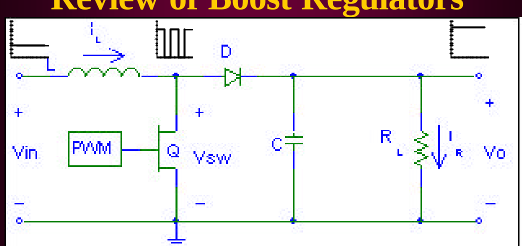
FLYBACK CONVERTERS

Astec Custom Power

Lecture Outline

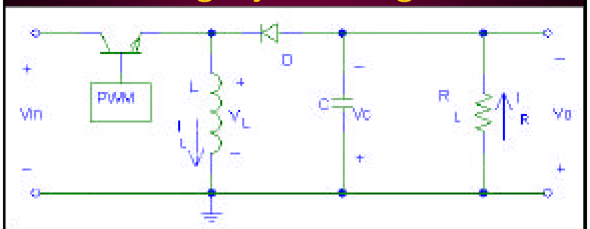
- Review of Boost Regulators
- Flyback Regulator Characteristics
- Basic Operation of a Flyback Converter
- Volt-Second Equality and Reflected Voltage
- Turns Ratio, Frequency and Output Voltage
- Energy and Power Relations
- Design Considerations
  - Leakage Inductance, Snubber Loss, etc.

Review of Boost Regulators



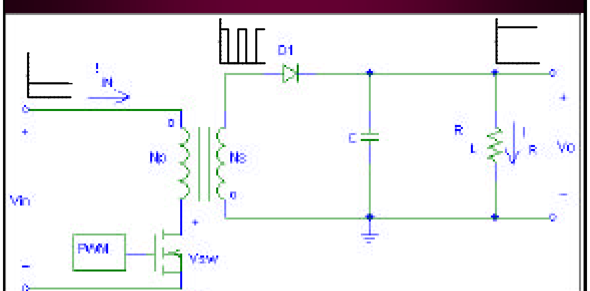
- A boost regulator also employs the “flyback” mode of operation, whereby energy stored in the inductor during ON time “flies back” out of the inductor and into the capacitor and load during OFF time.

“Buck-Boost Regulator” or “Inverting Flyback Regulator”



- Similar in operation to “Boost Converter” (uses the “flyback effect”)
- Called “Buck-Boost” because it can be both a step down (buck) and a step up (boost) converter.
- Do not confuse “Inverting Flyback Regulator” w/ “Flyback Converter

Flyback Converter Circuit Diagram



Characteristics of a Flyback Converter

- DC-DC switching regulator
- OUTPUT voltage may be higher or lower than the INPUT voltage
- OUTPUT is usually isolated from the INPUT

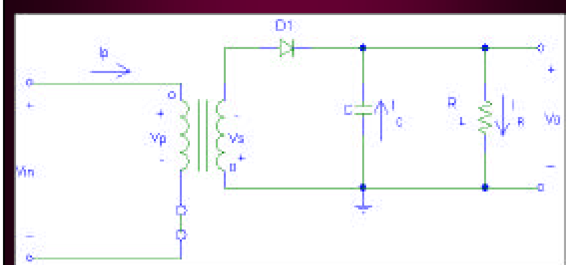
Basic Operation of a Flyback Converter

- Similar to boost and buck-boost regulators except that storage inductor is replaced by a transformer:

(actually works as a combined boost and buck-boost regulator)

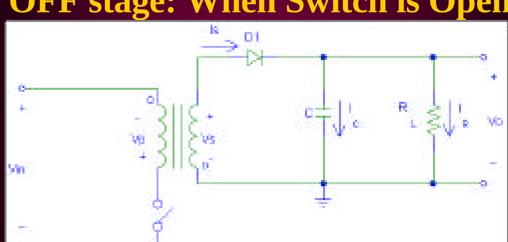
  - DC input voltage is chopped by the switch Q to produce a rectangular voltage with respect to ground across the primary winding of the transformer.
  - Energy stored in transformer during ON time is fed to the output capacitor C and load resistor R_L through the rectifying diode D during OFF time.
  - Regulation of the output voltage is accomplished by varying the duty cycle of the switch wrt input voltage changes.

Flyback Converter "ON" Stage



- Transistor SW is ON, Vin causes I_P to ramp up linearly as energy is stored in transformer core.
- Load current I_R is supplied by capacitor C.

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 transformer voltages reverse.
- Energy stored in L is delivered to the load and excess inductor current I_C recharges capacitor C, smoothing out load current I_R.

Reflected Voltage During OFF Stage

- The voltage across the primary during turn OFF is:

  $V_{Poff} = -V_O(n_P/n_S)$ *[Eq. 1]*

- The term $V_O(n_P/n_S)$ is the approximate voltage across the secondary winding REFLECTED to the primary ($V_{P:S}$).

- Taking into consideration the forward voltage drop across the freewheeling diode, the actual REFLECTED VOLTAGE must be:

  $V_{P:S} = (V_O + V_D)(n_P/n_S)$ *[Eq. 2]*

  but term in *[Eq. 1]* is usually a good approximation.

- Notice that the reflected voltage is dependent on turns ratio (n_P/n_S) and output voltage (V_O), which is related to output power (P_O).

Duty Cycle of Flyback Regulator in Continuous Mode

Knowing that $I_P = (V_{IN})(t_{ON}) / L_P$ and

$I_S = (Vo)(T - t_{ON}) / L_S$,

with $I_P = I_S(n_S/n_P)$:

$(V_{IN})(t_{ON}) / L_P = (V_O)(T - t_{ON})(n_S/n_P) / L_S$

Taking note than $L_P/L_S = n_P^2/n_S^2$:

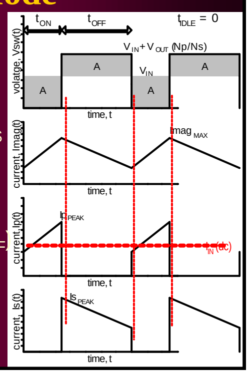
$V_{IN}(t_{ON})/n_P = [(V_O)(T) - (V_O)(t_{ON})]/n_S$ or

$V_O/V_{IN} = (n_S/n_P)D/(1-D) = (n_S/n_P)(t_{ON}/t_{OFF})$

[Eq. a]

Calculating for the duty cycle D:

$D = t_{ON}/T = V_O(n_P)/[V_{IN}(n_S)+V_O(n_P)]$



Discontinuous Flyback Operation

The equation, $V_O/V_{IN} = (n_S/n_P)\ D/(1-D)$ is only true during the continuous and the critically discontinuous modes.

During the discontinuous mode:

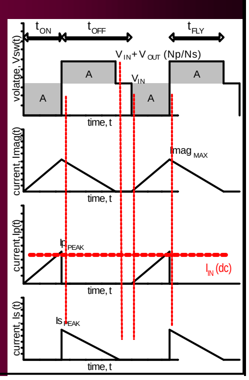
$(V_{IN})(t_{ON}) / L_P = (V_O)(T - t_{ON} - t_{IDLE})(n_S/n_P) / L_S$

where $t_{IDLE} = T - t_{ON} - t_{FLY}$

This yields:

$V_O/V_{IN} = (t_{ON}/t_{FLY})(n_S/n_P)$ *[Eq. b]*

which is actually a more general form of *[Eq. a]*



Switching Voltage

- Notice from the switching waveforms that the maximum voltage stress on the transistor during turn OFF was said to be:

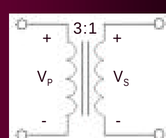
  $Vsw_{OFF} = V_{IN} + V_O(n_P/n_S)$

- Actually, the voltage drop across the series diode during OFF time adds to this switching stress:

  $Vsw_{OFFmax} = V_{IN} + (V_O + V_D)(n_P/n_S)$ *[Eq. c]*

- However, an allowance (e.g. 30% more) should be provided to accommodate the large voltage spikes which occur at the start of turn OFF when the n_P/n_S ratio is large, because of the large di/dt at the transformer windings.

Example # 1



Given:

- The output voltage of a flyback converter is known to be 3V and its input is 12V.
- The ratio of the primary turns to the secondary turns is 3:1.

Required:

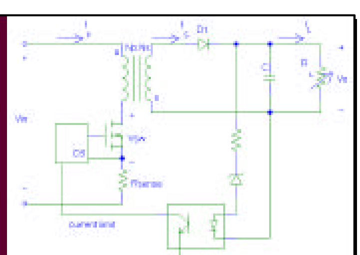
- What is the voltage across the primary winding during turn OFF, assuming the converter is operating in continuous mode. (Neglect diode drops.)

Answer:

$V_{P:Soff} = (V_O)(n_P/n_S)$

$V_{P:Soff} = (3V)(3/1) = 9V$

Example # 2



Given:

- $V_{IN} = 400V$, $V_O = 20V$
- $V_{D1} = 1V$
- $n_P = 40$, $n_S = 10$

Required:

- What will be the peak voltage seen by the MOSFET? (Neglect leakage inductance.)

Answer:

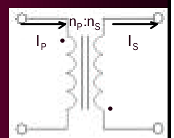
$Vsw_{OFF} = V_{IN} + (V_O + V_D)(n_P/n_S)$

$Vsw_{OFF} = 400V + (21V)(4) = 400V + 84V$

$Vsw_{OFF} = 484V$

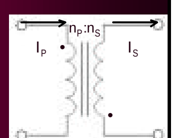
The Flyback Transformer VS the Forward Transformer

- Unlike a forward transformer, the secondary winding of a flyback transformer has a polarity opposite that of the primary winding.
- Whereas a forward transformer is a voltage transformer in the practical sense, the flyback transformer is effectively an ENERGY TRANSFORMER.
  - (This concept can be better understood from the concept of volt-second balance.)
- The turns ratio is usually determined by the ratio between the flyback voltage (reflected voltage) and the input voltage.



Current Through the Windings

- V = Ldi/dt
- When 1V is applied across a 1µH winding, the current through it will rise at the rate of 1A/µsec.
- Doubling the applied voltage doubles the rate of current rise.
- Doubling the number of turns (4 x L) means it will take four times as long for current to ramp up.
- (turns)



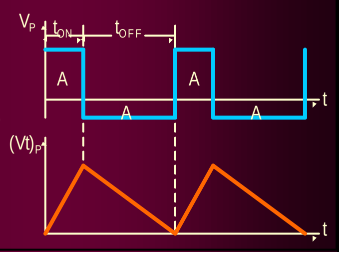
Volt-Second Balance in an Inductor

- Since the net change in energy in an inductor must be zero (the average voltage is zero) over one cycle, the integral of voltage over time (volt-seconds) across an inductor during turn ON must equal the volt-seconds during turn OFF:
- $V_{Lon}t_{ON} = V_{Loff}t_{RESET}$ *[Eq. 3]*
- This can also be deduced from the fact that, for constant output, the change in current ΔI must be constant. Therefore,
- $L\Delta I = V\Delta t =$ constant *[Eq. 4]*

Transformer Volt-Second Balance

- Since the net change in energy in the transformer must be zero over one cycle, the volt-seconds across the primary during turn ON must equal the volt-seconds across the secondary during turn OFF, reflected to the primary:

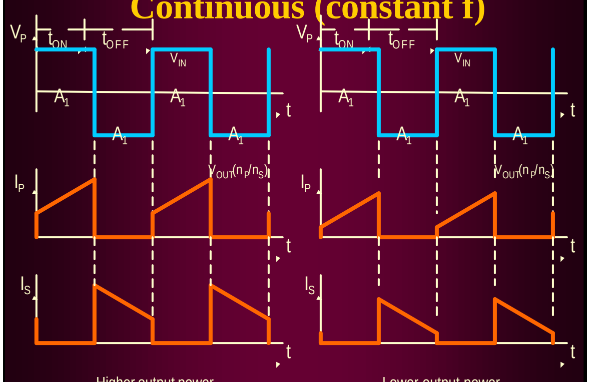
- $V_{Pon}t_{ON} = V_{P:Soff}t_{RESET}$ *[Eq. 5]*
- $V_{Pon}t_{ON} = V_{Soff}t_{RESET}(n_P/n_S)$ *[Eq. 6]*
- $(Vt)_P \propto (Vt)_S$



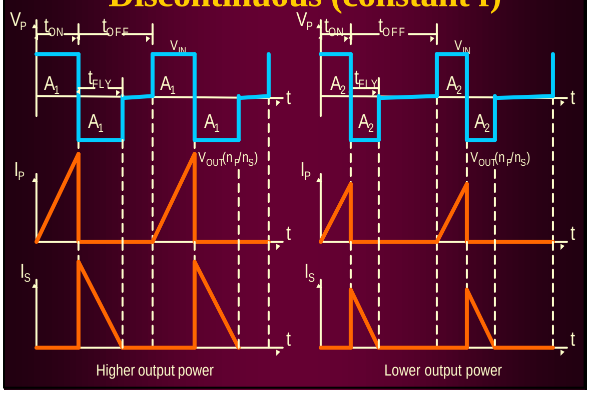
Modes of Flyback Operation

- Flyback converters are generally classified as either CONSTANT FREQUENCY flyback converters or VARIABLE FREQUENCY (SELF-OSCILLATING) flyback converters.
- With constant frequency flyback converters, there are basically two modes of operation:
  - CONTINUOUS
  - DISCONTINUOUS
- The self-oscillating flyback converter generally operates in CRITICALLY DISCONTINUOUS mode.

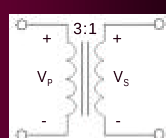
Continuous (constant f)



Discontinuous (constant f)



Example # 3



Given:

- V_{Pon} = 12V V_{soff} = 3V
- n_P/n_S = 3 t_{ON} = 5µsec
- Flyback converter operating in continuous mode.

Required:

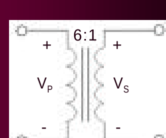
- How long is the turn OFF time of the switch?
- What is the flyback period if the converter is operating in discontinuous mode?

Answer:

$t_{OFF} = V_{Pon} t_{ON} / V_{P:Soff}$, where $V_{P:Soff}$ = 9V *(from Example # 1)*

t_{OFF} = (12V)(5µsec)/(9V) = (6.67µsec) = $t_{FLYBACK}$

Example # 4



Given:

- Same specs as in *Example # 3*, except n_P/n_S = 6

Required:

- How is flyback period affected by doubling the turns ratio?

Answer:

$t_{OFF} = V_{Pon} t_{ON} / V_{P:Soff}$, where $V_{P:Soff} = V_O(n_P/n_S)$

$t_{OFF} = V_{Pon} t_{ON} / [V_O(n_P/n_S)]$ = (12V)(5µsec)/[(3V)(6/1)]

t_{OFF} = (12V)(5µsec)/(18V) = (3.33µsec)

∴ Flyback period is halved by doubling turns ratio *(for same output)*.

Energy & Power Relations

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

$$E_{STORED} = \tfrac{1}{2}L_P I_{P2}^2 - \tfrac{1}{2}L_P I_{P1}^2 \qquad \text{[Eq. 7a]}$$

The throughput power going into the primary winding is therefore:

$$P_{IN} = \tfrac{1}{2}L_P(I_{P2}^2 - I_{P1}^2)f \qquad \text{[Eq. 8a]}$$

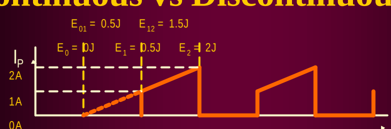
Similarly, the energy and power delivered by the secondary are:

$$E_{DELIVERED} = \tfrac{1}{2}L_S I_{S2}^2 - \tfrac{1}{2}L_S I_{S1}^2 \qquad \text{[Eq. 7b]}$$

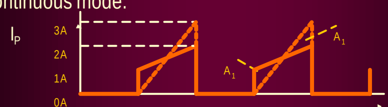
$$P_{OUT} = \tfrac{1}{2}L_S(I_{S2}^2 - I_{S1}^2)f \qquad \text{[Eq. 8b]}$$

Ideally, $E_{STORED} = E_{DELIVERED}$ and $P_{IN} = P_{OUT}$.

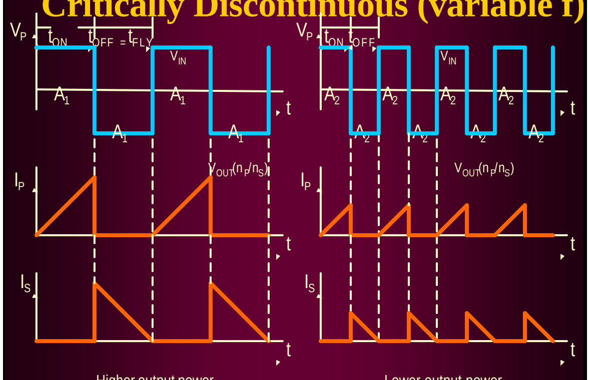
Power Considerations: Continuous vs Discontinuous Mode



- Given the same current excursion ΔI, larger throughput power is provided by continuous mode.
- For same output power, peak currents are higher during discontinuous mode.



Critically Discontinuous (variable f)



Critically Discontinuous Operation

- Critically Discontinuous Operation is the transition point between Continuous Mode and Discontinuous Mode.
- With critically discontinuous mode of operation, primary winding current starts from zero at every cycle.
- Secondary winding current goes down to zero just when primary winding current starts ramping up again.
- OFF time = flyback period. There is no idle period.
- Equations for both continuous and discontinuous apply for crit disc.

Critically Discontinuous Operation: Output Power Considerations

- Given a constant turn ON period, output current is a function of turn OFF period.
- *RULE OF THUMB*: for 50% duty cycle, you have to transfer twice the total P_{OUT} (i.e., the total output energy) within the ON period.
- From *[Eq. 8]*, $P_{OUT} = ½L_S(I_{Speak}{}^2)f$, where $I_1 = 0$. *[Eq. 9]*
- At first glance, it seems that frequency is proportional to load, however, the opposite is actually true.
- This is because it is actually the peak current which is proportional to load, and frequency adjusts correpondingly.

Critically Discontinuous Operation: Peak Current VS Output Power

- Assuming $P_{IN} = P_{OUT}$, *[Eq. 9]* also translates to $P_{OUT} = ½L_P(I_{Ppeak}{}^2)f$
- Solving for peak primary current: $I_{Ppeak} = \sqrt{[2 P_{OUT} (t_{ON} + t_{OFF})/L_P]}$,
  where $t_{ON} = I_{Ppeak}L_P/V_{IN}$
  and $t_{OFF} = I_{Ppeak}L_P/(V_{OUT}n_P/n_S) = I_{Ppeak}L_P/(V_{P:S})$
- This yields: $I_{Ppeak}{}^2 = 2 P_{OUT} I_{Ppeak}(1/V_{IN} + 1/V_{FLY})$

$\therefore$ $I_{Ppeak} = 2 P_{OUT} (1/V_{IN} + 1/V_{FLY})$ *[Eq. 10]*

- Peak current is directly proportional to load given a constant input V

Critically Discontinuous Operation: Frequency VS Output Power

- Assuming a regulated output, frequency depends on V_{IN} & P_{OUT}.
- With $T = t_{ON} + t_{OFF}$, where $t_{ON} = I_{Ppeak}L_P/V_{IN}$ & $t_{OFF} = I_{Ppeak}L_P/(V_{P:S})$
- Substituting *[Eq. 10]* yields: $T = 2P_{OUT}(V_{IN} + V_{P:S})^2L_P/(V_{IN}V_{P:S})^2$

  or $f = (V_{IN}V_{P:S})^2/[2P_{OUT}L_P(V_{IN} + V_{P:S})^2]$ *[Eq. 11]*
- If V_{IN} = const, for HALF the original power, frequency will DOUBLE.
- At no load (no output power), frequency will go VERY VERY high.

  ∴ You have to determine a MINIMUM as well as a maximum load.

Critically Discontinuous Operation: Frequency VS Input Voltage

- From *[Eq. 11]*, $f = (V_{IN}V_{P:S})^2/[2P_{OUT}L_P(V_{IN} + V_{P:S})^2]$
- If the output parameters (V_{OUT} & P_{OUT}) are constant, increasing V_{IN} with increase the frequency.
- Taking the limit as the input voltage approaches infinity:
-
- $\lim_{V_{IN}\to\infty} f(V_{IN}) = V_{P:S}^2/(2P_{OUT}L_P)$ *[Eq. 12]*

∴ The frequency limit is determined by V_{OUT}, P_{OUT} and L_P.

Example # 5

Given: Crit. Disc. Mode

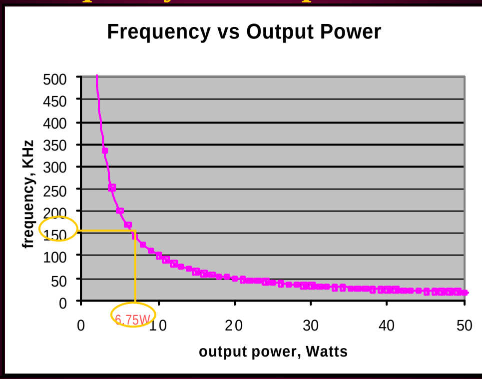
- $V_{IN} = 90V$, $V_O = 10V$
- $n_P/n_S = 1$
- $P_{FL} = 25W$
- primary inductance = 40μH

Required:

- How will the frequency change from No Load to Full Load?
- What should be the minimum load if the frequency is not to exceed 150KHz?

Solution: The reflected voltage is calculated as $V_{P:S} = V_On_P/n_S = 10V$. From *[Eq. 11]*, with $P_{OUT} = P_{FL} = 25W$, the frequency is 40.5KHz, but at No Load, the frequency is infinite. For the minimum load, $P_{OUT} = (V_{IN}V_{P:S})^2/[2fL_P(V_{IN} + V_{P:S})^2]$, where $f = f_{MAX} = 150KHz$. This yields $P_{MIN} = 6.75W$.

Frequency VS Output Power



Example # 6

Given: Crit. Disc. Mode

- $V_O = 10V$
- $n_P = n_S$
- $f = 324kHz$ @ $V_{IN} = 90V$
- P_{OUT} = constant

Required:

- How will the frequency change as input voltage is increased from zero to infinity?
- What should be the minimum load if the frequency is not to exceed 150KHz?

Solution: From *[Eq. 11]*, $f = (V_{IN}V_{P:S})^2/[2P_{OUT}L_P(V_{IN} + V_{P:S})^2]$.

$V_{P:S} = V_O n_P/n_S = 10V$, while $(P_{OUT} L_P)$ is a constant which can be determined from the given case: $f = 324kHz$ @ $V_{IN} = 90V$

Frequency VS Input Voltage

$P_{OUT}L_P = (V_{IN}V_{P:S})^2/ 2f(V_{IN} + V_{P:S})^2$, where $f = 324kHz$ @ $V_{IN} = 90V$

$P_{OUT}L_P = (900)^2/ 2(324k)(100)^2 = 125\,\mu WH$ = constant

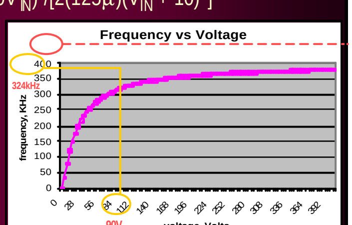
Therefore, in general, $f = (10V_{IN})^2/[2(125\mu)(V_{IN} + 10)^2]$

- The relationship between f & V_{IN} for *Example # 6* can be rewritten as:

$f = 400kV_{IN}^2/(V_{IN} + 10)^2$

$\therefore\ 0 < f < 400kHz$

(consistent with *[Eq. 12]*)



Transformer Core Considerations

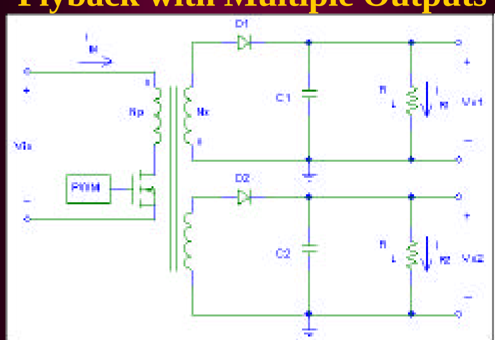
Unlike the forward converter, the flyback converter does not need a reset winding since the core is made to “de-saturate” during turn OFF.

On the other hand, in a flyback converter, the core is made to store all the input energy during turn ON before it is allowed to deliver the energy to the load during turn OFF.

Therefore, with same loading conditions, a higher-power transformer is needed for the flyback than for the forward converter.

Note: To be able to store significant amounts of energy in the core, an air gap is required since considerably more energy can be stored in the gap than in the ferromagnetic part of the core.

Flyback with Multiple Outputs



- $I_{Ppeak} = (I_{S1peak} n_{S1} + I_{S2peak} n_{S2}) / n_P$ *[Eq. 13]*

Feedback Considerations

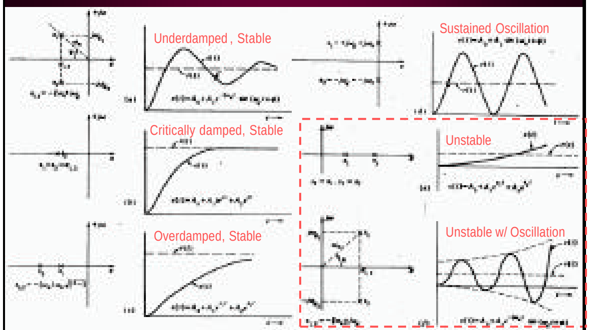
Only one output can be directly regulated, with other outputs acting as “slaves”.

Feedback loop is easily stabilized with discontinuous mode operation.

Recalling that the DC gain of the flyback regulator in continuous current mode is $V_O/V_{IN} = Dn_S/n_P(1\text{-}D)$, the term (1-D) in the denominator constitutes a RIGHT HALF PLANE ZERO and has a dramatic effect on the response of the circuit to sudden load changes, reducing gain slope by 20dB/decade but increading phase lag by 90º.

The only way to stabilize the feedback loop during continuous mode is to drastically reduce the error amplifier bandwidth (i.e., reduce response time).

Right Half Plane Zero



- Right half plane zeroes in the characteristic equation {1 + G(s)H(s)} tends to destabilize the system.

Advantages: Continuous VS Discontinuous

CONTINUOUS
- Lower peak currents
  - Lower transistor rating required

DISCONTINUOUS
- More rapid response
- No right half plane zero
  - Less feedback problems
- A slow recovery secondary diode can be used

Disadvantages: Continuous VS Discontinuous

CONTINUOUS
- Needs bigger transformer
- Commutating the secondary diode can cause switching noise around the output diode and ringing in the transformer
- Can give worse EMI results

DISCONTINUOUS
- High capacitor ripple current
- High peak diode current
- Higher FET current

Flyback Advantages & Disadvantages Over Forward Converters

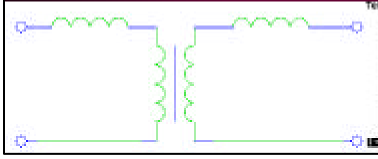
- ADVANTAGES
  - Output voltage range highly flexible wrt input voltage range.
  - Simple design (only 1 diode & FETs are source grounded)
  - Only one output diode needed
- DISADVANTAGES
  - Generally less efficient
  - Leakage inductance energy needs to be dissipated in snubber (in forward the energy goes back to the source via the reset winding)

Design Considerations

- Effective Leakage Inductance & Causes
- Energy Stored in Leakage Inductance
- Snubber Voltage vs Snubber Loss
- Short Circuit Current
- Cross Regulation
- Diode Voltage Drops
- Capacitor Ripple Voltage
- Open Loop Flyback Operation

Leakage Inductance

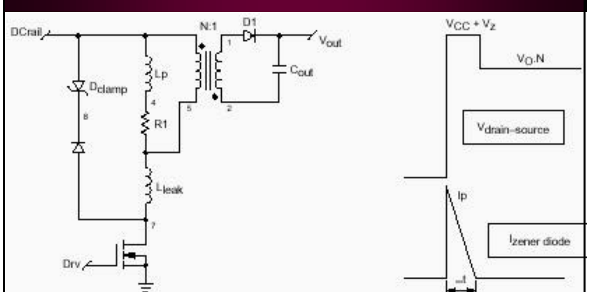
- Leakage is caused by the imperfect coupling between the primary and the secondary windings.
- It is not affected by changing the core material.
- Usually expressed as a percentage of winding inductance.
  - (e.g., 3% leakage)



Minimizing the Effects of Leakage Inductance

- Make sure windings are tightly coupled
  - between PRI & SEC to minimize transistor spike
  - between SEC & AUX for better regulation (for primary side controlled flybacks)
- Use snubbers or clamping circuits
  - after it is no longer possible to improve magnetics

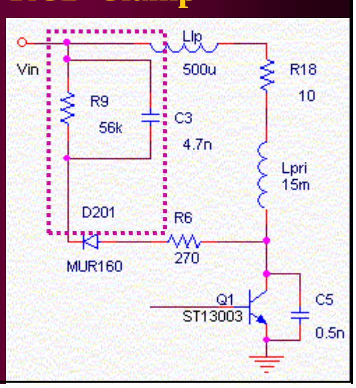
The DZ Clamp



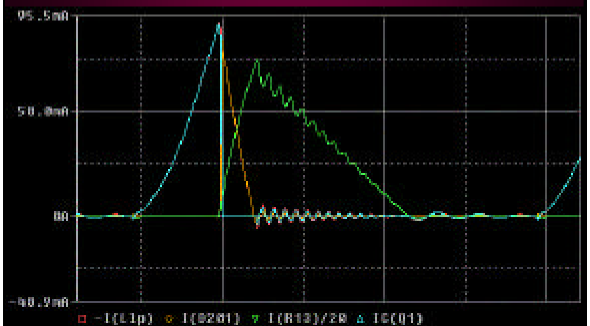
- Zener diode effectively “clips” the voltage spike until the leakage energy is totally dissipated in the zener diode.

The RCD Clamp

- Energy stored in leakage inductance is fed into the parallel RC combination via the diode, effectively clamping the winding voltage to Vc.
- Leakage inductance oscillates with diode capacitance when the diode current goes to zero.
- R continuously dissipates energy stored in C.

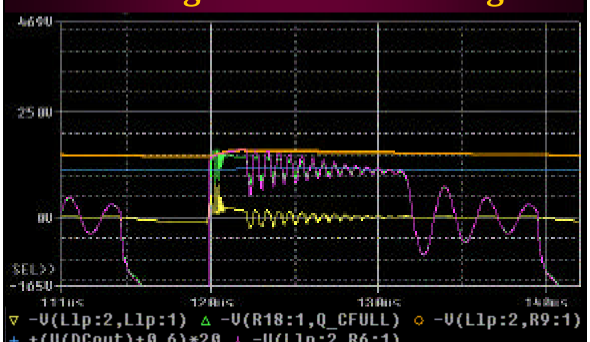


Leakage Inductance Energy



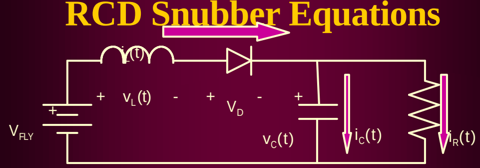
– Secondary current rises as leakage current falls.

Leakage Inductance Voltage



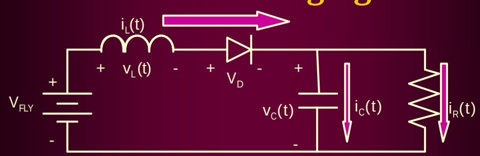
- Leakage current charges C_{clamp}, then L_{leak} oscillates with C_{diode}

RCD Snubber Equations



- By KVL: $v_C = V_{FLY} - L di_L/dt$ (neglecting V_D) [eq1]
- By KCL: $i_L = C dv_C/dt + v_C/R$ [eq2]
- Since from [eq1] $dv_C/dt = -L d^2 i_L/dt^2$, [eq2] translates to
  $i_L = C(-L d^2 i_L/dt^2) + (V_{FLY} - L di_L/dt)/R = -(CL) d^2 i_L/dt^2 - (L/R) di_L/dt - (V_{FLY}/R)$
  or $(CL) d^2 i_L/dt^2 + (L/R) di_L/dt + i_L = (V_{FLY}/R)$ [eq3]
- [eq3] is a 2nd order differential equation, whose solution is of the form
  i_L = [Transient i(t)] + [Steady State I] , where [Steady State I] = V_{FLY}/R (at $t = \infty$)
  and [Transient i(t)] = $e^{-t/\tau}(K_1 \sin\omega_o t + K_2 \cos\omega_o t)$, where $\tau = 2RC$ and $\omega_o = 1/\sqrt{(LC)}$
- Using boundary conditions $v_C(0) = V_{FLY}$ and $i_L(0) = Ipri_{PEAK}$, K_1 and K_2 are solved as
  $K_1 = [Ipri_{PEAK} - V_{FLY}/R] / [\tau\, \omega_o]$ and $K_2 = [Ipri_{PEAK} - V_{FLY}/R]$

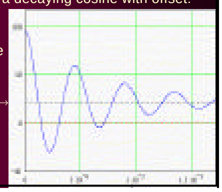
RCD Snubber Charging Current



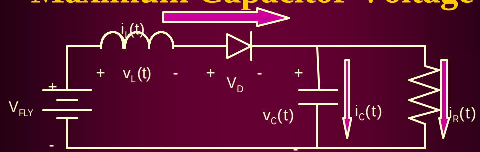
- From the preceding discussion, since $|L| << |R|$, $[\tau\, \omega_o]$ is very large, and $K_1 << K_2$.
- Thus, the snubber charging current is approximately a decaying cosine with offset:

  $i_L = (Ipri_{PEAK} - V_{FLY}/R)\, e^{-t/2RC} \cos\omega_o t + (V_{FLY}/R)$ [eq4]

- This equation is only true while the current is positive (while diode is forward biased).



Maximum Capacitor Voltage



- From [eq1]: $v_C = V_{FLY} - L\,di_L/dt$

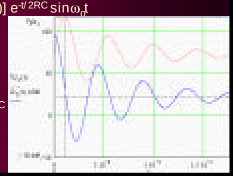
  The capacitor voltage is determined by substituting the derivative of [eq4] into [eq1]:

  $v_C = V_{FLY} + [(L/\tau)(Ipri_{PEAK} - V_{FLY}/R)]\, [(\tau\omega_o) + 1/(\tau\omega_o)]\, e^{-t/2RC} \sin\omega_o t$

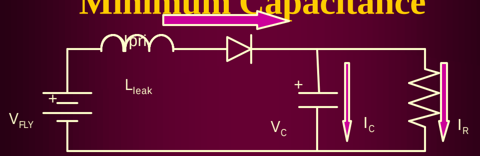
  where $\tau = 2RC$ and $\omega_o = 1/\sqrt{(LC)}$
- It can be seen that the capacitor voltage reaches its peak at an angle of approx90º. Therefore:

  $v_{Cpeak} \sim$

  $V_{FLY} + [(L/\tau)(Ipri_{PEAK} - V_{FLY}/R)]\, [(\tau\omega_o) + 1/(\tau\omega_o)]\, e^{-\pi\sqrt{(LC)}/4RC}$



Minimum Capacitance

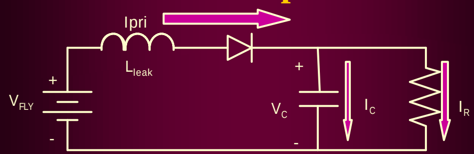


- Leakage inductance energy charges the clamp capacitor: $E_{leak} \sim E_C$
- Requirement: $V_C = (V_{FLY} + Vspike) < Vds_{MAX} - Vin$
- Given L_{leak} and $Ipri_{PEAK}$, we have $E_{leak} = ½L_{leak}(Ipri_{PEAK})^2$ (which eventually dies to 0)
- Knowing $E_C = ½C(V_C)^2$, with an initial stored energy of $E_{Co} = ½C(V_{FLY})^2$, we have:

  $½L_{leak}(Ipri_{PEAK})^2 = ½C\, [\, (V_{FLY} + Vspike)^2 - V_{FLY}^2\,]$

  or $C = L_{leak}(Ipri_{PEAK})^2 / [\, (V_{FLY} + Vspike)^2 - V_{FLY}^2\,]$
- Must be a low-loss type capacitor to reduce power dissipation due to high $Ipri_{PEAK}$.

Minimum Clamp Resistance



- Capacitor voltage must decay to original value (V_{FLY}) by the start of the next cycle (i.e., after approximately one period T)
- $V_C = V_{FLY} = (V_{FLY} + Vspike)\, e^{-T/RC}$
- Therefore:
- $1/R = f_{SW}\, C \ln(1 + Vspike/V_{FLY})$
- Power rating: $PR = V_{FLY}^2/R + ½L_{leak}(Ipri_{PEAK})^2 f_{SW}$

Self-Oscillating Flyback Converter