Flyback Transformer Leakage Inductance

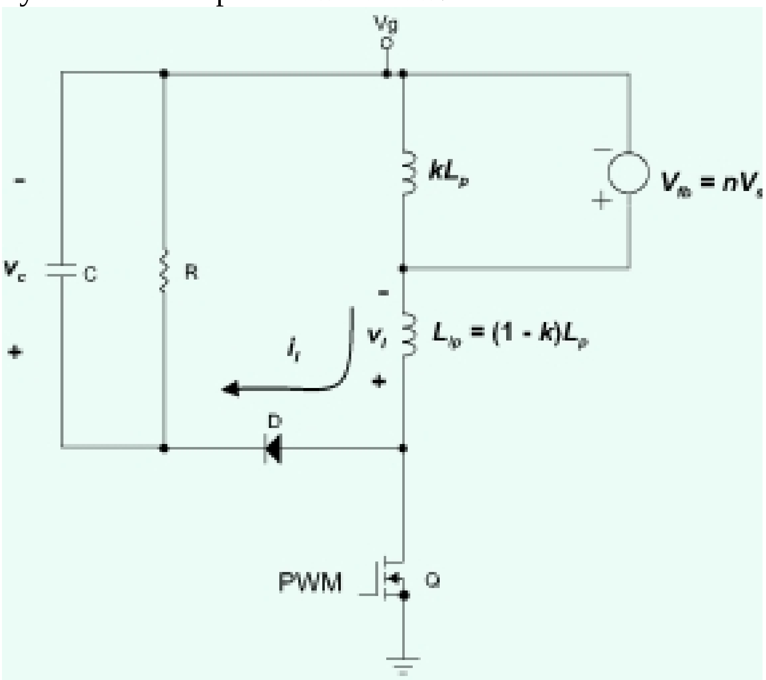
Part 3: RC Leakage Inductance Clamps

by Dennis L Feucht

Due to the impracticality of high-voltage Zener-diode clamps, an alternative for the primary circuit of a flyback converter is the RC clamp. It is more complex to design than the constant-voltage Zener clamp because its capacitance resonates with the leakage inductance being clamped. The clamp is analyzed here with the goal of deriving the necessary design equations.

RC Clamp Circuit

The circuit model of the flyback RC clamp is shown below.

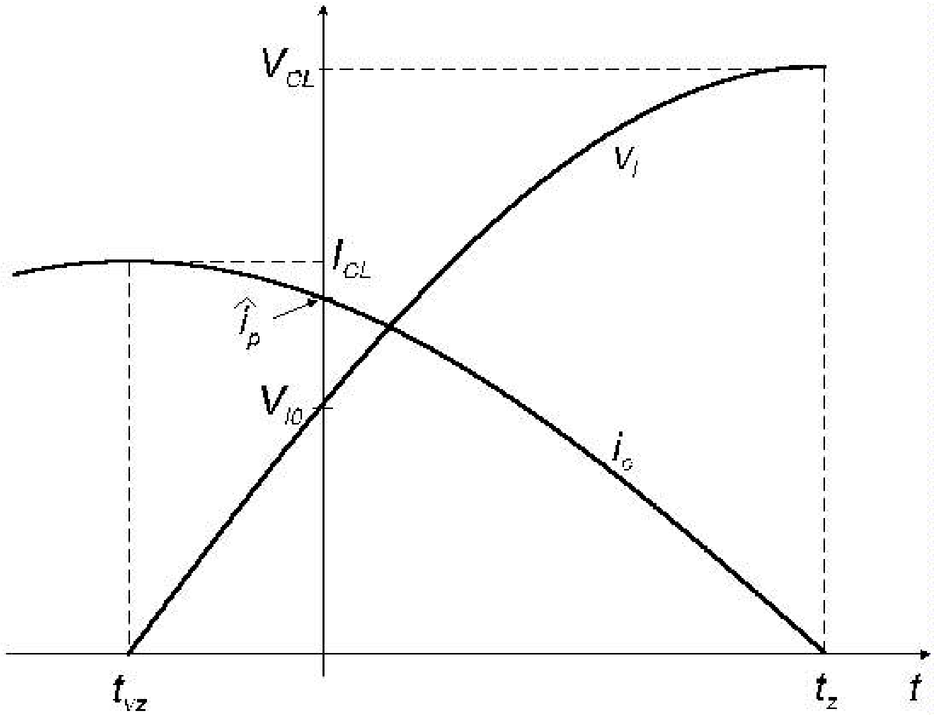


The Zener clamp has been replaced by a parallel RC network which forms a parallel resonant circuit with the transformer leakage inductance. Diode, D, conducts when Q turns off at $t = 0$ during the clamp time, which is the winding-current transfer time, t_d. (see Part 2 http://www.analogZONE.com/col093003.htm). The mutual inductance of the primary winding, $k \cdot L_p$, is held at V_{fb}, the flyback voltage, by the secondary voltage, as shown, during the secondary conduction time. The primary leakage inductance, $L_{lp} = (1 - k) \cdot L_p$, is free to resonate with C during the clamp time, while D conducts.

At turn-off the capacitor has voltage, V_{c0}, across it. The initial voltage across the leakage inductance opposing its current is V_{l0}. It is the minimum clamp voltage across the leakage inductance, and occurs at turn-off. As C charges its voltage increases and opposes the current from L_l, causing it to decrease until it reaches zero at t_z, when D disconnects. This ends the clamping interval. The maximum voltage across C at t_z is V_{CP}:

$$V_{CP} = V_{CL} + V_{fb}$$

where, V_{CL} is the maximum $v_l(t)$ and is its amplitude. The waveforms are shown below.



Clamp current, $i_l(t)$, is maximum at I_{CL}, the amplitude of the current sinusoid. Current i_l flows into C (shown as as i_c in the graph) and decreases as $v_c(t)$ increases until i_c becomes zero and v_l peaks at V_{CL} and t_z.

Having chosen V_{CP} as the maximum capacitor voltage, then:

$$V_{CL} = V_{CP} - V_{fb}$$

Also, $v_c(0) = V_{c0}$ is:

$$V_{c0} = V_{l0} + V_{fb}$$

With these quantities defined, the capacitance value can be derived from energy considerations. C charges at the end of the clamp period, t_z, to its maximum of V_{CP}, then exponentially decays by discharging through R to the value V_{c0} at the end of the cycle ($t = T_s$). The total energy dissipated in R must then equal the leakage-inductance energy stored in C during the clamp period. Equating the C and L_l energies:

$$\tfrac{1}{2} \cdot L_l \cdot \hat{i}_p^2 = \tfrac{1}{2} \cdot C \cdot (V_{CP}^2 - V_{c0}^2)$$

Then solving for C:

$$C = \frac{L_l \cdot \hat{i}_p^2}{V_{CP}^2 - V_{c0}^2}$$

This energy transfer occurs at a rate of f_s, the converter switching frequency. So, the power dissipated in R is:

$$P_R = \tfrac{1}{2} \cdot L_l \cdot \hat{i}_p^2 \cdot f_s = \tfrac{1}{2} \cdot C \cdot (V_{CP}^2 - V_{c0}^2) \cdot f_s$$

The clamp resistance value is found by solving the decaying exponential equation, with time constant RC, for R:

$$R = -\frac{T_s - t_z}{C \cdot \ln\left(1 - \frac{V_{c0}}{V_{CP}}\right)}$$

C discharges for the cycle period, T_s, except during the clamp period, t_z. To find R, t_z must be derived.

Because of the non-zero clamp voltages and current at turn-off, the peak current, I_{CL}, would have occurred before turn-off. The actual waveforms begin at $t = 0$ but the equations for them have a phase offset, ϕ. The clamp waveforms can be described by the following resonant-circuit equations for infinite R:

$$i_c(t) = i_l(t) = I_{CL} \cdot \cos(\omega_n \cdot t + \phi)$$

$$v_c(t) - V_{fb} = v_l(t) = V_{CL} \cdot \sin(\omega_n \cdot t + \phi)$$

The phase offset, ϕ, is found by applying the conditions at $t = 0$ to these equations:

$$\phi = \sin^{-1}\left(\frac{V_{l0}}{V_{CL}}\right) = \cos^{-1}\left(\frac{\hat{i}_p}{I_{CL}}\right)$$

The resonant frequency and impedance can be found from the given circuit values:

$$\omega_n = \frac{1}{\sqrt{L_l \cdot C}}$$

and:

$$Z_n = \sqrt{\frac{L_l}{C}} = \frac{V_{CL}}{I_{CL}}$$

Solving the above sinusoidal equations:

$$I_{CL} = \frac{\hat{i}_p}{\sqrt{1 - \left(\frac{V_{l0}}{V_{CL}}\right)^2}}$$

Alternatively:

$$I_{CL} = \hat{i}_p \cdot \sqrt{1 + \left(\frac{V_{l0}}{\hat{i}_p \cdot Z_n}\right)^2}$$

Then the time at which the extrapolated (not actual) v_l waveform crosses zero and i_l peaks at I_{CL} is:

$$t_{vz} = -\frac{\phi}{\omega_n}$$

For proper clamping action, $v_c(0) > V_{fb}$ and $\phi > 0$. This causes the sine and cosine waveforms to be shifted to the left of the origin on the graph by ϕ. Applying the condition:

$$i_l(t_z) = 0$$

and solving:

$$t_z = \frac{\frac{\pi}{2} - \phi}{\omega_n}$$

All the quantities of interest for the design are now derived.

It is of further passing interest to note the relationship of clamp quantities to V_{CL}, which can be expressed as:

$$V_{CL} = \sqrt{V_{l0}^2 + (Z_n \cdot \hat{i}_p)^2}$$

Geometrically, V_{CL} is the hypotenuse of a right-angle triangle formed by sides V_{l0} and $Z_n \cdot \hat{i}_p$. This expression is found by solving:

$$v_l(0) = V_{l0} = V_{CL} \cdot \sin\phi \text{, substituting } Z_n = V_{CL}/I_{CL}$$

Closure

Some simplification has been allowed in the above derivations. Notably, the sinusoid equations are for the simpler, undamped case (where $R \to \propto$). While R does damp the clamping action somewhat, the undamped case is a worst-case analysis for voltages. An R so small that it severely damps the clamp resonance is an R that will also discharge C excessively so that at Q turn-off, $v_l(0)$ will be aiding rather than opposing i_l, defeating clamping function.

The flyback RC clamp design procedure has been codified as a MathCAD 11 program, presented below. If you do not use MathCAD, it is still useful. MathCAD is written in standard mathematical notation and can be modified for use with Matlab or other math programs. The procedure can also be followed manually with a calculator. The amount of calculation is not tedious, though a computer program makes experimentation with parameter values easier and quicker. A typical low-power flyback design has been used as an example. Supply the yellow highlighted quantities as input design parameters. MathCAD users might have to scale the graphs for optimal presentation.

For those of you who use this procedure in actual converter design, please inform me of the results: how well the program predictions corresponded to measurements, and any improvements you might have made or errors you have corrected. Send feedback or e-mail requests for the program file, in MathCAD 11, to: dennis@innovatia.com Please do not resell the program, but be free to pass it on to fellow designers. Thanks.

Flyback RC Clamp

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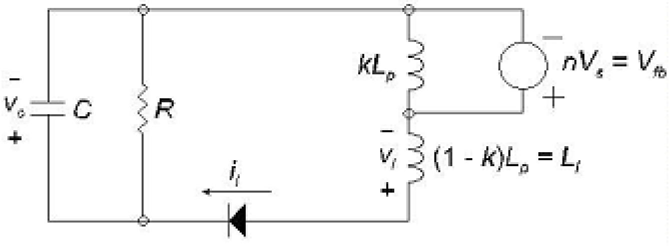


Highlighted quantities are input design parameters.

$\mu s \equiv 10^{-6} \cdot s$ $\quad ns \equiv 10^{-9} \cdot s$

max v_C = $V_{CP} := 60 \cdot V$ $\quad V_s := 6 \cdot V$ $\quad f_s := 40 \cdot kHz$ $\quad T_s := \frac{1}{f_s}$ $\quad T_s = 25\mu s$

$L_p := 3.5 \cdot mH$ $\quad k := 0.99$ $\quad n := 5$

At $t = 0$ (switch turn-off), $v_l(0) = V_{l0}$ (initial clamp voltage at turn-off) and $i_l(0) = i_{ppk}$.

$V_{l0} := 10 \cdot V$ $\quad i_{ppk} := 500 \cdot mA$

$L_l := (1 - k) \cdot L_p$ $\quad L_l = 35\mu H$

$V_{fb} := n \cdot V_s$ $\quad V_{fb} = 30V$

$V_{CL} := V_{CP} - V_{fb}$ $\quad V_{CL} = 30V$ $\quad V_{CL} := \sqrt{V_{l0}^2 + (Z_n \cdot i_{ppk})^2}$

$V_{c0} := V_{l0} + V_{fb}$ $\quad V_{c0} = 40V$

$$C := \frac{L_l \cdot i_{ppk}^2}{V_{CP}^2 - V_{c0}^2} \qquad C = 4.375nF$$

$$Z_n := \sqrt{\frac{L_l}{C}} \qquad Z_n = 89.443\Omega \qquad Z_n := \frac{V_{CL}}{I_{CL}}$$

$$\omega_n := \frac{1}{\sqrt{L_l \cdot C}} \qquad \omega_n = 2.556MHz$$

$$I_{CL} := \frac{i_{ppk}}{\sqrt{1 - \left(\frac{V_{l0}}{V_{CL}}\right)^2}} \qquad I_{CL} = 0.53A \qquad I_{CL} := i_{ppk} \cdot \sqrt{1 + \left(\frac{V_{l0}}{i_{ppk} \cdot Z_n}\right)^2}$$

$$\phi := \operatorname{asin}\left(\frac{V_{l0}}{V_{CL}}\right) \qquad \phi = 19.471deg$$

For infinite R:

$$i_c(t) := I_{CL}\cdot\cos\left(\omega_n\cdot t + \phi\right)$$

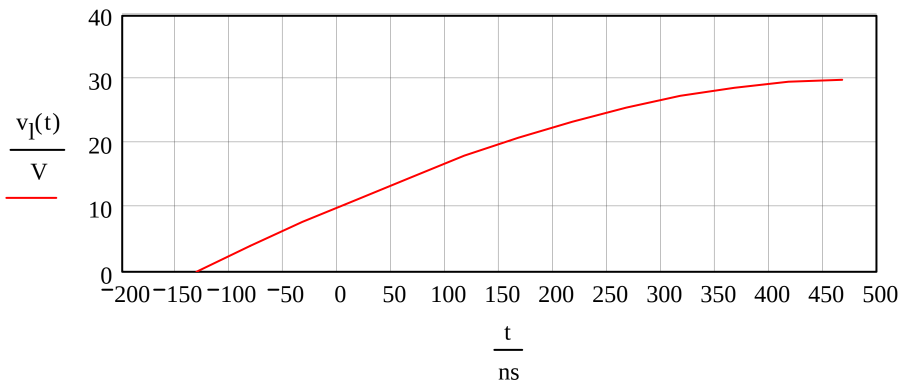
$$v_l(t) := V_{CL}\cdot\sin\left(\omega_n\cdot t + \phi\right) \qquad v_c(t) := v_l(t) + V_{fb}$$

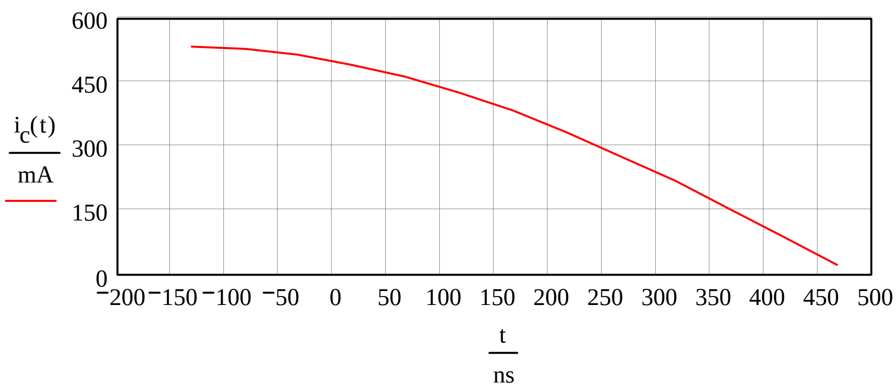
$v_l(t_{vz}) = 0$ and $i_l(t_{vz}) = I_{CL}$. Then $t_{vz} := -\dfrac{\phi}{\omega_n}$ $\qquad t_{vz} = -132.982\,ns$

$i_c(t_z) = i_l(t_z) = 0$

$$t_z := \frac{\frac{\pi}{2} - \phi}{\omega_n} \qquad t_z = 481.689\,ns$$

$$t := t_{vz}, t_{vz} + 50ns \,..\, t_z$$





$$P_R := \frac{C}{2}\cdot\left(V_{CP}{}^2 - V_{c0}{}^2\right)\cdot f_s \qquad P_R = 0.175W \qquad P_R := \frac{L_l}{2}\cdot i_{ppk}{}^2\cdot f_s$$

$$R := -\frac{T_s - t_z}{C\cdot\ln\left(1 - \frac{V_{c0}}{V_{CP}}\right)} \qquad R = 5.101k\Omega$$