Snubber Circuits

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Function of Snubber Circuits

- Protect semiconductor devices by:
  - Limiting device voltages during turn-off transients
  - Limiting device currents during turn-on transients
  - Limiting the rate-of-rise ($\frac{di}{dt}$) of currents through the semiconductor device at device turn-on
  - Limiting the rate-of-rise ($\frac{dv}{dt}$) 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.

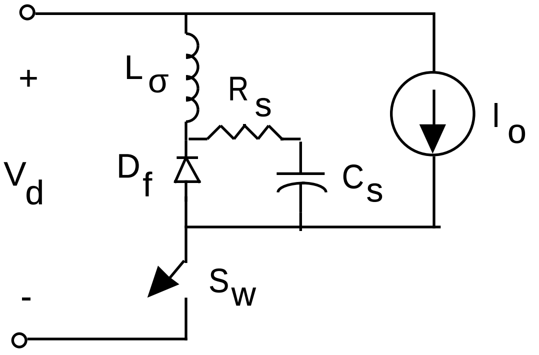
   - Limit $\frac{dv}{dt}$ during device turn-off

3. Polarized L-R snubbers

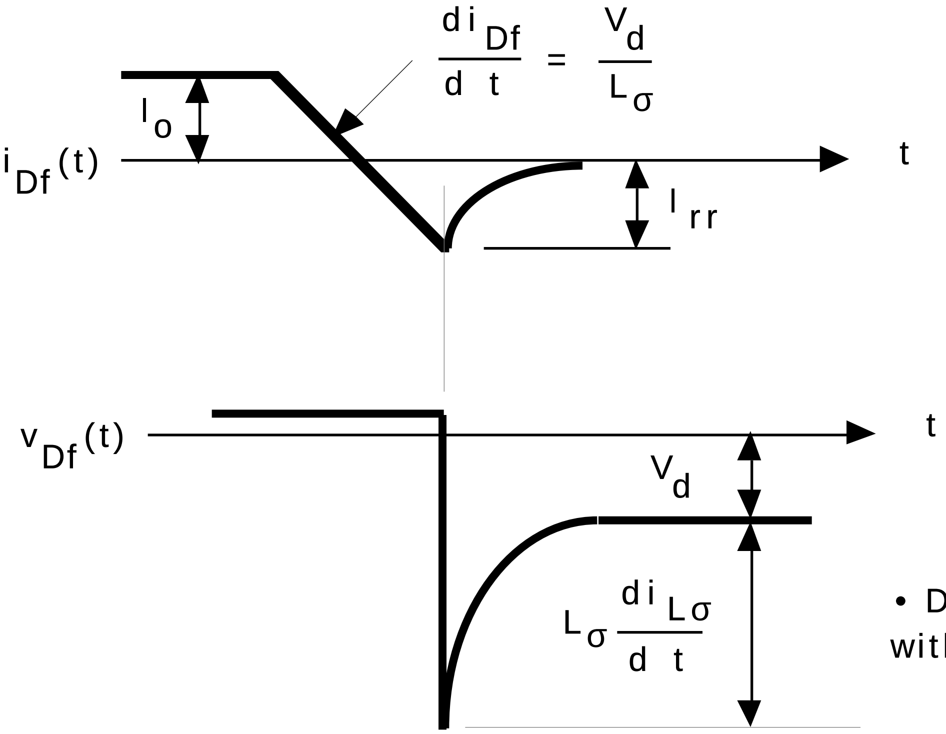
   - Used as turn-on snubbers to shapte the turn-off switching trajectory of controlled switches.

   - Limit $\frac{di}{dt}$ during device turn-on

Need for Diode Snubber Circuit



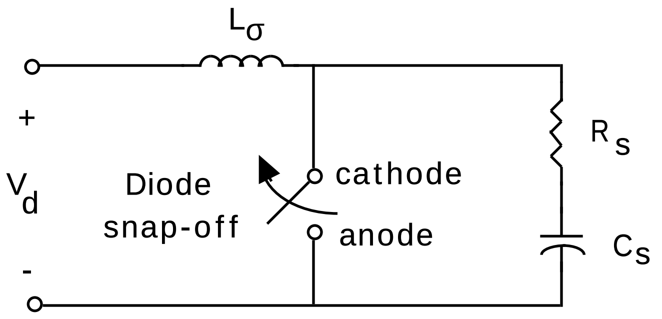
- L_σ = stray inductance
- S_w closes at $t = 0$
- R_s - C_s = snubber circuit

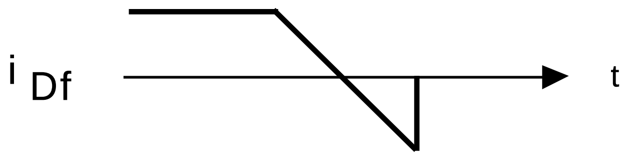


- Diode voltage without snubber

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

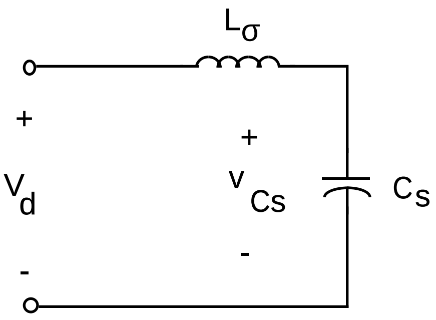
Equivalent Circuits for Diode Snubber





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

- Simplified snubber - the capacitive snubber



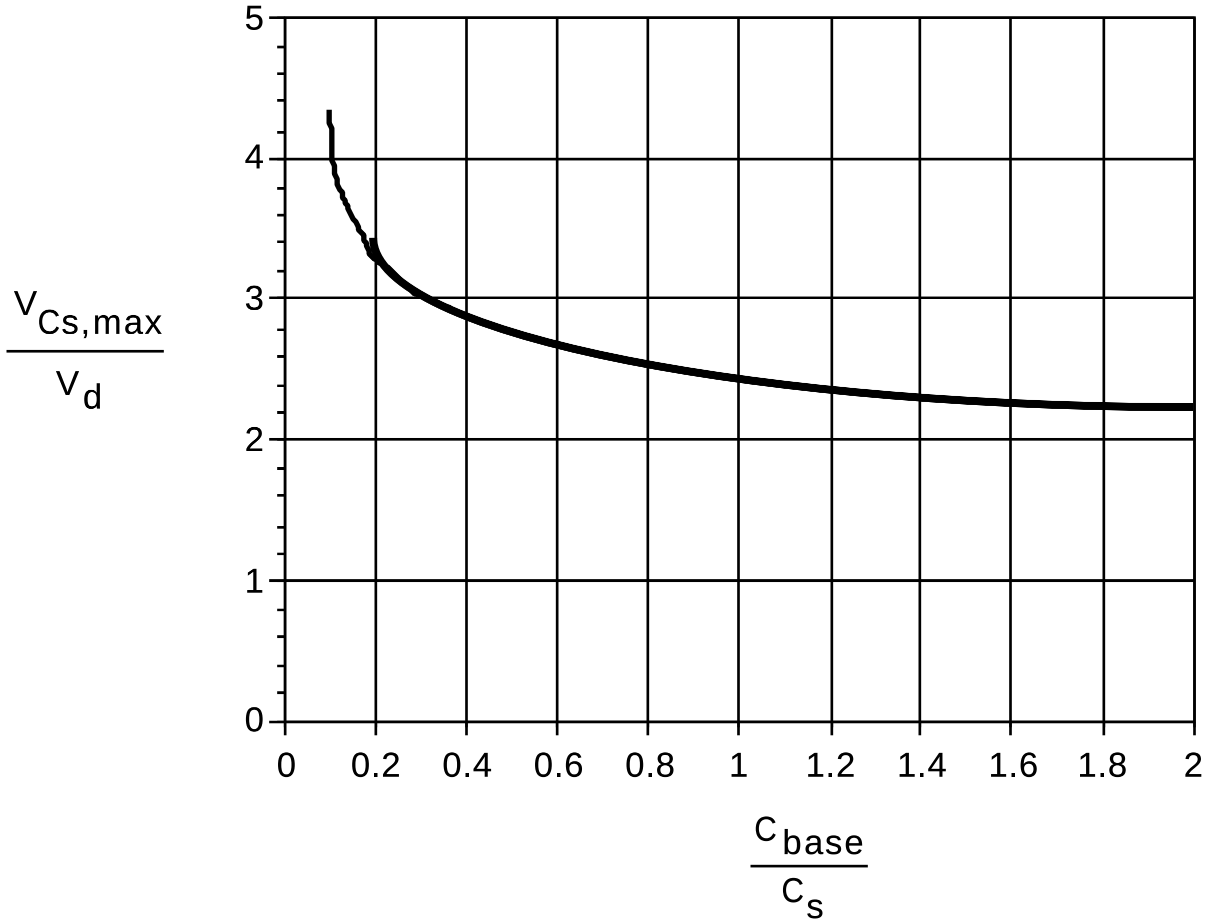
- $R_s = 0$
- $v_{Cs} = -v_{Df}$

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

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

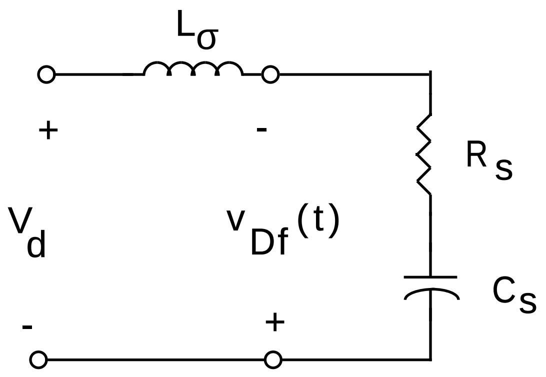
Performance of Capacitive Snubber

- $v_{Cs}(t) = V_d - V_d \cos(\omega_o t) + V_d \sqrt{\frac{C_{base}}{C_s}} \sin(\omega_o t)$
- $\omega_o = \frac{1}{\sqrt{L_\sigma C_s}}$; $C_{base} = L_\sigma \left[\frac{I_{rr}}{V_d}\right]^2$
- $V_{cs,max} = V_d \left\{ 1 + \sqrt{1 + \frac{C_{base}}{C_s}} \right\}$



Effect of Adding Snubber Resistance

- Equivalent circuit with snubber resistance R_s



- Governing equation $L_\sigma C_s \dfrac{d^2 v_{Df}}{dt^2} + R_s C_s \dfrac{dv_{Df}}{dt} + v_{Df} = -V_d$

- Boundary conditions

$$v_{Df}(0^+) = -I_{rr}R_s \quad \text{and} \quad \frac{dv_{Df}(0^+)}{dt} = -\frac{I_{rr}}{C_s} - \frac{R_s V_d}{L_\sigma} + \frac{I_{rr}R_s^2}{L_\sigma}$$

- Solution for $v_{Df}(t)$

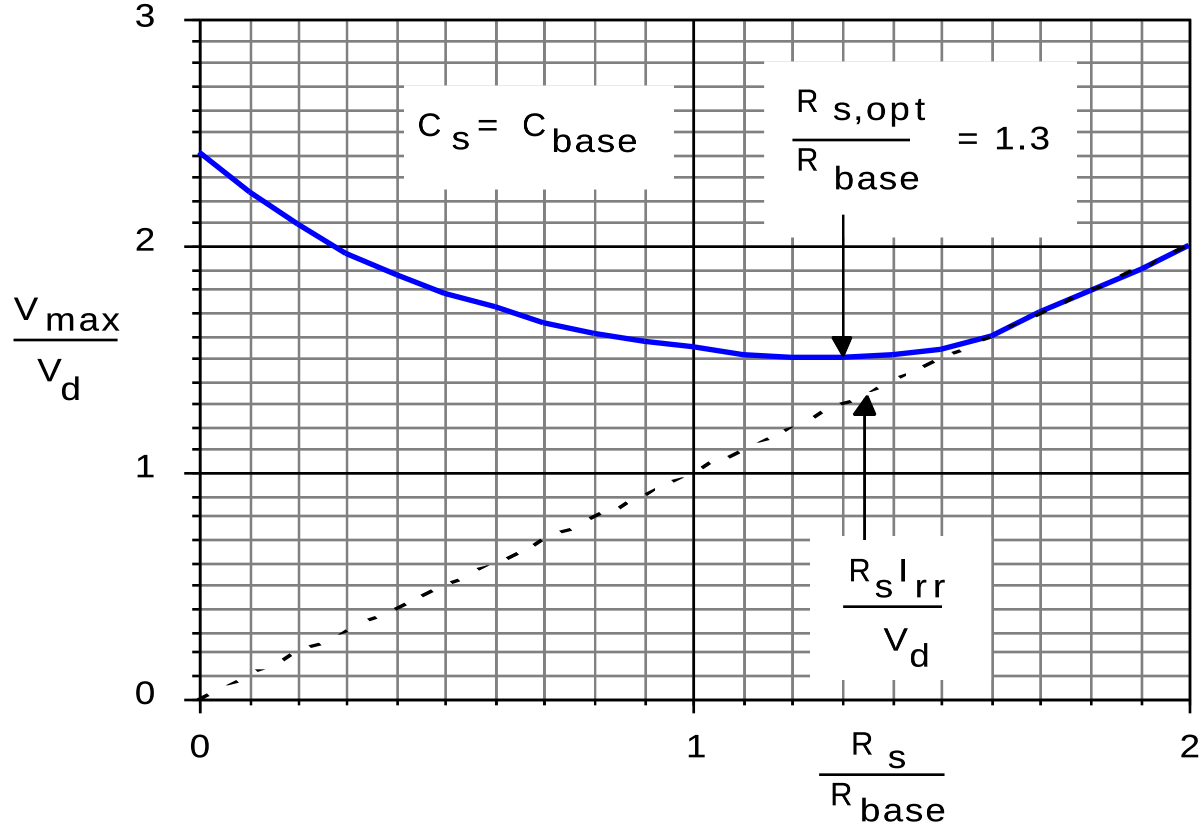
$$v_{Df}(t) = -V_d - V_d e^{-\alpha t}\sqrt{\frac{C_{base}}{C_s}}\sin(\omega_a t - \varphi - \xi)$$

$$\omega_a = \omega_o\sqrt{1 - \frac{\alpha^2}{\omega_o^2}} \quad ; \quad \omega_o = \frac{1}{\sqrt{L_\sigma C_s}} \quad ; \quad \alpha = \frac{R_s}{2L_\sigma}$$

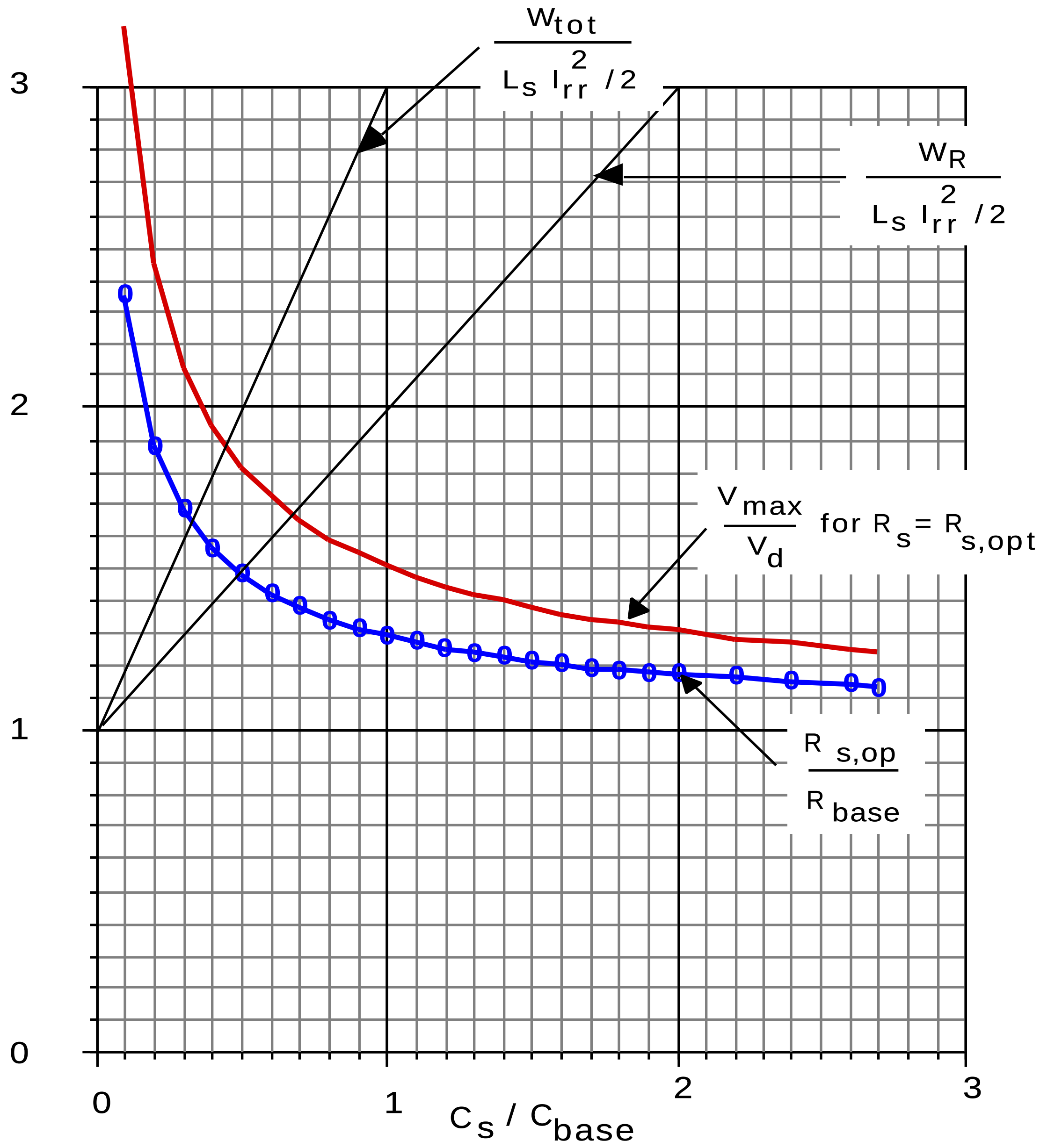
$$\tan(\varphi) = -\frac{R_b}{\omega_a L_\sigma} - \frac{\alpha}{\omega_a}\ ;\ \tan(\xi) = \frac{\alpha}{\omega_a}\ ;\ R_{base} = \frac{V_d}{I_{rr}}\ ,\ C_{base} = \frac{L_\sigma}{(V_d/I_{rr})^2}$$

Performance of R-C Snubber

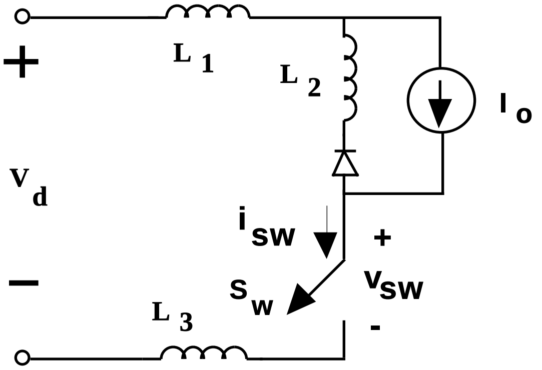
- At $t = t_m$ $v_{Df}(t) = V_{max}$
  - $t_m = \frac{\tan^{-1}(\omega_a/\alpha)}{\omega_a} + \frac{\varphi - \xi}{\omega_a} \geq 0$
  - $\frac{V_{max}}{V_d} = 1 + \sqrt{1 + C_N^{-1} - R_N} \exp(-\alpha t_m)$
    - $C_N = \frac{C_s}{C_{base}}$ and $R_N = \frac{R_s}{R_{base}}$
    - $C_{base} = \frac{L_s I_{rr}^2}{V_d^2}$ and $R_{base} = \frac{V_d}{I_{rr}}$



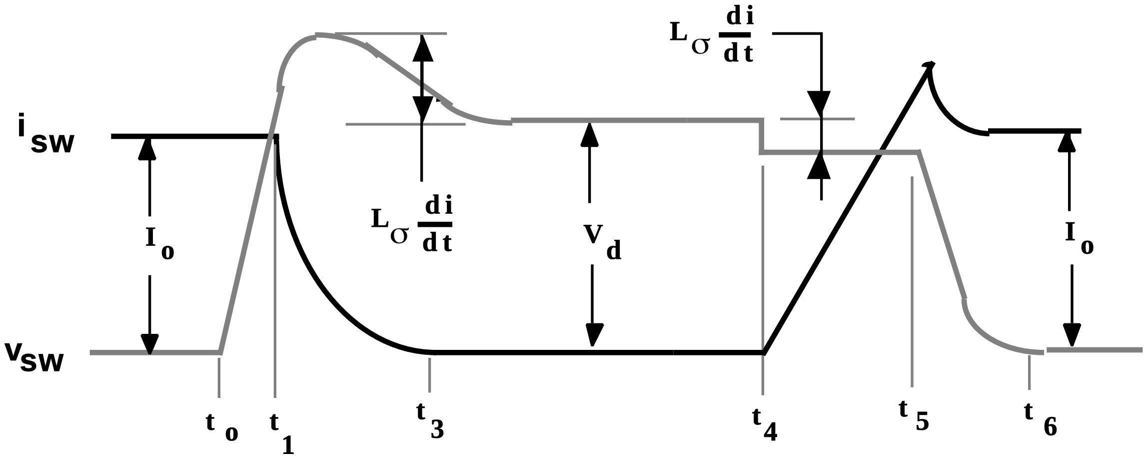
Diode Snubber Design Nomogram

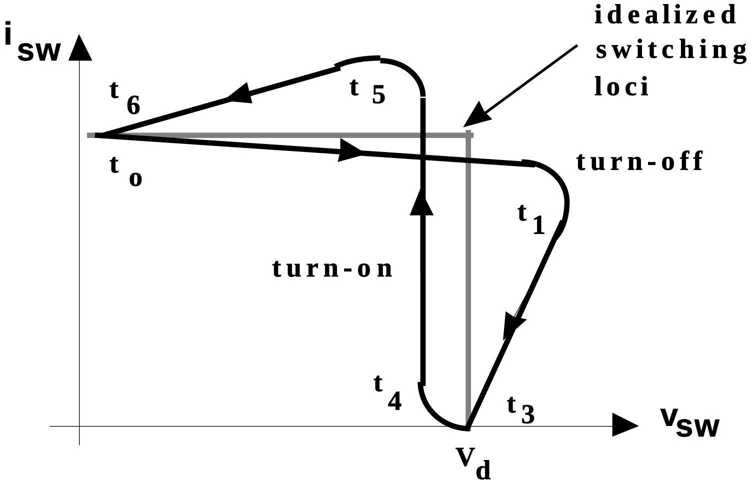


Need for Snubbers with Controlled Switches



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

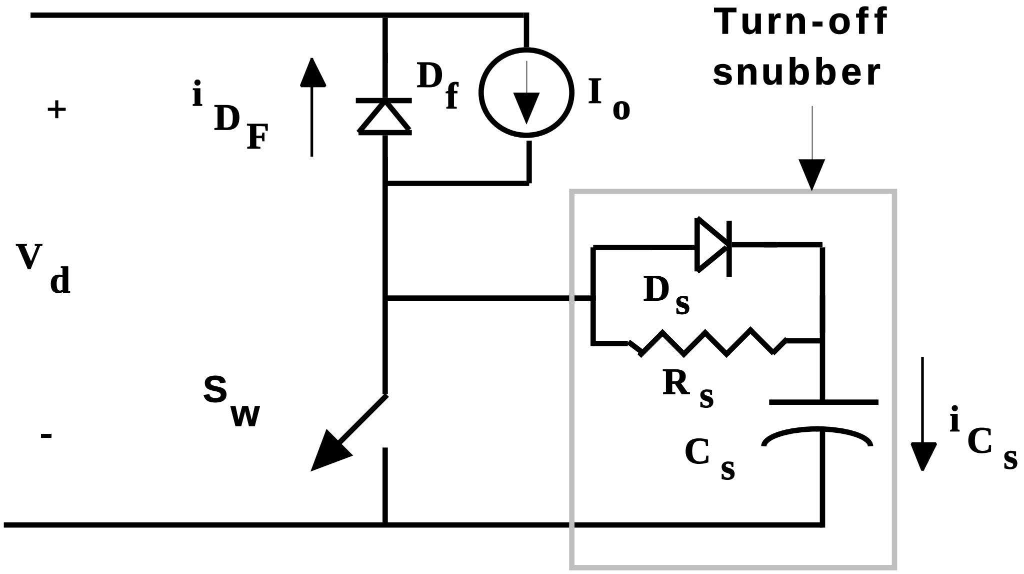




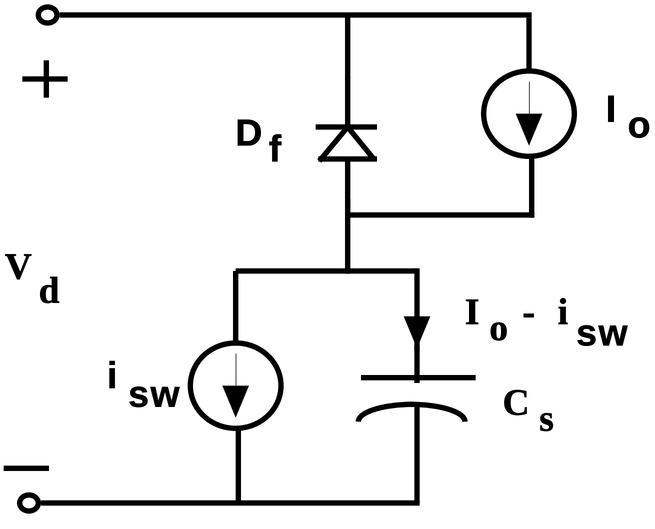
- Overvoltage at turn-off due to stray inductance
- Overcurrent at turn-on due to diode reverse recovery

Turn-on Snubber for Controlled Switches

- Circuit configuration



- Equivalent circuit during switch turn-off

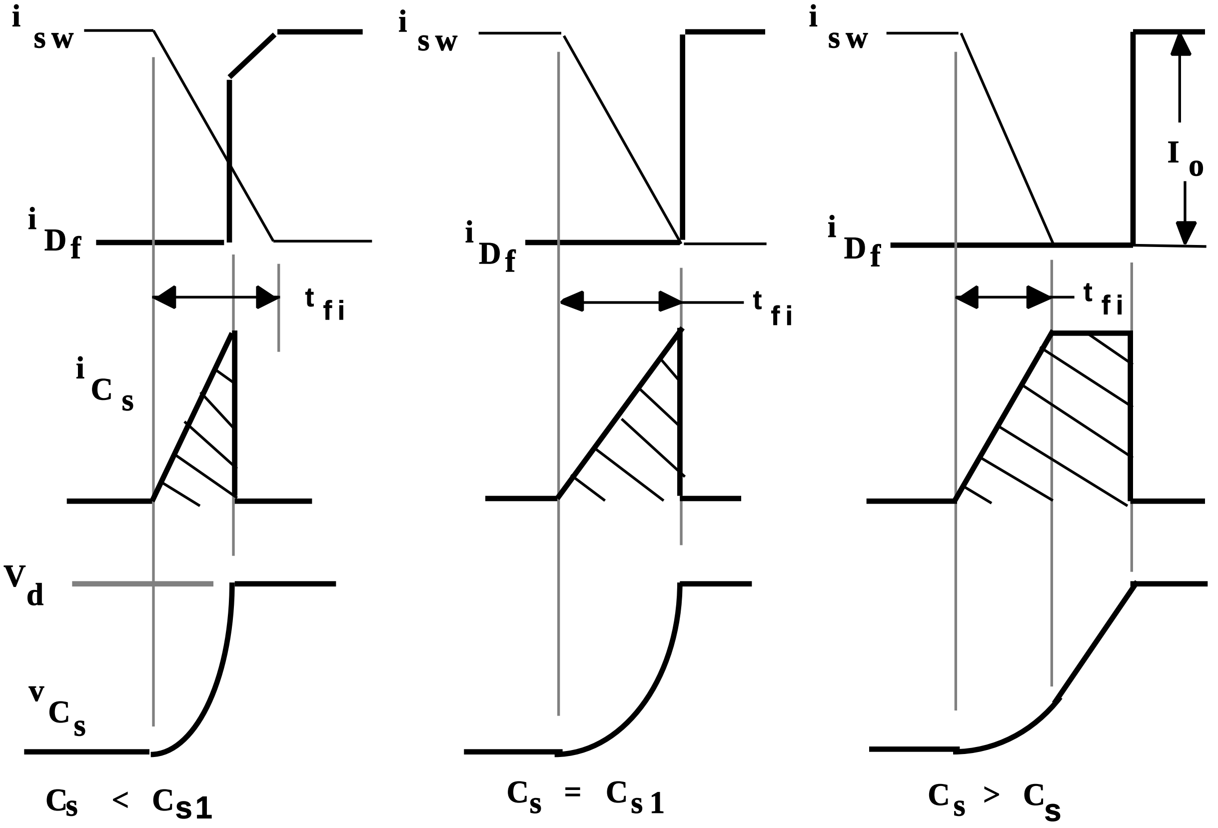


- Assumptions

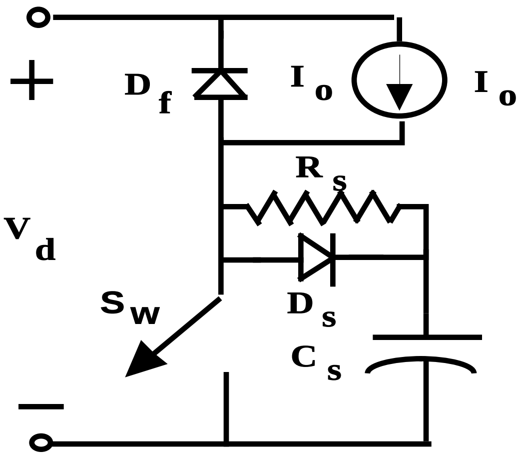
  1. No stray inductance.
  2. $i_{sw}(t) = I_o(1 - t/t_{fi})$
  3. $i_{sw}(t)$ uneffected by snubber circuit.

Turn-off Snubber Operation

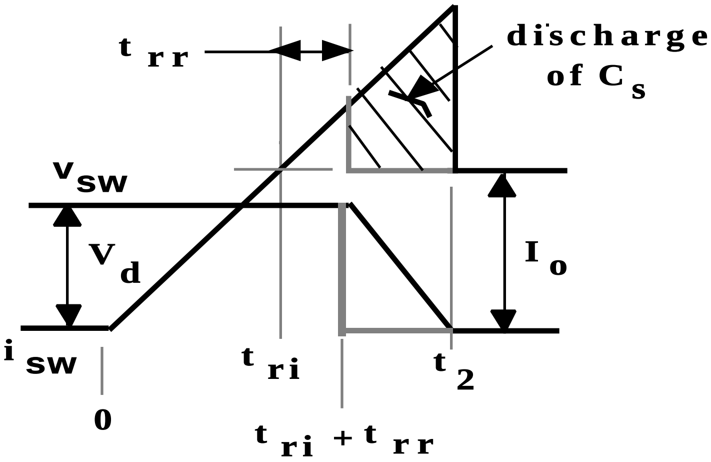
- Capacitor voltage and current for $0 < t < t_{fi}$
  - $i_{Cs}(t) = \dfrac{I_o t}{t_{fi}}$ and $v_{Cs}(t) = \dfrac{I_o t^2}{2C_s t_{fi}}$
- For $C_s = C_{s1}$, $v_{Cs} = V_d$ at $t = t_{fi}$ yielding $C_{s1} = \dfrac{I_o t_{fi}}{2V_d}$
- Circuit waveforms for varying values of C_s



Benefits of Snubber Resistance at S_w Turn-on

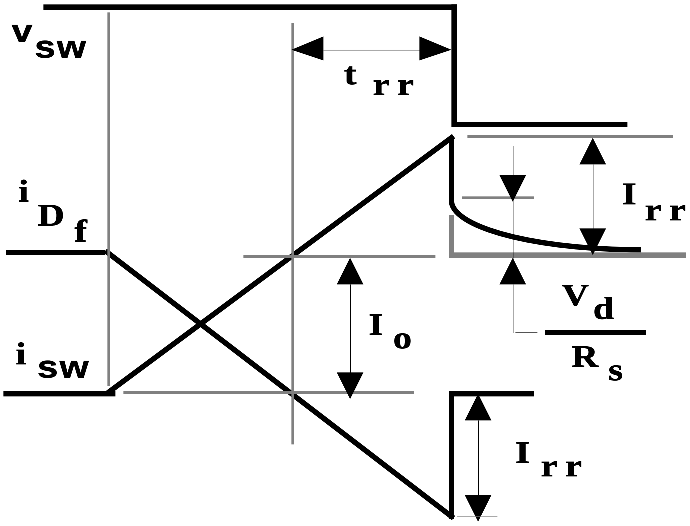


- D_s shorts out R_s during S_w turn-off.
- During S_w turn-on, D_s reverse-biased and C_s discharges thru R_s.



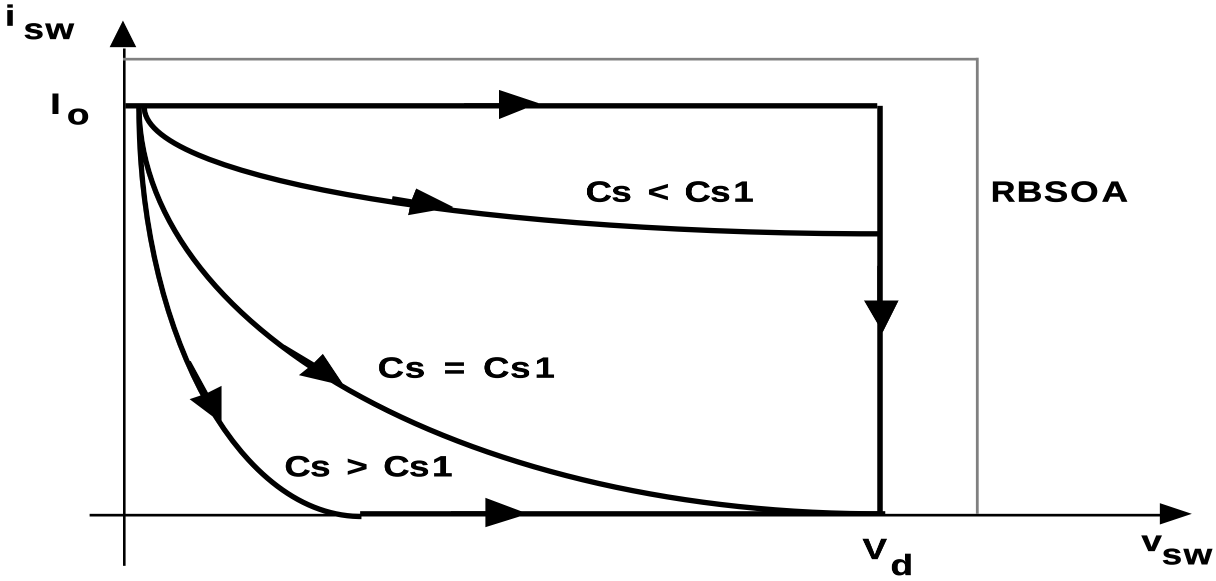
- Turn-on with $R_s = 0$
  - Energy stored on C_s dissipated in S_w.
  - Extra energy dissipation in S_w because of lengthened voltage fall time.

- 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.

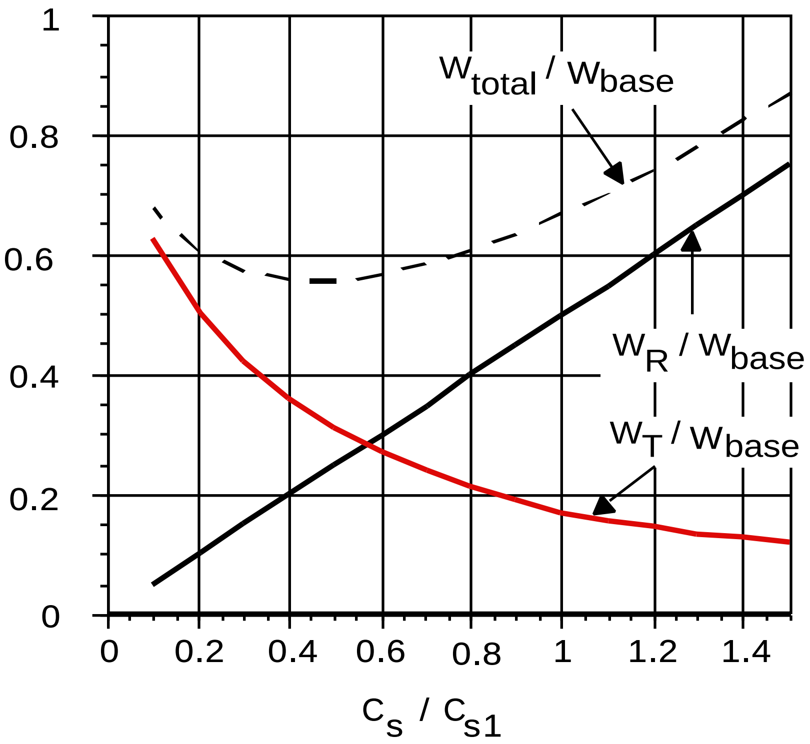


Effect of Snubber Capacitance

- Switching trajectory



- Energy dissipation



W_R = dissipation in resistor

W_T = dissipation in switch S_w

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

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

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

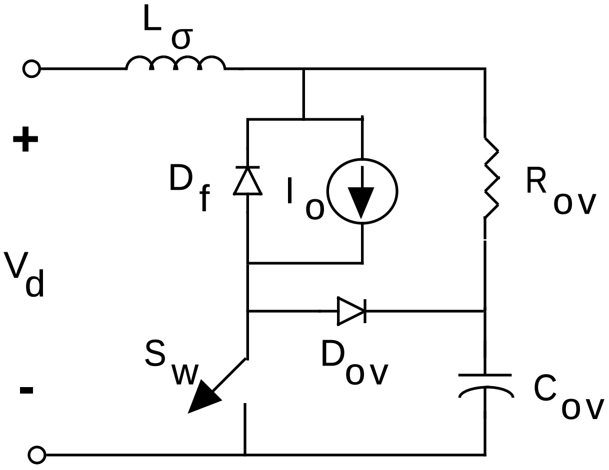
Turn-off Snubber Design Procedure

- 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 for Controlled Switches

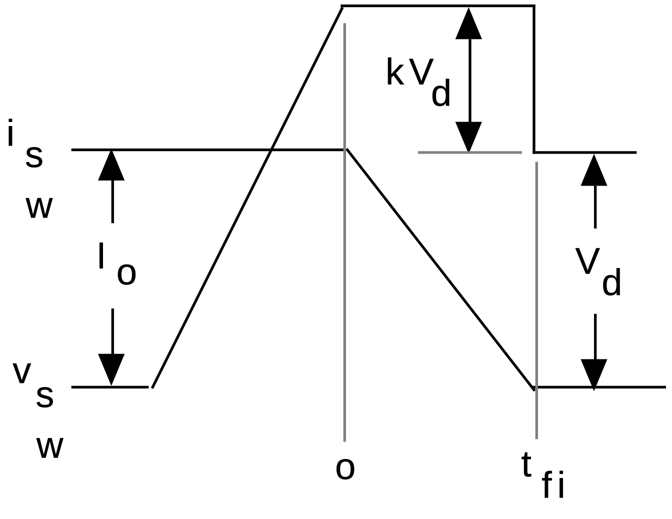
- Circuit configuration - D_{ov}, R_{ov}, and C_{ov} form overvoltage snubber



- Overvoltage snubber limits magnitude of voltage developed across S_w as it turns off.

- Switch S_w waveforms without overvoltage snubber

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



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

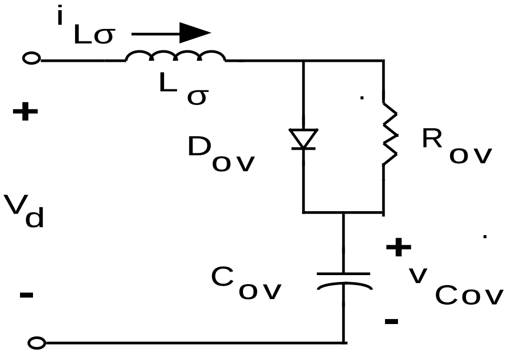
- $L_\sigma = \frac{kV_d t_{fi}}{I_o}$

Operation of Overvoltage Snubber

- D_{ov}, C_{ov} provide alternate path for inductor current as S_w turns off.
  - Switch current can fall to zero much faster than L_σ current.

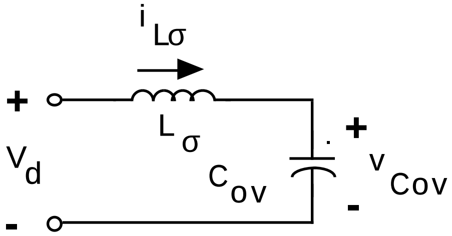
- D_f forced to be on (approximating a short ckt) by I_o after S_w is off.

- Equivalent circuit after turn-off of S_w.



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

- $t_{fi} << \dfrac{\pi\sqrt{L_\sigma C_{ov}}}{2}$



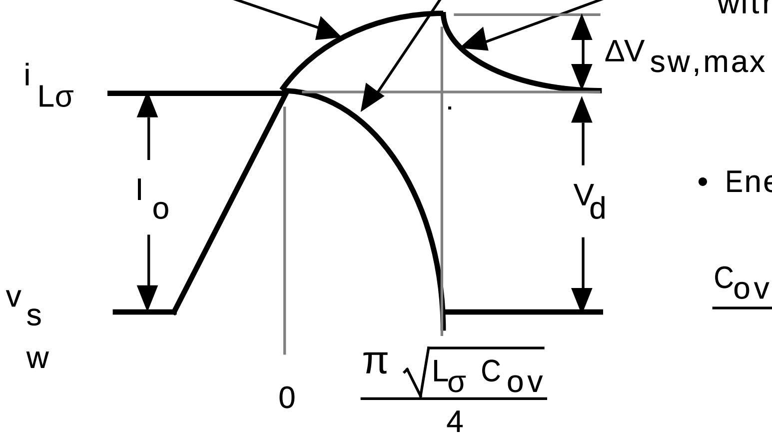
- Equivalent circuit while inductor current decays to zero

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

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

Charge-up of C_{ov} from L_σ

Discharge of C_{ov} thru R_{ov} with time constant $R_{ov}C_{ov}$



- Energy transfer from L_σ to C_{ov}

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

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

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

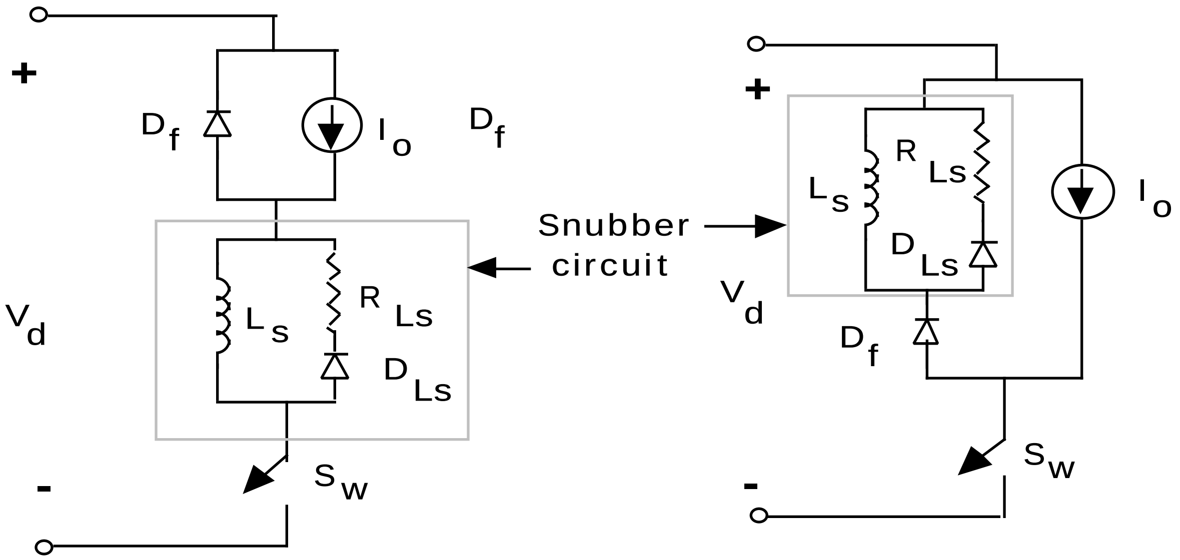
  - $C_{ov} = 200\, C_{s1}$ where $C_{s1} = \dfrac{t_{fi} I_o}{2V_d}$ which is used in turn-off snubber

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

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

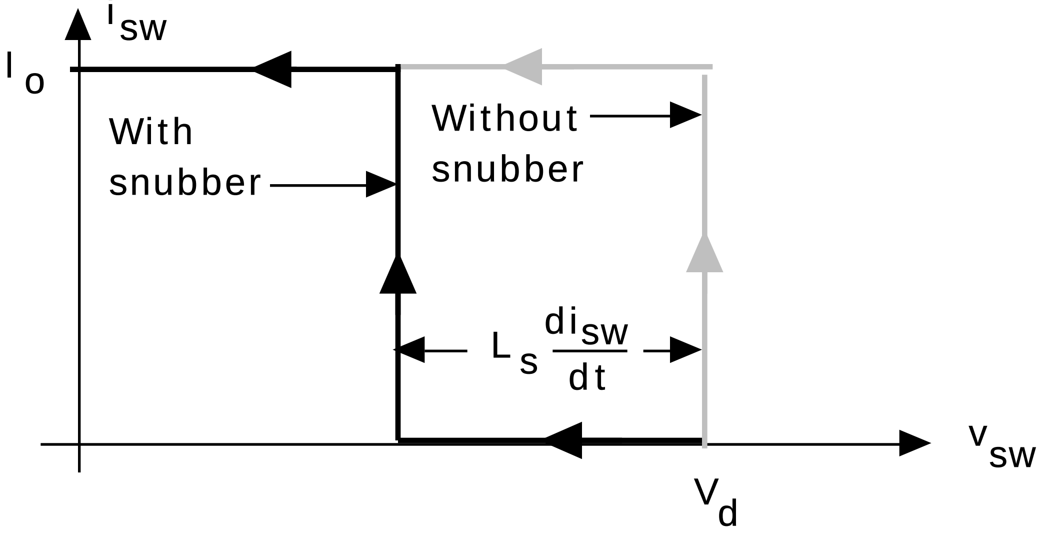
Turn-on Snubber Circuit

- Circuit topology



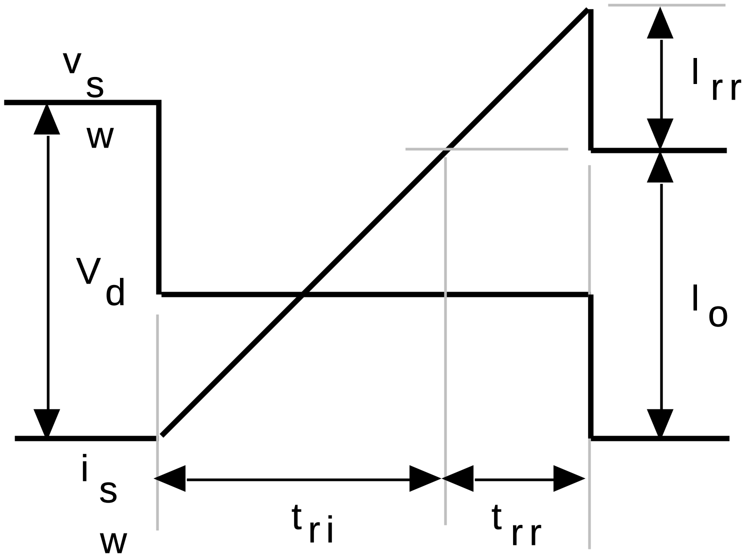
- Circuit reduces V_{sw} as switch S_w turns on. Voltage drop $L_s \frac{di_{sw}}{dt}$ provides the voltage reduction.

- Switching trajectories with and without turn-on snubber.



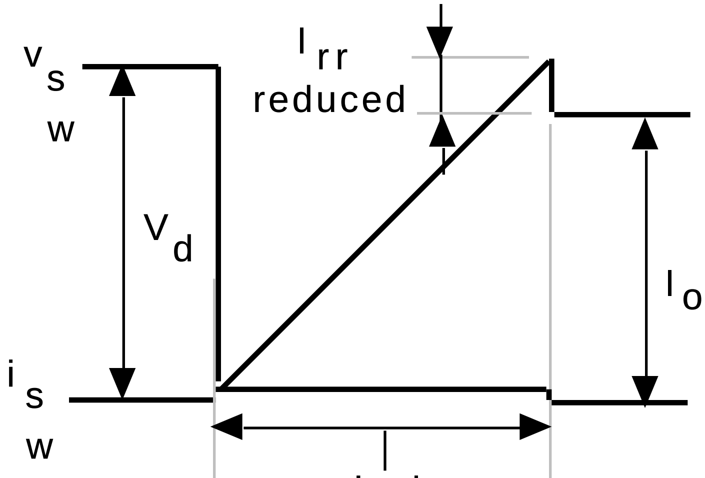
Turn-on Snubber Operating Waveforms

- 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 ($L_s > L_{s1}$).

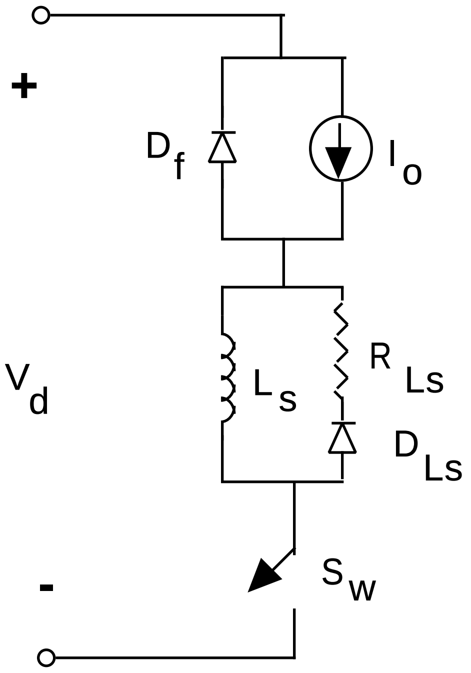


$$t_{on} \approx \frac{L_s I_o}{V_d} > t_{ri} + t_{rr}$$

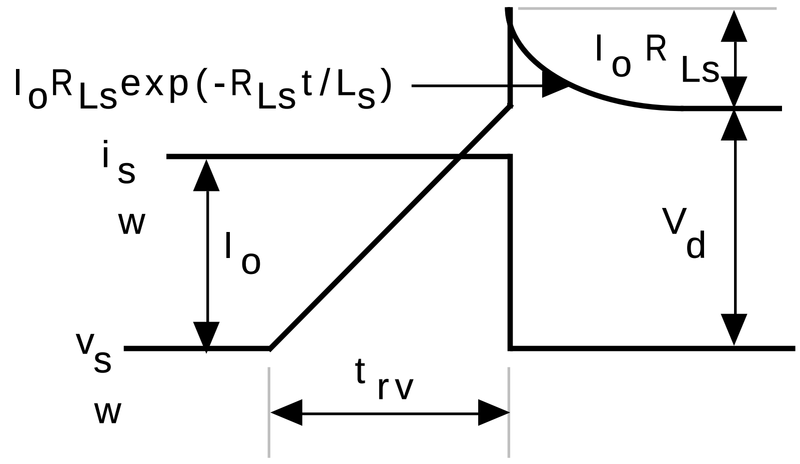
- $\frac{di_{sw}}{dt}$ limited by circuit to $\frac{V_d}{L_s} < \frac{I_o}{t_{ri}}$
- $L_{s1} = \frac{V_d t_{ri}}{I_o}$

- 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



- Assume switch current fall time $t_{ri} = 0$.
- Inductor current must discharge thru D_{Ls}- R_{Ls} series segment.



- Switch waveforms at turn-off with turn-on snubber in circuit.

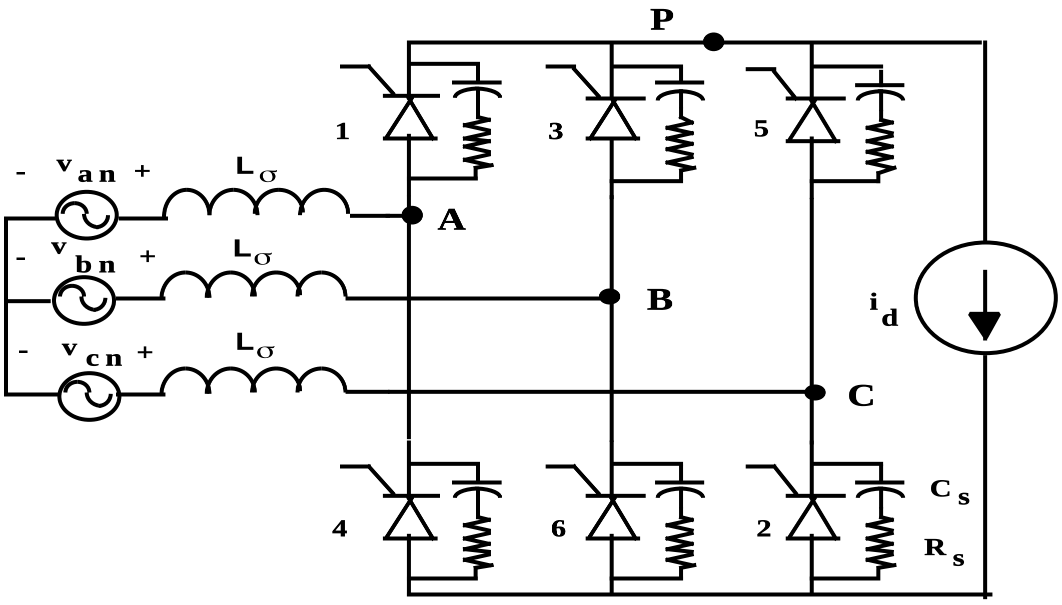
- Overvoltage smaller if t_{fi} smaller.
- Time of 2.3 L_s/R_{Ls} required for inductor current to decay to 0.1 I_o
- Off-time of switch must be > 2.3 L_s/R_{Ls}

Turn-on Snubber Design Trade-offs

- Selection of inductor L_s
  - 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

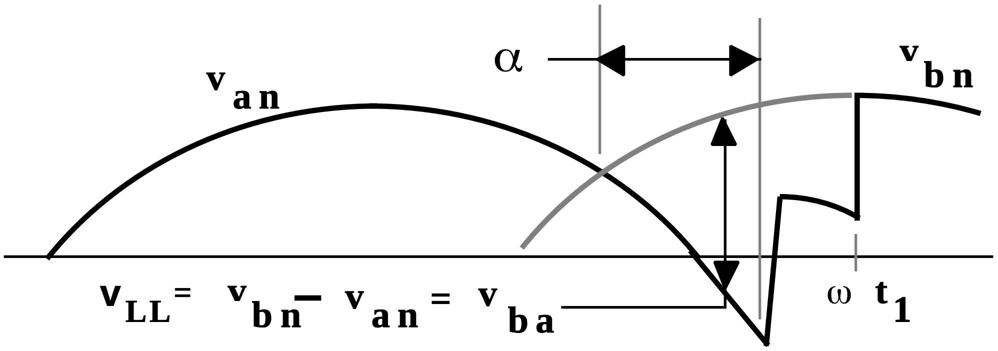
- Selection of resistor R_{Ls}
  - Smaller values of R_{Ls} reduce switch overvoltage $I_o R_{Ls}$ at turn-off
    - Limiting overvoltage to $0.1V_d$ yields $R_{Ls} = 0.1 V_d/I_o$
  - Larger values of R_{Ls} shortens minimum switch off-time of $2.3 L_s/R_{Ls}$

Thyristor Snubber Circuit



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

- Phase-to-neutral waveforms

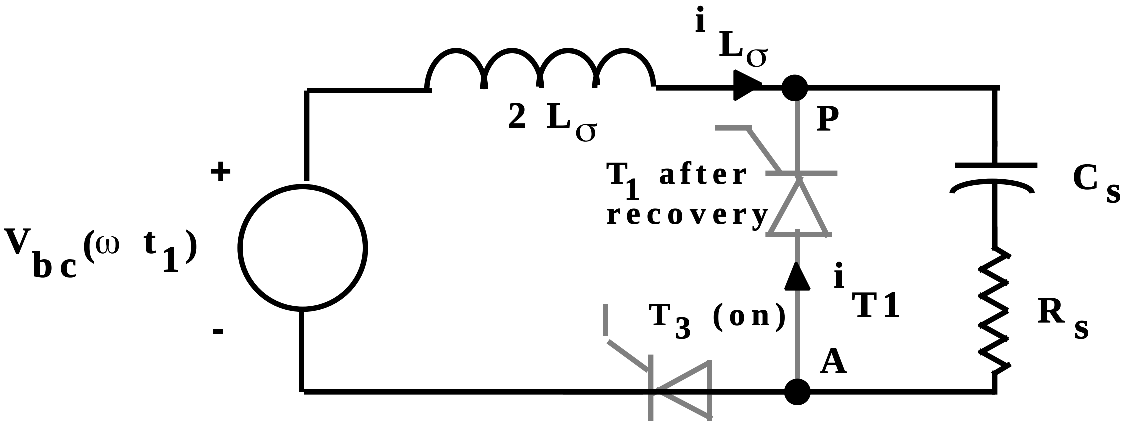


- $v_{LL}(t) = \sqrt{3}\, V_s \sin(\omega t - 60°)$

- Maximum rms line-to-line voltage $V_{LL} = \sqrt{\frac{3}{2}}\, V_s$

Equivalent Circuit for SCR Snubber Calculations

- Equivalent circuit after T1 reverse recovery



- Assumptions
  - Trigger angle α = 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 $v_{bc}(\omega t_1) = \sqrt{2}\ V_{LL}$
  - Worst case stray inductance L_σ 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.
    - $\omega L_\sigma = 0.05\ \dfrac{V_{LL}}{\sqrt{3} I_{a1}}$

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 $2\,L_\sigma \frac{di_{L\sigma}}{dt} = \sqrt{2}\,V_{LL}$
  - $I_{rr} = \frac{di_{L\sigma}}{dt}\,t_{rr} = \frac{\sqrt{2}V_{LL}}{2L_\sigma}\,t_{rr} = \frac{\sqrt{2}V_{LL}}{2\,\frac{0.05\,V_{LL}}{\sqrt{3}\,I_{a1}\omega}}\,t_{rr} = 25\,\omega I_{a1} t_{rr}$
  - $V_d = \sqrt{2}\,V_{LL}$
  - $C_s = C_{base} = \frac{0.05\,V_{LL}}{\sqrt{3}\,I_{a1}\omega}\left[\frac{25\,\omega I_{a1} t_{rr}}{\sqrt{2}V_{LL}}\right]^2 = \frac{8.7\,\omega I_{a1} t_{rr}}{V_{LL}}$
  - 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
    - $W_R = \frac{L_\sigma I_{rr}^2}{2} + \frac{C_s V_d^2}{2} = 18\,\omega\,I_{a1}\,V_{LL}(t_{rr})^2$