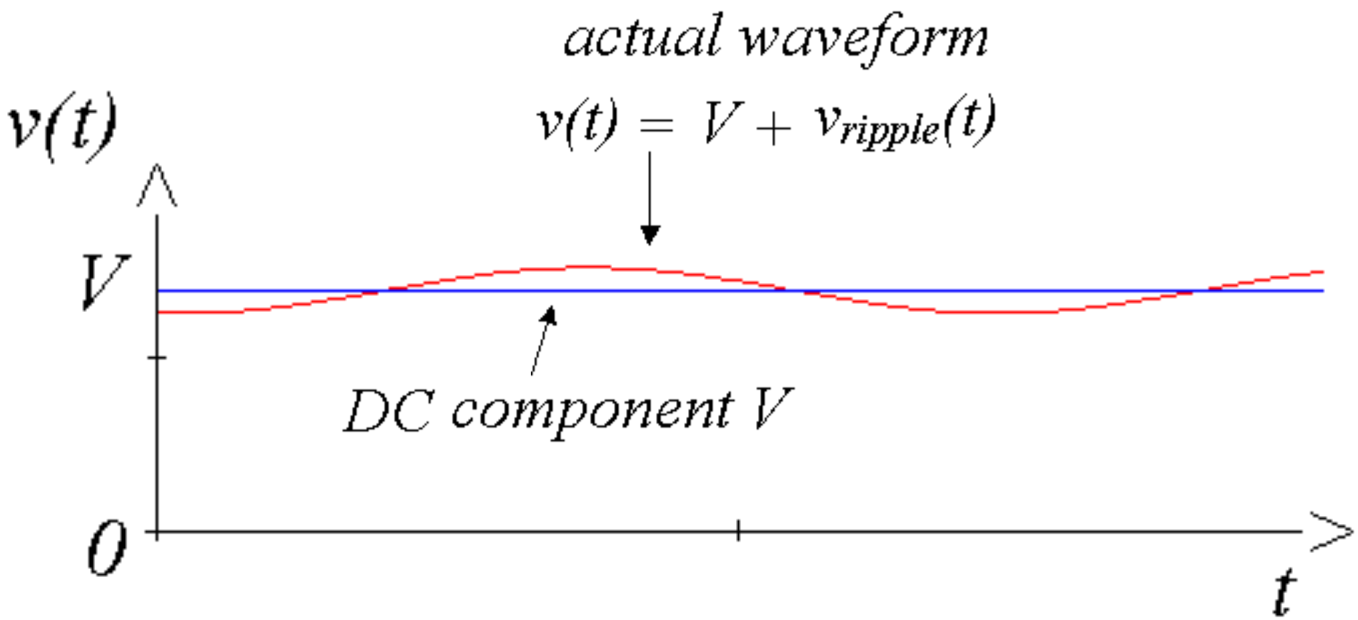
Analysis of Classic Converter Topologies

- Analysis will assume lossless components
- Exact steady state analysis would involve solution of nonlinear, 2nd Order system, we will simplify to a 1st Order System with:
  - Since RC>>Ts, output voltage nearly constant over switching period
    - Since ripple is assumed small, we assume Vo a constant during analysis (output cap not considered)
- We assume analysis of converter takes place at after it has reached steady state
  - Since steady state, average inductor voltage equals zero over switching interval (volt-sec balance)
  - Since steady state, average capacitor current over one switching interval equals zero (charge balance)

Analysis of Classic Converter Topologies

- The preceding concepts can be expressed in terms of mathematical relations.
- These are tools for analysis:
  - $P_{out}=P_{in}$ (Power Conservation)
  - $i_L(t_o)=i_L(t_o+T_s)$ (Steady State)
  - $I_{cavg}=0$ (Charge Balance) $$I_c = \frac{1}{T}\int_{t_0}^{T+t_0} i_c(t)dt = 0$$
  - $V_{Lavg}=0$ (volt-sec balance) $$V_L = \frac{1}{T}\int_{t_0}^{T+t_0} v_L(t)dt = 0$$

Converter Analysis Principle
Small Ripple Approximation



In a well-designed converter, the output voltage ripple is small. Hence, the waveforms can be easily determined by ignoring the ripple:

$$|v_{ripple}| << V$$

$$v(t) \approx V$$

Converter Analysis Principle
Inductor Volt-Second Balance

Inductor defining relation:

$$v_L(t) = L\frac{di_L(t)}{dt}$$

Integrate over one complete switching period :

$$i_L(T_s) - i_L(0) = \frac{1}{L}\int_0^{T_s} v_L(t)dt$$

In periodic steady state, the net change in inductor current is zero :

$$0 = \int_0^{T_s} v_L(t)dt$$

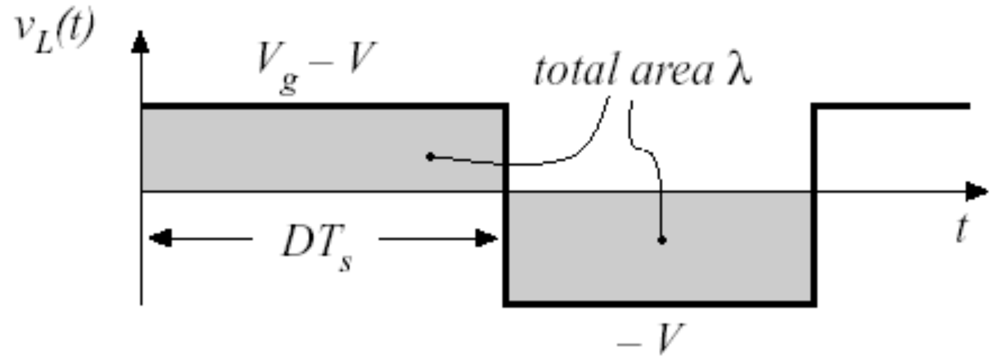
Hence, the total area (or volt-seconds) under the inductor voltage waveform is zero whenever the converter operates in steady state.
An equivalent form:

$$0 = \frac{1}{T}\int_0^{T_s} v_L(t)dt = \langle v_L \rangle$$

The average inductor voltage is zero in steady state

Converter Analysis Principle Volt-Second Balance gives Voltage Gain, M

Inductor voltage waveform, previously derived:



Example is for Buck

Integral of voltage waveform is area of rectangles:

$$\lambda = \int_0^{T_s} v_L(t)\,dt = (V_g - V)(DT_s) + (-V)(D'T_s)$$

Average voltage is

$$\langle v_L \rangle = \frac{\lambda}{T_s} = D(V_g - V) + D'(-V)$$

Equate to zero and solve for *V:*

$$0 = DV_g - (D + D')V = DV_g - V \qquad \Rightarrow \qquad V = DV_g$$

Converter Analysis Principle
Capacitor Charge Balance

Capacitor defining relation:

$$i_C(t) = C\frac{dv_C(t)}{dt}$$

Integrate over one complete switching period

$$v_C(T_S) - v_C(0) = \frac{1}{C}\int_0^{T_s} i_C(t)dt$$

In periodic steady state, the net change in capacitor voltage is zero:

$$0 = \frac{1}{T}\int_0^{T_s} i_C(t)dt = \langle i_C \rangle$$

Hence, the area (or charge) under the capacitor current waveform is zero whenever the converter operates in steady state. The average capacitor current is then zero.

Figures of Merit for the PWM DC-DC Converter "Plan of Attack"

- Classic Converter Analysis (CCM)
  - Voltage Conversion Ratio (M=Gain)
    - Use Inductor Volt-second balance
  - Average Input and Output Currents
    - Use waveform analysis and
    - Capacitor charge balance and small ripple approximation (I_{cavg}=0)
  - Output Voltage Ripple via Charge approximation
    - Small ripple approximation means all ac component of output current seen by capacitor, DC to load R
  - Inductor current Ripple
    - Derived from inductor current waveform
  - Boundary Between CCM and DCM
    - Concept of Critical Inductance derived from i_L expressions