Lecture Notes

Snubber Circuits

Outline

A. Overview of Snubber Circuits

B. Diode Snubbers

C. Turn-off Snubbers

D. Overvoltage Snubbers

E. Turn-on Snubbers

F. Thyristor Snubbers

Overview of Snubber Circuits for Hard-Switched Converters

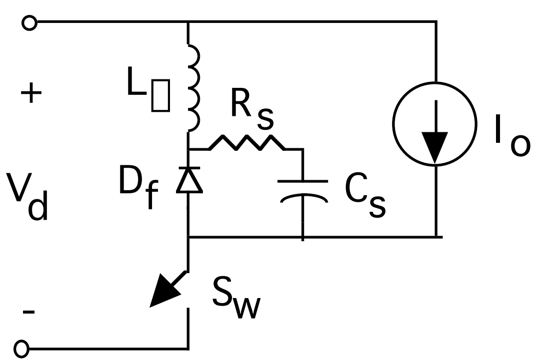
Function: Protect semiconductor devices by:

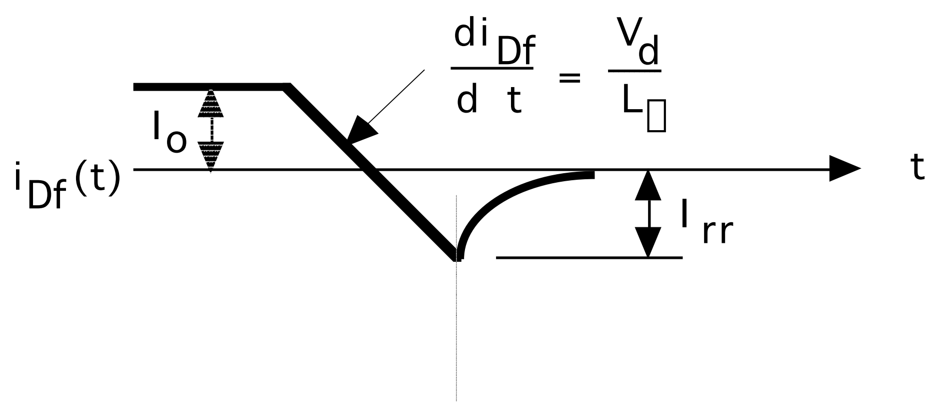
- Limiting device voltages during turn-off transients
- Limiting device currents during turn-on transients
- Limiting the rate-of-rise (di/dt) of currents through the semiconductor device at device turn-on
- Limiting the rate-of-rise (dv/dt) of voltages across the semiconductor device at device turn-off
- Shaping the switching trajectory of the device as it turns on/off

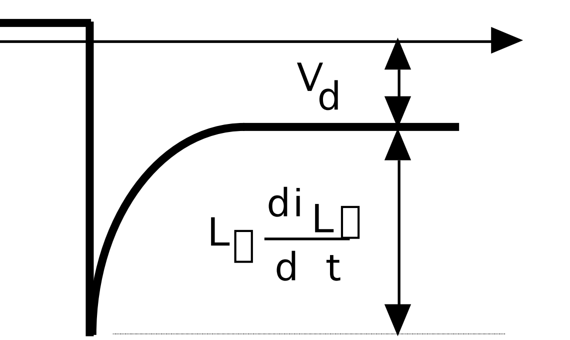
Types of Snubber Circuits

1. Unpolarized series R-C snubbers
   - Used to protect diodes and thyristors
2. Polarized R-C snubbers
   - Used as turn-off snubbers to shape the turn-on switching trajectory of controlled switches.
   - Used as overvoltage snubbers to clamp voltages applied to controlled switches to safe values.
   - Limit dv/dt during device turn-off
3. Polarized L-R snubbers
   - Used as turn-on snubbers to shape the turn-off switching trajectory of controlled switches.
   - Limit di/dt during device turn-on

Need for Diode Snubber Circuit





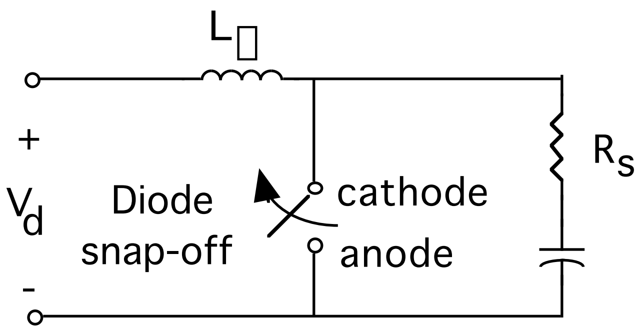


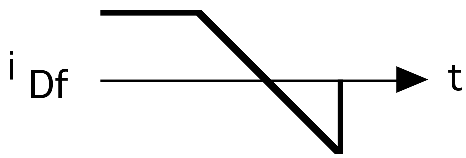
- L_{σ} = stray inductance
- S_w closes at $t = 0$
- R_s - C_s = snubber circuit

- Diode voltage without snubber

- Diode breakdown if $V_d + L_{\sigma}\frac{di_{L\sigma}}{dt} > BV_{BD}$

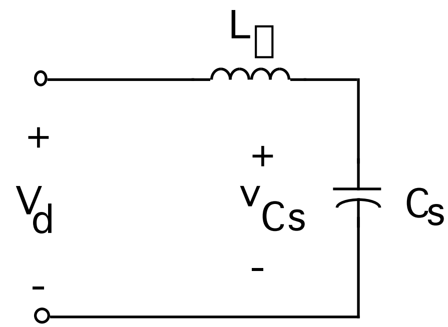
Equivalent Circuits for Diode Snubber





- Worst case assumption- diode snaps off instantaneously at end of diode recovery

- Simplified snubber - the capacitive snubber



- $R_s = 0$
- $v_{Cs} = -v_{Df}$

- Governing equation - $\frac{d^2 v_{Cs}}{dt^2} + \frac{v_{Cs}}{L_\sigma C_s} = \frac{V_d}{L_\sigma C_s}$

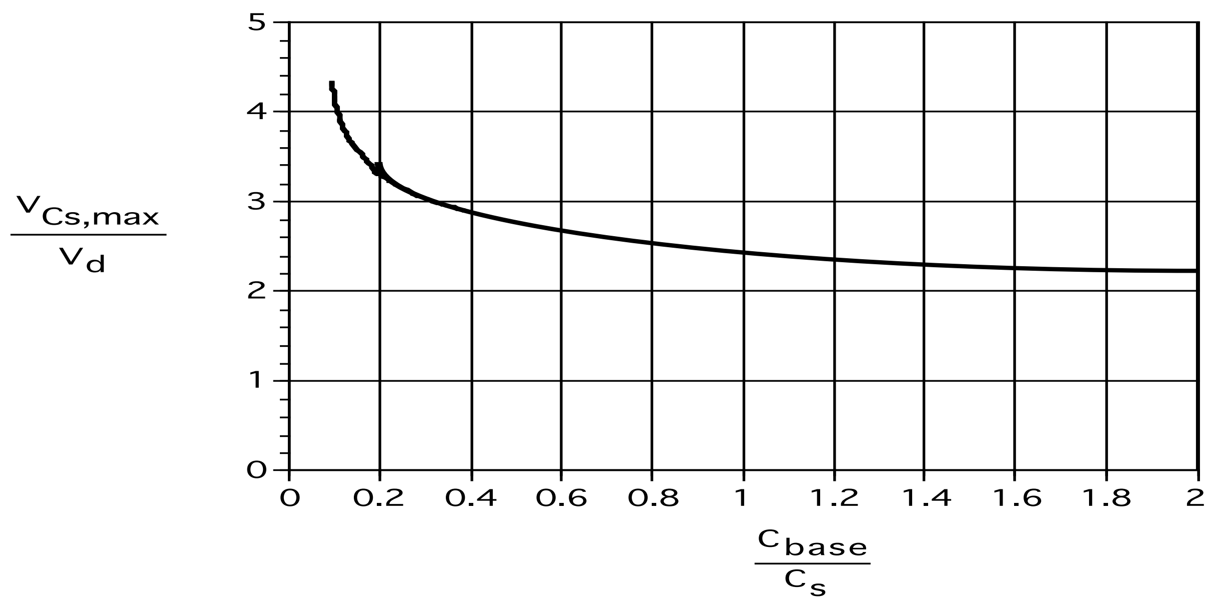
- Boundary conditions - $v_{Cs}(0^+) = 0$ and $i_{L_\sigma}(0^+) = I_{rr}$

Performance of Capacitive Snubber

- $v_{Cs}(t) = V_d - V_d \cos(\omega_o t) + V_d \sqrt{\frac{C_{base}}{C_s}} \sin(\omega_o t)$

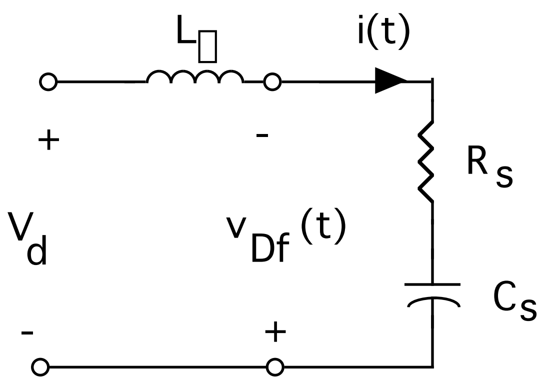
- $\omega_o = \frac{1}{\sqrt{L_\sigma C_s}}$; $C_{base} = L_\sigma \left(\frac{I_{rr}}{V_d}\right)^2$

- $V_{cs,max} = V_d \left[1 + \sqrt{1 + \frac{C_{base}}{C_s}}\right]$



Effect of Adding Snubber Resistance

Snubber Equivalent Circuit



- Governing equation $L_\sigma \frac{d^2 i}{dt^2} + R_s \frac{di}{dt} + \frac{i}{C_s} = 0$
- Boundary conditions

  $i(0^+) = I_{rr}$ and $\frac{di(0^+)}{dt} = \frac{V_d - I_{rr} R_s}{L_\sigma}$

Diode voltage as a function of time

$$\frac{V_{df}}{V_d}(t) = -1 - \frac{e^{-\alpha t}}{\sqrt{\zeta}\cos(\phi)} \sin(\omega_a t - \phi + \theta) \;;\; R_s \le 2 R_b$$

$$\omega_a = \omega_o \sqrt{1 - (\alpha/\omega_o)^2} \;;\; \alpha = \frac{R_s}{2 L_\sigma} \;;\; \omega_o = \frac{1}{\sqrt{L_\sigma C_s}} \;;\; \phi = \tan^{-1}\left[\frac{(2-x)\sqrt{\zeta}}{\sqrt{4 - \zeta x^2}}\right]$$

$$\zeta = \frac{C_s}{C_b} \;;\; x = \frac{R_s}{R_b} \;;\; R_b = \frac{V_d}{I_{rr}} \;;\; C_b = \frac{L_\sigma [I_{rr}]^2}{V_d^2} \;;\; \theta = \tan^{-1}(\alpha/\omega_a)$$

Performance of R-C Snubber

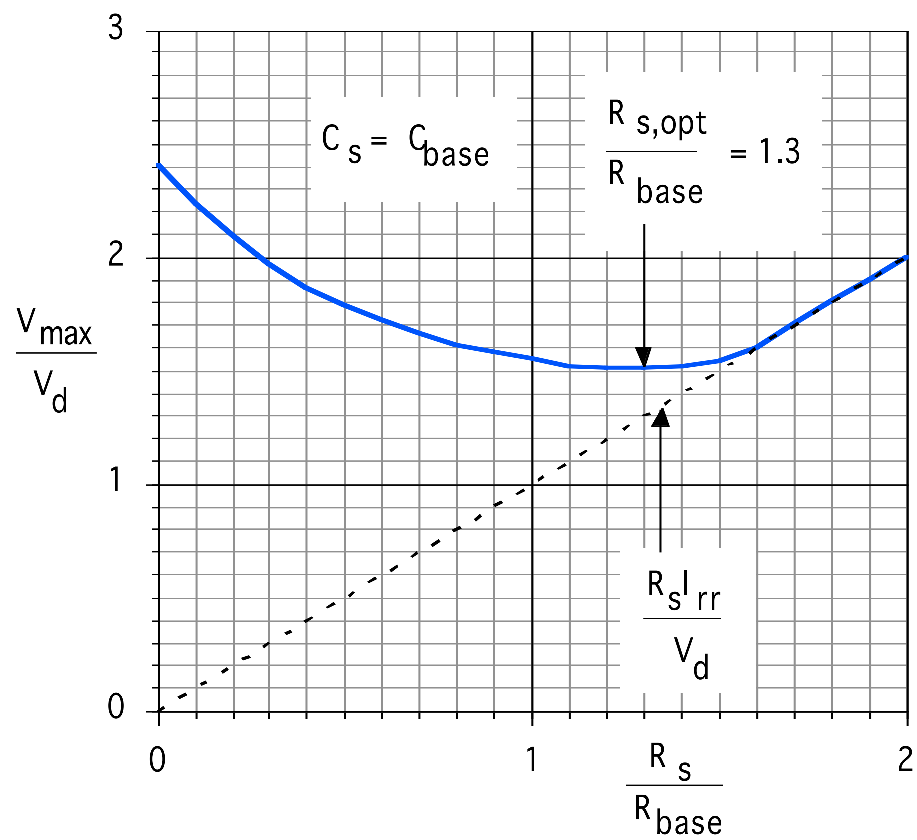
- At $t = t_m$ $v_{Df}(t) = V_{max}$

- $t_m = \dfrac{\tan^{-1}(\square_a/\square)}{\square_a} + \dfrac{\square\square - \square\square}{\square_a} \geq 0$

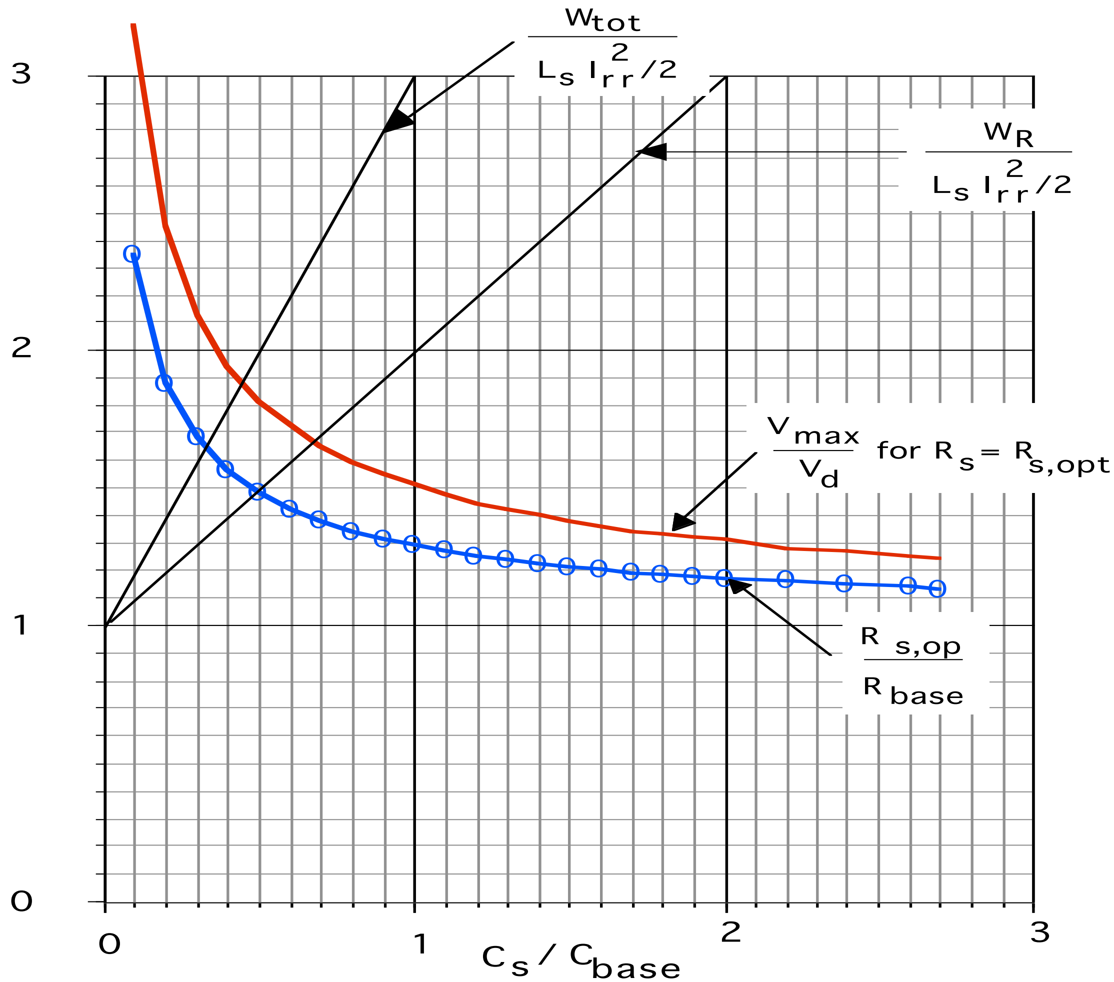
- $\dfrac{V_{max}}{V_d} = 1 + \sqrt{1\square + \square\square^{-1}\square - \square x}\ \exp(-\square t_m)$

- $\square = \dfrac{C_s}{C_{base}}$ and $x = \dfrac{R_s}{R_{base}}$

- $C_{base} = \dfrac{L_s \square I_{rr}^2}{V_d^2}$ and $R_{base} = \dfrac{V_d}{I_{rr}}$

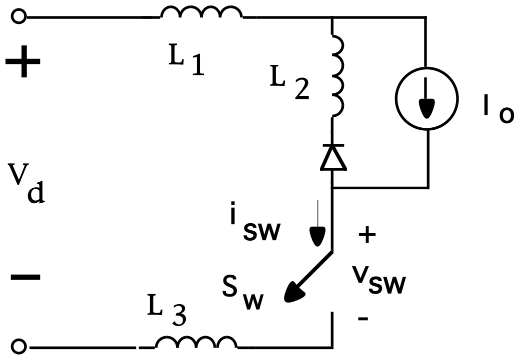


Diode Snubber Design Nomogram

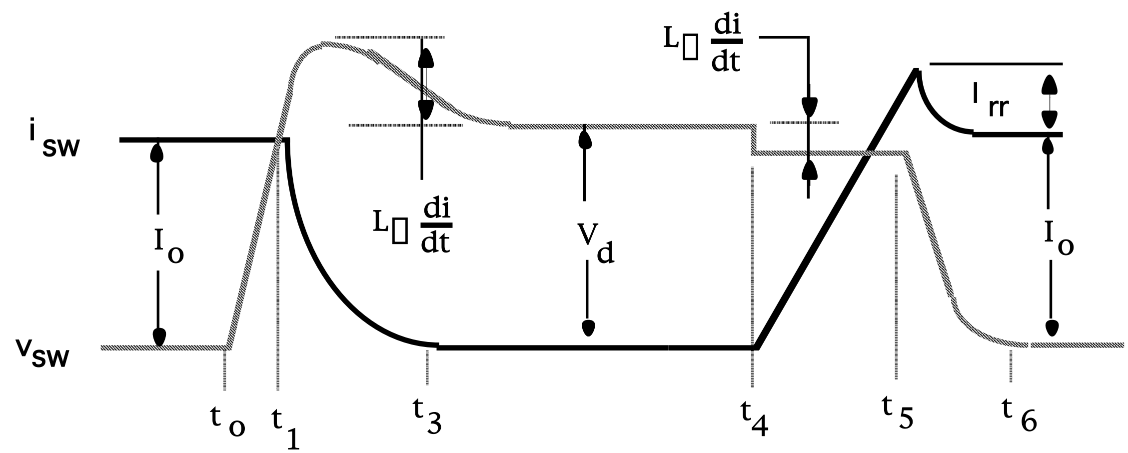


Need for Snubbers with Controlled Switches

Step-down converter

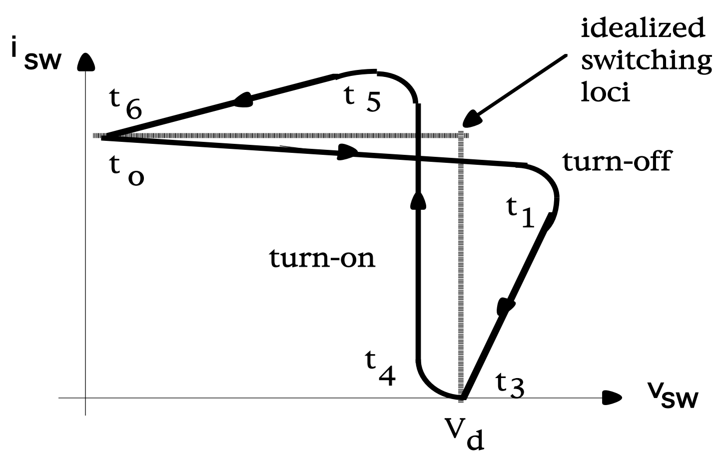


Switch current and voltage waveforms



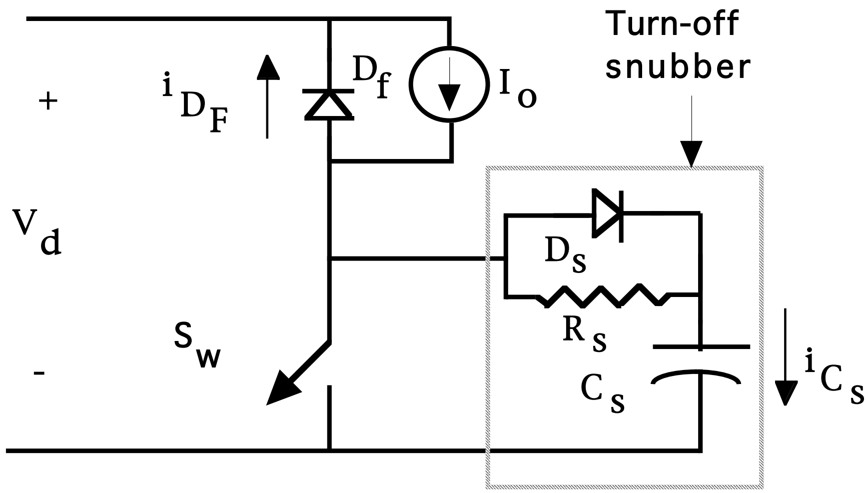
- L_1 , L_2, L_3 = stray inductances
- $L_\sigma = L_1 + L_2 + L_3$

Switching trajectory of switch

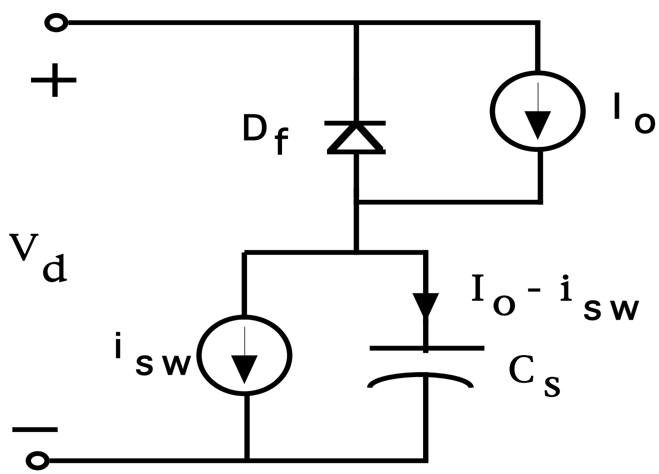


- Overvoltage at turn-off due to stray inductance
- Overcurrent at turn-on due to diode reverse recovery

Turn-off Snubber for Controlled Switches



Step-down converter with turn-off snubber



Equivalent circuit during switch turn-off.

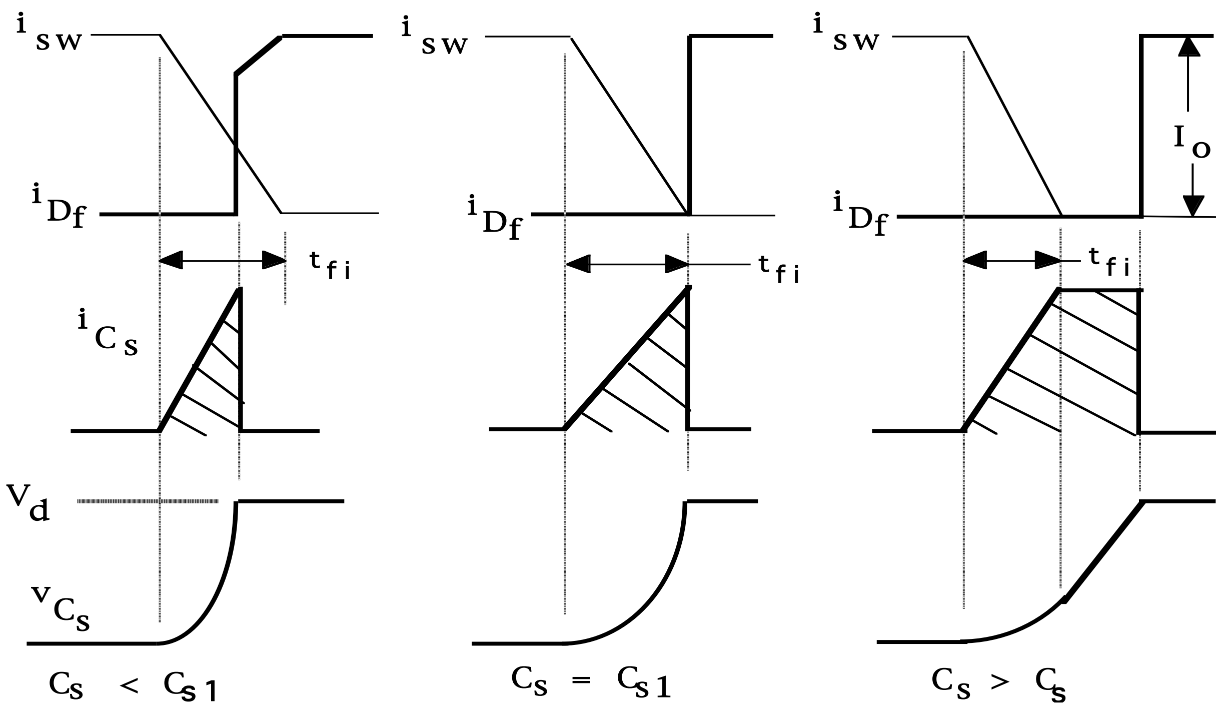
- Simplifying assumptions
  1. No stray inductance.
  2. $i_{sw}(t) = I_o(1 - t/t_{fi})$
  3. $i_{sw}(t)$ uneffected by snubber circuit.

Turn-off Snubber Operation

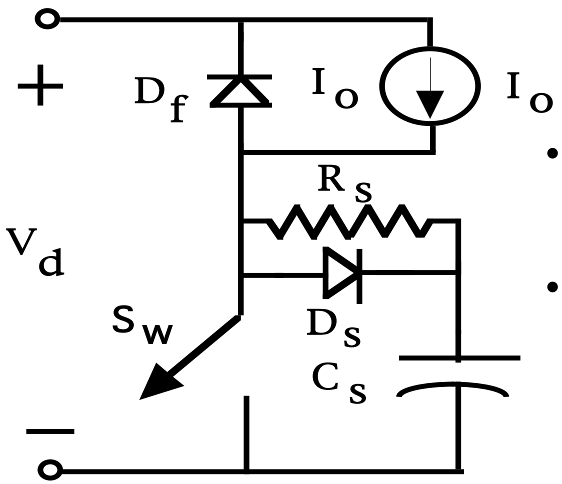
- Capacitor voltage and current for $0 < t < t_{fi}$ $\quad i_{Cs}(t) = \frac{I_o t}{t_{fi}}$ and $v_{Cs}(t) = \frac{I_o t^2}{2 C_s t_{fi}}$

- For $C_s = C_{s1}$, $v_{Cs} = V_d$ at $t = t_{fi}$ yielding $C_{s1} = \frac{I_o t_{fi}}{2 V_d}$

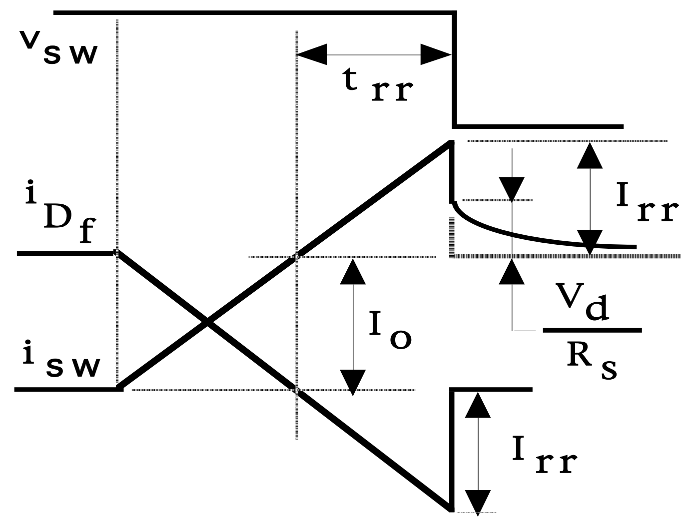
Circuit waveforms for varying values of C_s

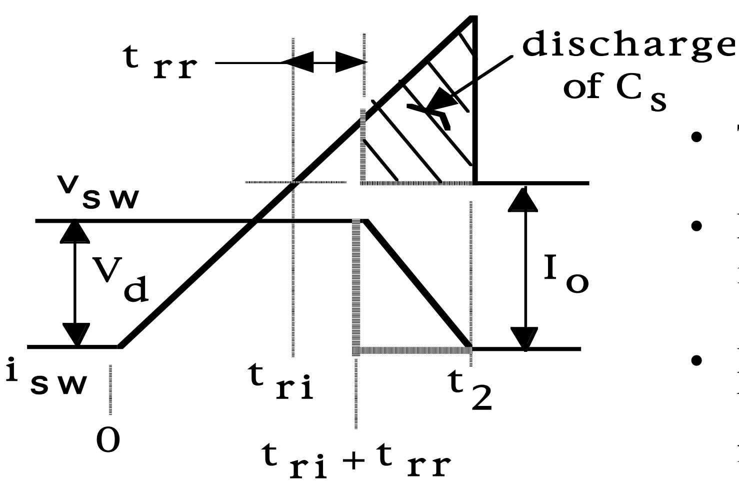


Benefits of Snubber Resistance at Switch Turn-on



- D_s shorts out R_s during S_w turn-off.
- During S_w turn-on, D_s reverse-biased and C_s discharges thru R_s.

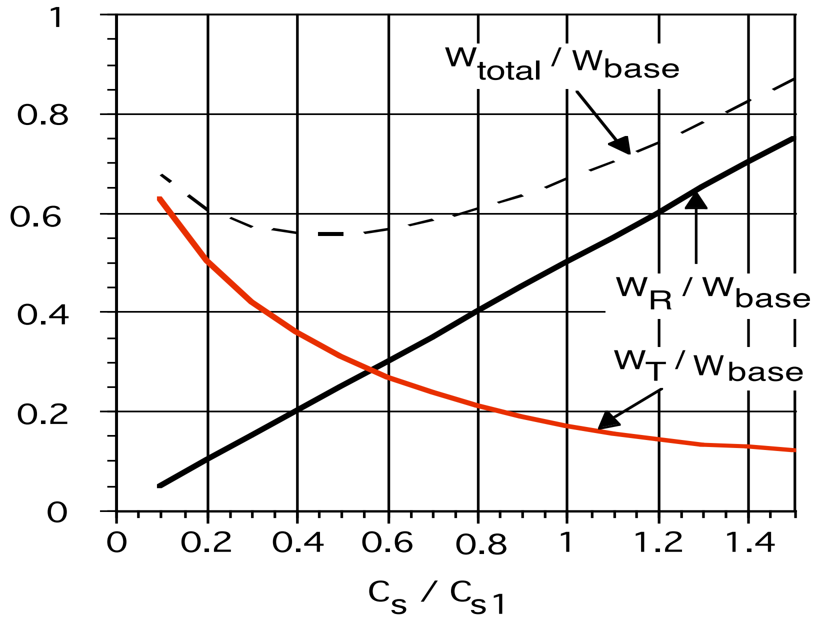


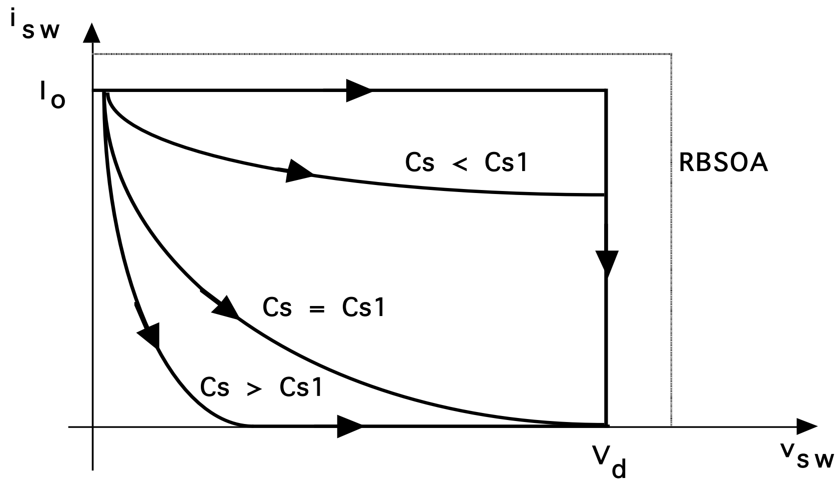


- Turn-on with $R_s = 0$
- Energy stored on C_s dissipated in S_w.
- Extra energy dissipation in S_w because of lengthened voltage fall time.

- Turn-on with $R_s > 0$
- Energy stored on C_s dissipated in R_s rather than in S_w.
- Voltage fall time kept quite short.

Effect of Turn-off Snubber Capacitance





Energy dissipation

W_R = dissipation in resistor

W_T = dissipation in switch S_w

$$C_{s1} = \frac{I_o t_{fi}}{2V_d}$$

$$W_{total} = W_R + W_T$$

$$W_{base} = 0.5\, V_d I_o t_{fi}$$

Switching trajectory

Turn-off Snubber Design Procedure

Selection of C_s

- Minimize energy dissipation (W_T) in BJT at turn-on
- Minimize $W_R + W_T$
- Keep switching locus within RBSOA
- Reasonable value is $C_s = C_{s1}$

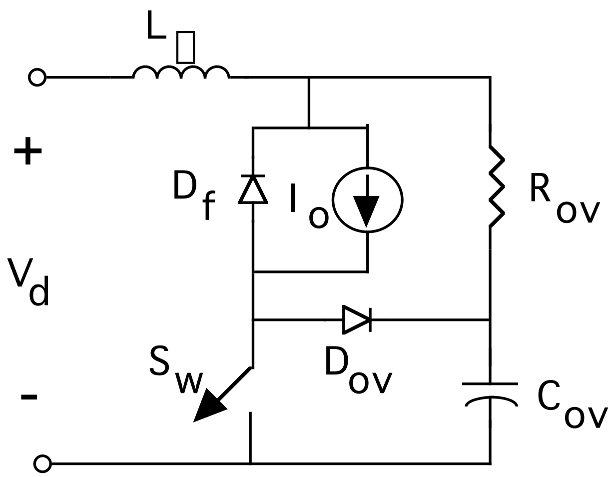
Selection of R_s

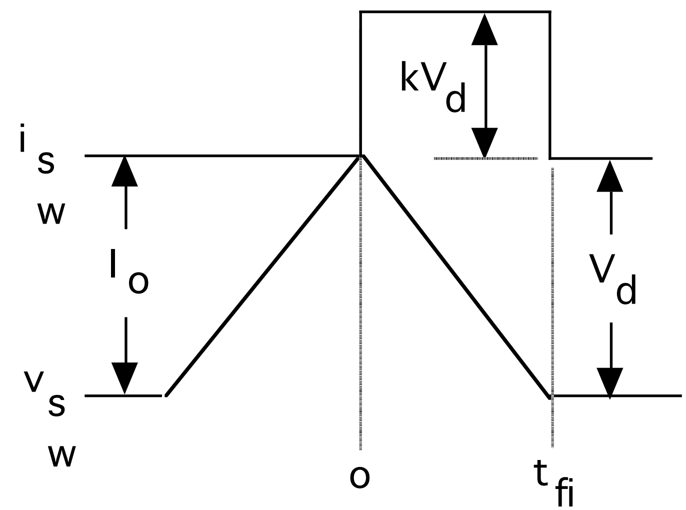
- Limit $i_{cap}(0^+) = \frac{V_d}{R_s} < I_{rr}$
- Usually designer specifies $I_{rr} < 0.2\ I_o$ so $\frac{V_d}{R_s} = 0.2\ I_o$

Snubber recovery time (BJT in on-state)

- Capacitor voltage $= V_d \exp(-t/R_sC_s)$
- Time for v_{Cs} to drop to $0.1V_d$ is $2.3\ R_sC_s$
- BJT must remain on for a time of $2.3\ R_sC_s$

Overvoltage Snubber





- Step-down converter with overvoltage snubber comprised of D_{ov}, C_{ov}, and R_{ov}.

- Overvoltage snubber limits overvoltage (due to stray I nductance) across Sw as it turns off.

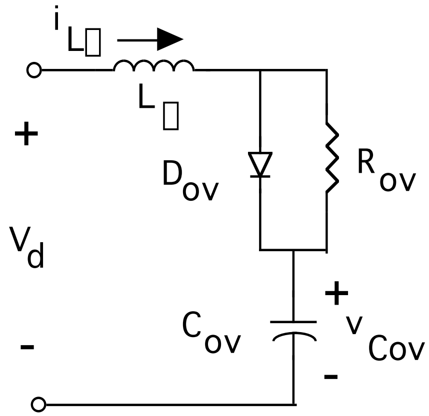
- Switch S_w waveforms without overvoltage snubber

- t_{fi} = switch current fall time ; kV_d = overvoltage on S_w

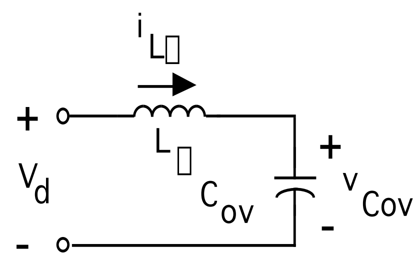
  - $kV_d = L_\sigma \frac{di_{L\sigma}}{dt} = L_\sigma \frac{I_o}{t_{fi}}$

  - $L_\sigma = \frac{kV_d t_{fi}}{I_o}$

Operation of Overvoltage Snubber



- D_{ov} on for $0 < t < \frac{\pi\sqrt{L_{\sigma}C_{ov}}}{2}$
- $t_{fi} << \frac{\pi\sqrt{L_{\sigma}C_{ov}}}{2}$

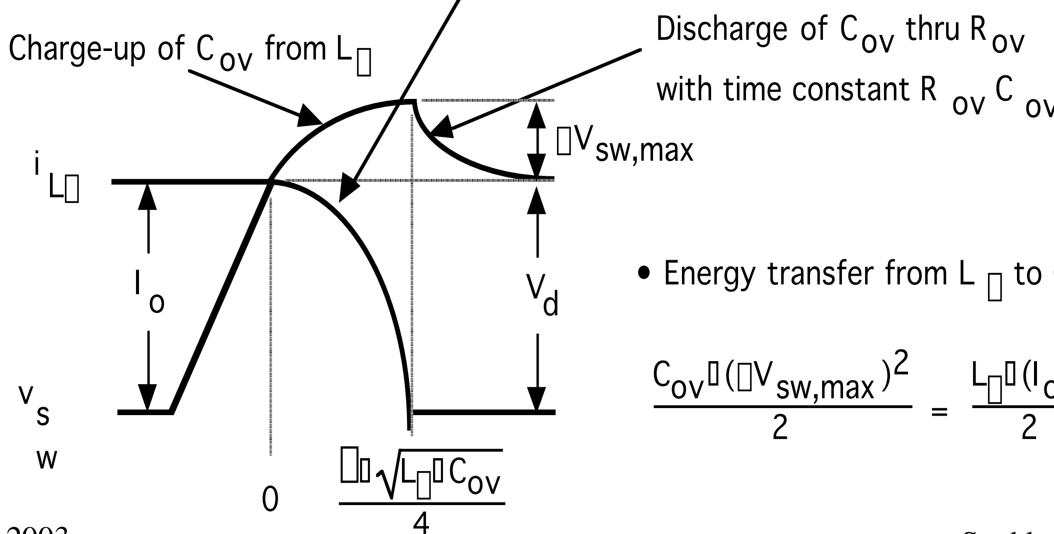


- Equivalent circuit while inductor current decays to zero

$v_{Cov}(0^+) = V_d \qquad i_{L\sigma}(0^+) = I_o$

$i_{L\sigma}(t) = I_o \cos\left[\frac{t}{\sqrt{L_{\sigma} \cdot C_{ov}}}\right]$

- D_{ov},C_{ov} provide alternate path for inductor current as S_w turns off.
- Switch current can fall to zero much faster than L_s current.
- D_f forced to be on (approximating a short ckt) by I_o after S_w is off.
- Equivalent circuit after turn-off of S_w.



- Energy transfer from L_{σ} to C_{ov}

$$\frac{C_{ov} \cdot (\Delta V_{sw,max})^2}{2} = \frac{L_{\sigma} \cdot (I_o)^2}{2}$$

Overvoltage Snubber Design

- $C_{ov} = \dfrac{L_s I_o^2}{(\Delta v_{sw,max})^2}$

- Limit $\Delta v_{sw,max}$ to $0.1V_d$

- Using $L_s = \dfrac{kV_d t_{fi}}{I_o}$ in equation for C_{ov} yields

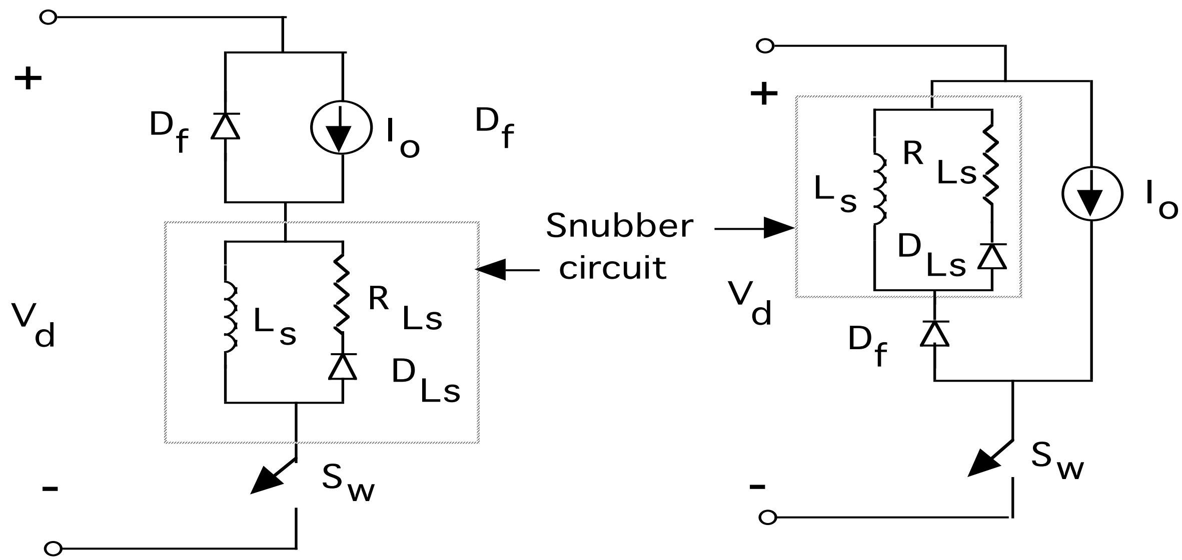
- $C_{ov} = \dfrac{kV_d t_{fi} I_o^2}{I_o (0.1V_d)^2} = \dfrac{100k\, t_{fi} I_o}{V_d}$

- $C_{ov} = 200\,k\,C_{s1}$ where $C_{s1} = \dfrac{t_{fi} I_o}{2V_d}$ which is used in turn-off snubber

- Recovery time of C_{ov} $(2.3R_{ov}C_{ov})$ must be less than off-time duration, t_{off}, of the switch Sw.

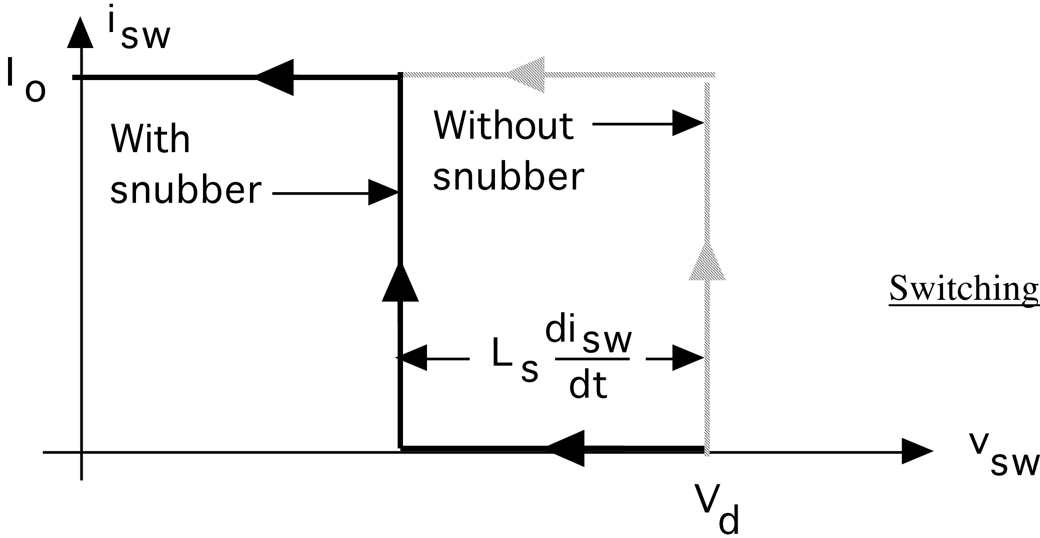
- $R_{ov} \approx \dfrac{t_{off}}{2.3\, C_{ov}}$

Turn-on Snubber



Step-down converter with turn-on snubber

- Snubber reduces V_{sw} at switch turn-on due drop across inductor L_s.
- Will limit rate-of-rise of switch current if L_s is sufficiently large.

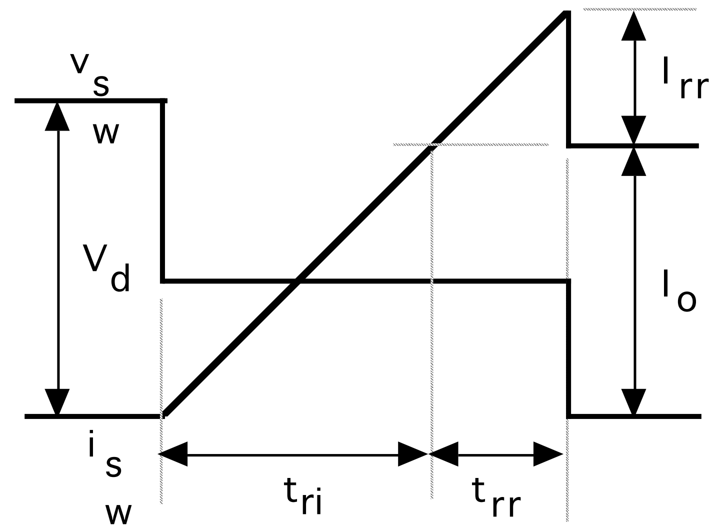


Switching trajectory with and without turn-on snubber.

Turn-on Snubber Operating Waveforms

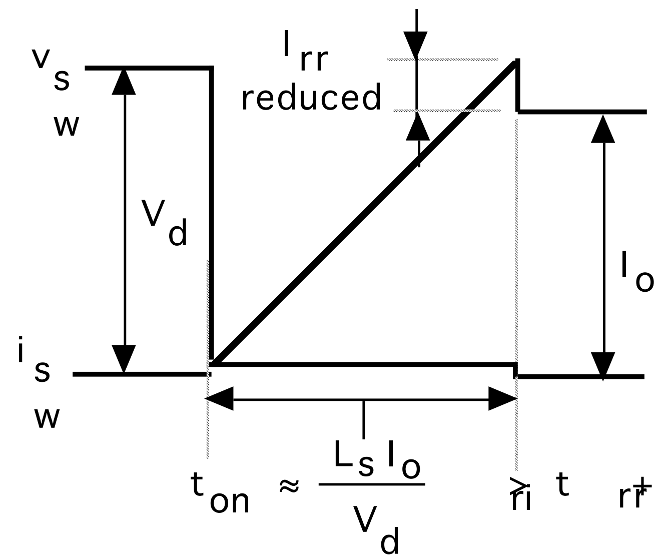
Small values of snubber inductance ($L_s < L_{s1}$)

- $\frac{di_{sw}}{dt}$ controlled by switch S_w and drive circuit.
- $\Delta v_{sw} = \frac{L_s I_o}{t_{ri}}$

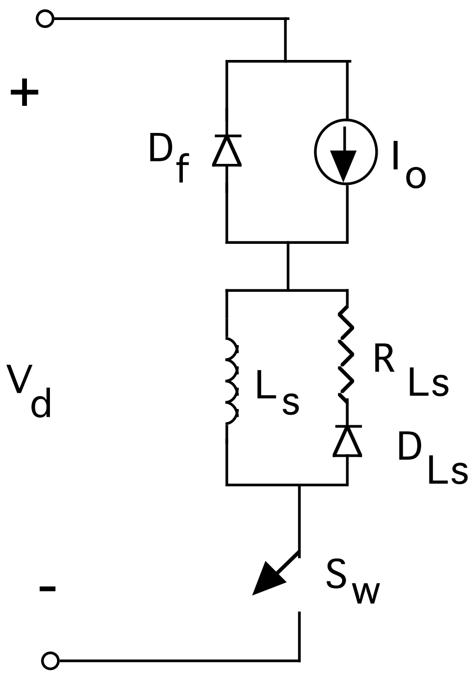


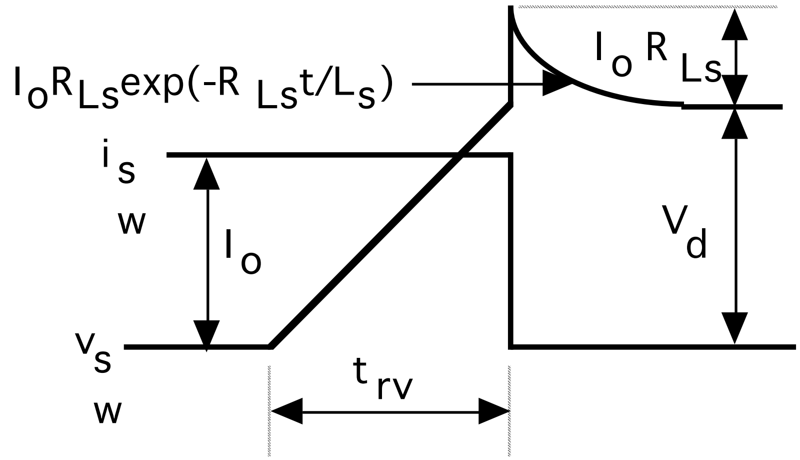
Large values of snubber inductance ($L_s > L_{s1}$)

- $\frac{di_{sw}}{dt}$ limited by circuit to $\frac{V_d}{L_s} < \frac{I_o}{t_{ri}}$
- $L_{s1} = \frac{V_d t_{ri}}{I_o}$
- I_{rr} reduced when $L_s > L_{s1}$ because I_{rr} proportional to $\sqrt{\frac{di_{sw}}{dt}}$



Turn-on Snubber Recovery at Switch Turn-off





- Switch waveforms at turn-off with turn-on snubber in circuit.
- Assume switch current fall time $t_{ri} = 0$.
- Inductor current must discharge thru D_{Ls} - R_{Ls} series segment.
- Overvoltage smaller if t_{fi} smaller.
- Time of 2.3 L_s/R_{Ls} required for inductor current to decay to 0.1 I_o
- Off-time of switch must be > 2.3 L_s/R_{Ls}

Turn-on Snubber Design Trade-offs

Selection of inductor

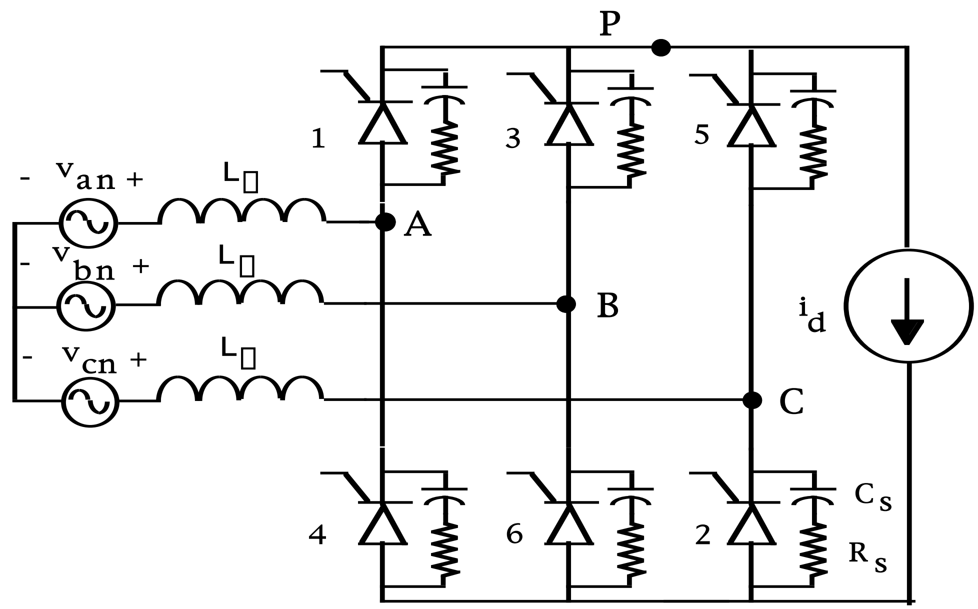
- Larger L_s decreases energy dissipation in switch at turn-on
  - $W_{sw} = W_B (1 + I_{rr}/I_o)^2 [1 - L_s/L_{s1}]$
  - $W_B = V_d I_o t_{fi}/2$ and $L_{s1} = V_d t_{fi}/I_o$
  - $L_s > L_{s1}$ $W_{sw} = 0$
- Larger L_s increases energy dissipation in R_{Ls}
  - $W_R = W_B L_s / L_{s1}$
- $L_s > L_{s1}$ reduces magnitude of reverse recovery current I_{rr}
- Inductor must carry current I_o when switch is on - makes inductor expensive and hence turn-on snubber seldom used

Selection of resistor R_{Ls}

- Smaller values of R_{Ls} reduce switch overvoltage $I_o R_{Ls}$ at turn-off
- Limiting overvoltage to $0.1V_d$ yields $R_{Ls} = 0.1 V_d/I_o$
- Larger values of R_{Ls} shortens minimum switch off-time of $2.3 L_s/R_{Ls}$

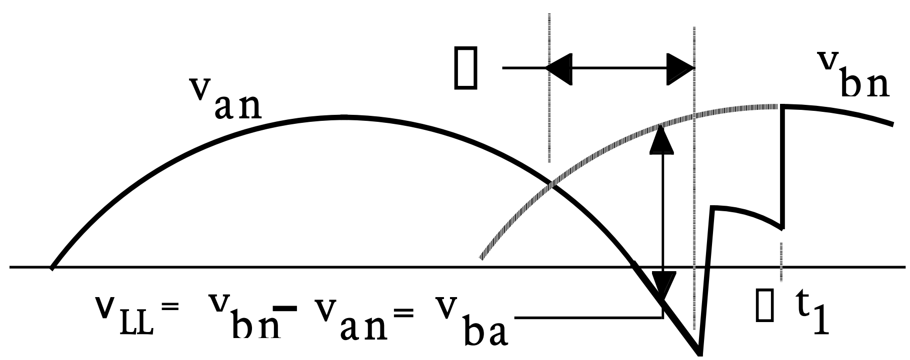
Thyristor Snubber Circuit

3-phase thyristor circuit with snubbers



- $v_{an}(t) = V_s\sin(\omega t)$, $v_{bn}(t) = V_s\sin(\omega t - 120°)$, $v_{cn}(t) = V_s\sin(\omega t - 240°)$

Phase-to-neutral waveforms



- $v_{LL}(t) = \sqrt{3}\,V_s\sin(\omega t - 60°)$
- Maximum rms line-to-line voltage $V_{LL} = \sqrt{\frac{3}{2}}\,V_s$

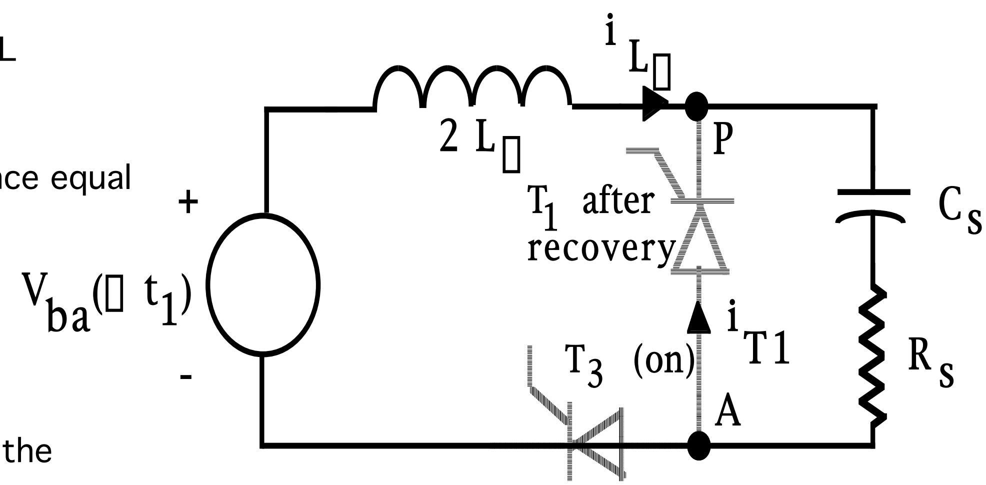
Equivalent Circuit for SCR Snubber Calculations

Assumptions

- Trigger angle □ = 90° so that $v_{LL}(t)$ = maximum = $\sqrt{2}\, V_{LL}$
- Reverse recovery time t_{rr} << period of ac waveform so that $v_{LL}(t)$ equals a constant value of $v_{ba}(\square t_1)$ = $\sqrt{2}\, V_{LL}$
- Worst case stray inductance $L_{\square}$ gives rise to reactance equal to or less than 5% of line impedance.
- Line impedance = $\dfrac{V_s}{\sqrt{2} I_{a1}} = \dfrac{\sqrt{2} V_{LL}}{\sqrt{6} I_{a1}} = \dfrac{V_{LL}}{\sqrt{3} I_{a1}}$

  where I_{a1} = rms value of fundamental component of the line current.
- $\square L_{\square} = 0.05 \dfrac{V_{LL}}{\sqrt{3} I_{a1}}$

Equivalent circuit after T1 reverse recovery



Component Values for Thyristor Snubber

- Use same design as for diode snubber but adapt the formulas to the thyristor circuit notation

- Snubber capacitor $C_s = C_{base} = L_\sigma \left(\frac{I_{rr}}{V_d}\right)^2$

  - From snubber equivalent circuit $2\, L_\sigma \frac{di_{L\sigma}}{dt} = \sqrt{2}\, V_{LL}$

  - $I_{rr} = \frac{di_{L\sigma}}{dt} t_{rr} = \frac{\sqrt{2} V_{LL}}{2 L_\sigma} t_{rr} = \frac{\sqrt{2} V_{LL}}{2 \frac{0.05 V_{LL}}{\sqrt{3}\, \omega I_{a1}}} t_{rr} = 25\, \omega I_{a1} t_{rr}$

  - $V_d = \sqrt{2}\, V_{LL}$

  - $C_s = C_{base} = \frac{0.05 V_{LL}}{\sqrt{3}\, \omega I_{a1}} \left(\frac{25\, \omega I_{a1} t_{rr}}{\sqrt{2} V_{LL}}\right)^2 = \frac{8.7\, \omega I_{a1} t_{rr}}{V_{LL}}$

  - Snubber resistance $R_s = 1.3\ R_{base} = 1.3 \frac{V_d}{I_{rr}}$

  - $R_s = 1.3 \frac{\sqrt{2} V_{LL}}{25\, \omega I_{a1} t_{rr}} = \frac{0.07 V_{LL}}{\omega I_{a1} t_{rr}}$

  - Energy dissipated per cycle in snubber resistance $= W_R$

  - $W_R = \frac{L_\sigma I_{rr}^2}{2} + \frac{C_s V_d^2}{2} = 18\, \omega\, I_{a1}\, V_{LL} (t_{rr})^2$