BOOST REGULATORS

Astec Custom Power

Lecture Outline

- Basic Converter Principles
- Boost Regulator Characteristics
- Basic Operation of a Boost Regulator
- Detailed Operation: “On” and “OFF” Stages
- Advantages and Disadvantages
- Applications
- Design Considerations

Basic Concepts: Inductor Current Slope vs Voltage

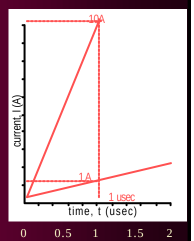
- In any given inductor with inductance L, the current slope dI_L/dt is proportional to the applied voltage V_L, with the proportionality constant equal to 1/L:
- $dI_L/dt = V_L/L$

Ratio and Proportion Examples

- Case 1a:
  - What will be the slope of the current through a 1μH inductor if a voltage of 1V is applied across it?
  - Answer:

  $di/dt = V/L = 1V/1\mu H = 1A/\mu sec$
- Case 1b:
  - How will the slope change in Case 1 if the voltage is increased to 10V?
  - Answer:

  $di/dt = V/L = 10V/1\mu H = 10A/\mu sec$

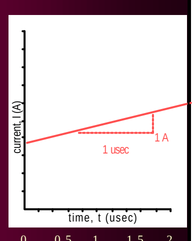


Ratio and Proportion Examples

- Case 2a:
  - If the current in an inductor is observed to increase at the rate of 1A/μsec when 3.3V is applied across its terminals, what is the inductance?
  - Answer:

  $L = V/(di/dt) = 3.3V/(1A/\mu sec) = 3.3\mu H$
- Case 2b:
  - What is the inductance if the same current slope (1A/μsec) is observed with 300V?
  - Answer:

  $L = V/(di/dt) = 300V/(1A/\mu sec) = 300\mu H$

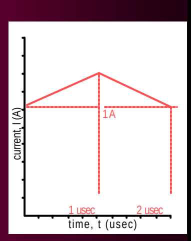


Ratio and Proportion Examples

- Case 3a:
  - What is the applied voltage across a 30μH inductor if a rising current of 1A/μsec is observed to flow through it?
  - Answer:

  $V = L(di/dt) = 30\mu H(1A/\mu sec) = 30V$
- Case 3b:
  - If the current through the same inductor (30μH) is now observed to decrease at the rate of 1A/μsec, what must be the voltage across it?
  - Answer:

  $V = L(di/dt) = 30\mu H(-1A/\mu sec) = -30V$



Ratio and Proportion Examples

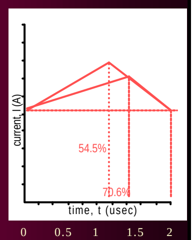
- Case 4a:
  - What is the duty cycle of a continuous boost converter if the inductor voltage magnitude changes from 5V when ON to 12V when OFF?
  - Answer:

$L\Delta i = V_{ON}t_{ON} = V_{OFF}t_{OFF}$

$t_{ON}/t_{OFF} = V_{OFF}/V_{ON} = 12V/5V = 2.4$

Letting $t_{OFF} = 1\mu sec$, $t_{ON} = 2.4\ \mu sec$

$D = t_{ON}/(t_{ON}+t_{OFF}) = 2.4/3.4 = 70.6\%$



- Case 4b:
  - How will the duty cycle change with 10V at "ON" and 12V at "OFF"?
  - Answer: $D = V_{OFF}/(V_{OFF}+V_{ON}) = 12/22 = 54.5\%$

Basic Concepts: Inductor Power vs Current

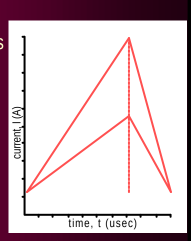
- In any given inductor with inductance L, the power absorbed and delivered by the inductor in one cycle is equal to the ff:
- $P_{CYCLE} = P_{ABSORBED} = P_{DELIVERED} = ½L(I_2^2-I_1^2)f$
- During steady state, the net power in the inductor per cycle is zero:
- $P_{Lnet} = P_{ABSORBED} + P_{DELIVERED} = 0$

Example

- Case 5:
  - If an inductor operating in critically discontinuous mode absorbs and delivers 50W per cycle when the current excursion is 1A, how much power does it handle when the current excursion is doubled while keeping frequency constant?
  - Answer:

$½Lf = P/(I_2^2-I_1^2) = \text{constant}$

$P_{new} = 50(2^2) = 200W$

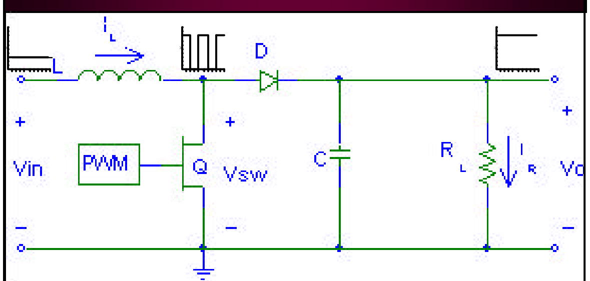


- Note: The fact that doubling ΔI quadrupled P is no longer true during continuous mode.

Characteristics of a Boost Regulator

- DC-DC switching regulator
- OUTPUT voltage is always higher than the INPUT voltage (during normal operation)
- OUTPUT cannot be isolated from the INPUT

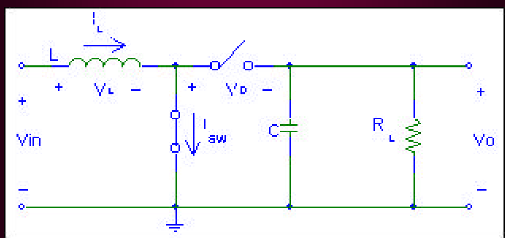
Boost Regulator Circuit Diagram



Basic Operation of a Boost Regulator

- DC input voltage is chopped by the switch Q to produce a rectangular voltage with respect to ground at the other end of inductor L.
- The inductor L feeds the output capacitor C and load resistor R_L through the rectifying diode D.
- Regulation of the output voltage is accomplished by varying the duty cycle of the switch wrt input voltage changes.

Detailed Operation: Boost Regulator "ON" Stage



– Transistor Q is ON, Vin causes I_L to ramp up linearly as energy is stored in inductor L.
– Load current I_R is supplied by capacitor C.

Boost Regulator: Analysis of Operation

- Assumption: CRITICALLY DISCONTINUOUS MODE
- With critically discontinuous mode of operation, the current in the inductor starts rising just when it reaches zero.

ON stage: When the switch is closed

$dI_L / dt = V_L/L$ *[Eq. 1]*

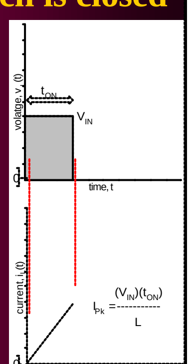
Ideal case: $V_{SW} = 0$,

$I_L / t_{ON} = V_{IN} /L$

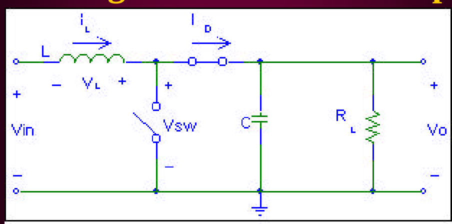
$I_L = (Vin)\ (t_{ON}) / L$ *[Eq. 2]*

$I_R = I_C$

$V_R = V_C$ *[Eq. 3]*



OFF stage: When Switch is Open



- When SW is opened, the voltage across Vsw will fly high. This is clamped by the voltage across capacitor C (assume C is very high)
- In trying to maintain its current, the voltage across L reverses.
- Energy stored in L is delivered to the load and excess inductor current I_C recharges capacitor C, smoothing out load current I_R.

Equations for "OFF" Stage

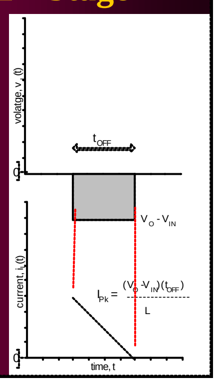
Ideal case: $V_D = 0$

$Vo = Vc = Vin + V_L$ *[Eq. 4]*

$Vo = Vin + L\ I_L / t_{OFF}$

$t_{OFF} = T - t_{ON}$

$I_L = (Vo-Vin)(T - t_{ON}) / L$ *[Eq. 5]*



Duty Cycle of Boost Regulator in Continuous Mode

Notice that I_L does not necessarily have to start from zero. Hence, the general expression I_L instead of Ipeak.

Looking at I_L and equating the right hand sides of *[Eq. 2]* and *[Eq. 5]*, we have the ff:

$(Vin)(t_{ON}) / L = (Vo-Vin)(T - t_{ON}) / L$

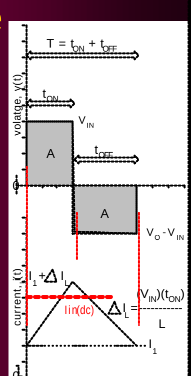
Eliminating L and expanding further, we have:

$Vin (t_{ON}) = (Vo-Vin)(T) - (Vo-Vin)(t_{ON})$

Calculating for the critical duty cycle D yields:

$D = t_{ON}/T = (Vo-Vin)/Vo = 1 - Vin/Vo$

or $Vo = Vin/(1-D)$ *[Eq. 6]*



Critically Discontinuous Operation

In a boost converter, since the inductor is in series with the input:

$I_{IN} = I_L$

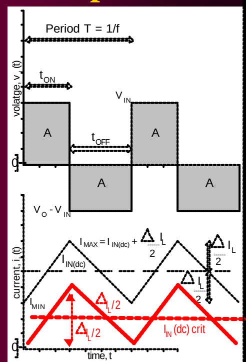
When I_{IN} is always greater than zero, the converter is said to operate in CONTINUOUS mode:

$I_{INmax} = I_{INdc} + ½\ \Delta I_L = I_{INdc} + ½\ V_{IN} t_{ON}/L$

$I_{INmin} = I_{INdc} - ½\ \Delta I_L = I_{INdc} - ½\ V_{IN} t_{ON}/L$

When the input current reaches zero just when the switch turns ON, CRITICALLY DISCONTINUOUS operation occurs:

$I_{INmax} = V_{IN} t_{ON}/L$ & $I_{INmin} = 0$



Discontinuous Mode of Operation

The equation, Vo = Vin/(1-D) is only true during the continuous and the critically discontinuous modes.

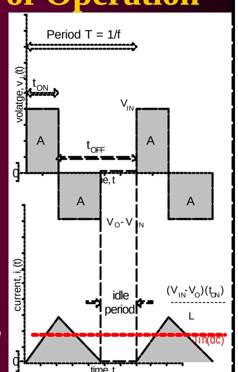
During the discontinuous mode, inductor current remains zero for certain "idle" periods.

$I_{IN(dc)} < \ I_L / 2$

$I_{INmax} = V_{IN} t_{ON}/L = (V_{OUT} - V_{IN})(T - t_{ON} - t_{IDLE})/L$

This yields: *[Eq. 7]*

$Vo/V_{IN} = (1 - t_{IDLE}/T)/(1 - t_{IDLE}/T - D)$



Discontinuous Switching Waveforms

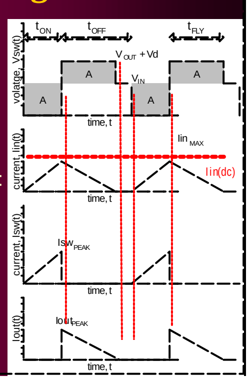
The voltage across the switching device exceeds the output voltage during turn off:

$Vsw_{PEAK} = Vout + Vd > V_{IN}$ *[Eq. 8]*

Input current flows through the switch during turn on and through the diode during turn off:

$I_{INmax} = Isw_{PEAK} = Id_{PEAK} = V_{IN} t_{ON}/L$

$= (V_{OUT} - V_{IN})(T - t_{ON} - t_{IDLE})/L$ *[Eq. 9]*



Continuous Switching Waveforms

The peak voltage across the switching device is the same as that for the discontinuous mode:

Vsw_{PEAK} = Vout + Vd

although temporary step, Vsw = Vin, is no longer present.

Since there is no longer any idle period for the input current:

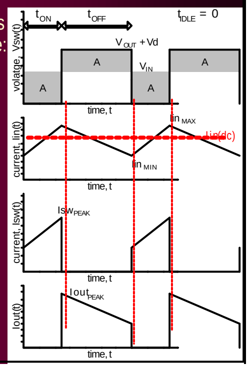
$I_{INmax} = Isw_{max} = Id_{max} = I_{INdc} + ½\, V_{IN} t_{ON}/L$

$= I_{INdc} + ½(V_{OUT} - V_{IN})(T - t_{ON})/L$ *[Eq. 10]*

Furthermore, the minimum current is not zero:

$I_{INmin} = Isw_{min} = Id_{min} = I_{INdc} - ½\, V_{IN} t_{ON}/L$

$= I_{INdc} - ½(V_{OUT} - V_{IN})(T - t_{ON})/L$ *[Eq. 11]*



Inductor Energy & Power Relations

The energy stored in the inductor during turn ON is given by:

$E_{STORED} = ½L(I_{PEAK})^2$ *[Eq. 11]*

where I_{PEAK} = peak inductor current

Ideally, all the energy stored in the inductor is eventually delivered to the load due to volt-second balance. Therefore the power delivered by the inductor to the load is:

$P_L = ½L(I_2^2 - I_1^2)/T$ *[Eq. 12]*

or $P_L = ½L(I_{PEAK}^2)/T$ for discontinuous or critically discontinuous modes.

Average Load Power: Critically Discontinuous Mode

However, during OFF time, the down-ramping current in the inductor is the same current flowing in from the source I_{IN}.

During OFF time, $Pdc_{IN} = Vdc_{IN}(½I_{PEAK})(t_{OFF}/T)$. *[Eq. 13]*

The total load power is therefore the sum of the OFF time input power and the power delivered by the inductor:

$P_T = P_L + Pdc_{IN} = ½[L(I_{PEAK})^2 + Vdc_{IN} I_{PEAK}(t_{off})]/T$ *[Eq. 14]*

Knowing $Vdc_{IN} = L(I_{PEAK})/t_{on}$ and $t_{off} = T - t_{ON}$, we obtain:

$P_T = ½L(I_{PEAK})^2[1 + (t_{off}/t_{on})]/T = ½L(I_{PEAK})^2 f/D$ *[Eq. 15]*

Average Load Power: Continuous Mode

In general, the power delivered to the load during OFF time is greater than the throughput power delivered by the inductor and the total load power is the sum of the OFF time input power and the power delivered by the inductor:

$P_L = \frac{1}{2}L(I_2^2 - I_1^2)f$

$Pdc_{IN} = Vdc_{IN}\frac{1}{2}(I_1 + I_2)(t_{off}/T)$, where $Vdc_{IN} = L(I_2 - I_1)/t_{on}$

or $Pdc_{IN} = \frac{1}{2}L(I_2^2 - I_1^2)f(t_{off}/t_{on})$

Therefore, in general:

$P_T = P_L + Pdc_{IN} = \frac{1}{2}L(I_2^2 - I_1^2)f/D$ *[Eq. 16]*

Advantages and Disadvantages

- ADVANTAGES
  - transistor is referred to GND making it simpler to drive
  - low ripple current reflected to the input
  - provides least-costly PFC solution
- DISADVANTAGES
  - no isolation bet. input and output
  - series diode contributes extra voltage drop
  - does not provide either in-rush current or short circuit protection
  - large output voltage spikes
  - large output capacitor required
  - high output ripple current

Boost Regulator Applications

- Low output power levels for auxiliary supply
  - e.g., to step-up a 5V computer logic level to 15V for use with Op-Amps.
- Almost exclusively used for Power Factor Correction (PFC)

Example

- Given: Ideal Boost Converter

  t_{ON} = 50 μsec (FIXED)

  Vin = 50V Vo = 75V

  L = 250 μH R_L = 2.5 Ω

- Required:

  a) f = ? t_{OFF} = ?

  b) I_{INdc} = ? I_{OUTdc} = ?

  c) $I_L(t)$ = ?

Solution

a) Assuming continuous mode of operation, from *[Eq. 6]*:

D = t_{ON}/T = (Vo-Vin)/Vo,

(50 μsec)/T = (75-50)/75 = 1/3

T = 150 μsec , f = 6.67kHz *[ANSWER to a]*

t_{OFF} = T - t_{ON} = 100 usec *[ANSWER to a]*

b) Knowing that, ideally, Pin = Pout, Vin(I_{INdc}) = Vout (I_{OUTdc})

I_{OUTdc} = Vo/R_L = (75V)/(2.5 Ω) = 30A *[ANSWER to b]*

I_{INdc} = Vout(I_{OUTdc})/Vin = (75V)(30A)/(50V) = 45A *[ANSWER to b]*

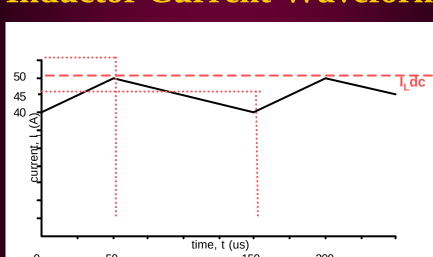
c) From *[Eq. 1]*, dI_L / dt = V_L/L

ΔI_L = Vin(t_{ON})/L = 50V(50 μsec)/(250 μH) = 10A

I_{INmax} = I_{INdc} + ½ ΔI_L = 45 + (10/2) = 50A

I_{INmin} = I_{INdc} - ½ ΔI_L = 45 - (5) = 40A

Inductor Current Waveform



- *[ANSWER to c]*

Design Considerations

- Choose L to be able to satisfy minimum output current requirement.
- Choose C to satisfy output ripple specification.
- Choose properly rated switching devices