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 shape the turn-off switching trajectory of controlled switches.
   - Limit $\frac{di}{dt}$ during device turn-on
Need for Diode Snubber Circuit

- $L_\sigma$ = stray inductance
- $S_W$ closes at $t = 0$
- $R_S \cdot C_S =$ snubber circuit

$V_{d(t)}$ $i_{Df(t)}$ $t$

\[
\frac{di_{Df}}{dt} = \frac{V_d}{L_\sigma}
\]

$V_{Df(t)}$ $t$

$$L_\sigma \frac{di_{L\sigma}}{dt}$$

- 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

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

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

\[
\begin{align*}
\nu_C(t) &= V_d - V_d \cos(\omega_0 t) + V_d \sqrt{\frac{C_{\text{base}}}{C_s}} \sin(\omega_0 t) \\
\omega_0 &= \frac{1}{\sqrt{L_0 C_s}} ; \quad C_{\text{base}} = L_\sigma \left[ \frac{I_{rr}}{V_d} \right]^2 \\
V_{C_{\text{max}}} &= V_d \left\{ 1 + \sqrt{1 + \frac{C_{\text{base}}}{C_s}} \right\}
\end{align*}
\]

\[
\frac{V_{C_{\text{max}}}}{V_d} = f \left( \frac{C_{\text{base}}}{C_s} \right)
\]
Effect of Adding Snubber Resistance

- Equivalent circuit with snubber resistance $R_S$

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

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

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

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

  $$ \tan(\phi) = -\frac{R_b}{\omega_a L_\sigma} - \frac{\alpha}{\omega_a} \quad ; \quad \tan(\xi) = \frac{\alpha}{\omega_a} \quad ; \quad R_{base} = \frac{V_d}{I_{rr}} \quad , \quad C_{base} = \frac{L_\sigma}{(V_d/ I_{rr})^2} $$
Performance of R-C Snubber

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

\[
    t_m = \frac{\tan^{-1}(\omega_a/\alpha)}{\omega_a} + \frac{\phi - \xi}{\omega_a} \geq 0
\]

- \( \frac{V_{\text{max}}}{V_d} = 1 + \sqrt{1 + C_N^{-1} - R_N \exp(-\alpha t_m)} \)

- \( C_N = \frac{C_s}{C_{\text{base}}} \) and \( R_N = \frac{R_s}{R_{\text{base}}} \)

- \( C_{\text{base}} = \frac{L_s I_{rr}^2}{V_d^2} \) and \( R_{\text{base}} = \frac{V_d}{I_{rr}} \)

![Graph showing the relationship between \( \frac{V_{\text{max}}}{V_d} \) and \( \frac{R_s}{R_{\text{base}}} \)]
Diode Snubber Design Nomogram

\[ \frac{W_{\text{tot}}}{L_s I_{rr}^2/2} \]

\[ \frac{W_R}{L_s I_{rr}^2/2} \]

\[ \frac{V_{\max}}{V_d} \text{ for } R_s = R_{s,\text{opt}} \]

\[ \frac{R_{s,\text{opt}}}{R_{\text{base}}} \]

\[ C_s / C_{\text{base}} \]
Need for Snubbers with Controlled Switches

- **L₁, L₂, L₃** = stray inductances
- **L₀ = L₁ + L₂ + L₃**

**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

\[
\begin{align*}
\text{Turn-off snubber} \\
V_d \quad S_W \\
- \quad + \\
D_f \quad I_o \\
C_s \quad \text{i}_{C_s} \\
\end{align*}
\]

- Equivalent circuit during switch turn-off

\[
\begin{align*}
V_d \quad i_{sw} \\
\text{i}_{sw} \quad I_o \quad \text{i}_{C_s} \\
- \quad + \\
\end{align*}
\]

- 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 $0 < t < t_{fi}$
  - $i_{Cs}(t) = \frac{i_o t}{t_{fi}}$ and $v_{Cs}(t) = \frac{i_o t^2}{2C_s t_{fi}}$

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

- 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**
  
  
  ![Diagram showing switching trajectory for different capacitance values](image)

  - $Cs < Cs1$
  - $Cs = Cs1$
  - $Cs > Cs1$

- **Energy dissipation**
  
  
  ![Graph showing energy dissipation](image)

  - $WR = \text{dissipation in resistor}$
  - $WT = \text{dissipation in switch } S_w$
  - $C_{s1} = \frac{I_o t_{fi}}{2V_d}$
  - $W_{\text{total}} = W_R + W_T$
  - $W_{\text{base}} = 0.5 V_d I_o t_{fi}$

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**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 $i_{\text{cap}(0^+)} = \frac{V_d}{R_S} < I_{rr}$
  - Usually designer specifies $I_{rr} < 0.2 \ I_0$ so
    \[
    \frac{V_d}{R_S} = 0.2 \ I_0
    \]

- Snubber recovery time (BJT in on-state)
  - Capacitor voltage $= V_d \exp(-t/R_{S}C_S)$
  - Time for $v_{CS}$ to drop to $0.1V_d$ is $2.3 \ R_S C_S$
  - BJT must remain on for a time of $2.3 \ R_S C_S$
Overvoltage Snubber for Controlled Switches

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

\[ V_d \]

\[ L_{\sigma} \]

\[ D_f \]

\[ I_o \]

\[ R_{ov} \]

\[ C_{ov} \]

- 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 $S_w$

\[ kV_d = \frac{di_{L_{\sigma}}}{dt} = L_{\sigma} \frac{l_o}{t_{fi}} \]

\[ L_{\sigma} = \frac{kV_d t_{fi}}{l_o} \]

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**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 $L_\sigma$ 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 $S_w$.

\[ i_{L_{\sigma}} \]
\[ + \]
\[ L_{\sigma} \]
\[ D_{ov} \]
\[ R_{ov} \]
\[ V_d \]
\[ - \]
\[ C_{ov} \]
\[ \overset{+}{v}_{Cov} \]
\[ \overset{-}{v}_{Cov} \]

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

- Equivalent circuit while inductor current decays to zero
  \[ v_{Cov}(0^+) = V_d \]
  \[ i_{L_{\sigma}}(0^+) = I_0 \]
  \[ i_{L_{\sigma}}(t) = I_0 \cos \left( \frac{t}{\sqrt{L_\sigma C_{ov}}} \right) \]

- Charge-up of $C_{ov}$ from $L_{\sigma}$
- Discharge of $C_{ov}$ thru $R_{ov}$ with time constant $R_{ov} C_{ov}$

- Energy transfer from $L_\sigma$ to $C_{ov}$
  \[ \frac{C_{ov} (\Delta V_{sw,\text{max}})^2}{2} = \frac{L_\sigma (I_0)^2}{2} \]

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Overvoltage Snubber Design

• \[ C_{ov} = \frac{L_s I_o^2}{(\Delta v_{sw,\text{max}})^2} \]

• Limit \( \Delta v_{sw,\text{max}} \) to 0.1\(V_d\)

• Using \( L_s = \frac{kV_d t_{fi}}{I_o} \) in equation for \( C_{ov} \) yields

• \[ C_{ov} = \frac{kV_d t_{fi} I_o^2}{I_o(0.1V_d)^2} = \frac{100k t_{fi} I_o}{V_d^2} \]

• \( C_{ov} = 200 C_{s1} \) where \( C_{s1} = \frac{t_{fi} I_o}{2V_d} \) which is used in turn-off snubber

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

• \[ R_{ov} \approx \frac{t_{off}}{2.3 C_{ov}} \]
Turn-on Snubber Circuit

• Circuit topology

\[
\begin{align*}
V_d &+ \\
D_f &\quad I_o \\
L_s &\quad D_f \\
S_w &- \\
- &
\end{align*}
\]

Snubber circuit

• 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.

\[
\begin{align*}
V_d &+ \\
I_o &\quad i_{sw} \\
L_s \quad \frac{di_{sw}}{dt} \\
V_{sw} &-
\end{align*}
\]
Turn-on Snubber Operating Waveforms

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

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

- $I_{rr}$ 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 $2.3 \frac{L_s}{R_{Ls}}$ required for inductor current to decay to $0.1 I_0$
- Off-time of switch must be $> 2.3 \frac{L_s}{R_{Ls}}$

- 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 $2.3 \frac{L_s}{R_{Ls}}$ required for inductor current to decay to $0.1 I_0$
- Off-time of switch must be $> 2.3 \frac{L_s}{R_{Ls}}$
**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

\[ v_{an}(t) = V_s \sin(\omega t), \quad v_{bn}(t) = V_s \sin(\omega t - 120^\circ), \quad v_{cn}(t) = V_s \sin(\omega t - 240^\circ) \]

- Phase-to-neutral waveforms

\[ v_{LL}(t) = \sqrt{3} V_s \sin(\omega t - 60^\circ) \]

- 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

![Equivalent Circuit Diagram]

- Assumptions
  - Trigger angle $\alpha = 90^\circ$ 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 $L_\sigma$ gives rise to reactance equal to or less than 5% of line impedance.
    - Line impedance $= \frac{V_s}{\sqrt{2}I_{a1}} = \frac{\sqrt{2}V_{LL}}{\sqrt{6}I_{a1}} = \frac{V_{LL}}{\sqrt{3}I_{a1}}$
      where $I_{a1} =$ rms value of fundamental component of the line current.
    - $\omega L_\sigma = 0.05 \frac{V_{LL}}{\sqrt{3}I_{a1}}$
Component Values for Thyristor Snubber

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

- Snubber capacitor $C_s = C_{\text{base}} = L_{\sigma} \left[ \frac{l_{rr}}{V_d} \right]^2$

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

- $l_{rr} = \frac{di_{L\sigma}}{dt} \quad t_{rr} = \frac{\sqrt{2}V_{LL}}{2L_{\sigma}} \quad t_{rr} = 25 \frac{\omega l_{a1} t_{rr}}{V_{LL}}$

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

- $C_s = C_{\text{base}} = \frac{0.05 V_{LL}}{\sqrt{3}} \frac{25 \frac{\omega l_{a1} t_{rr}}{\sqrt{2}V_{LL}}}{l_{a1} \omega} = \frac{8.7 \frac{\omega l_{a1} t_{rr}}{V_{LL}}}{V_{LL}}$

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

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

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

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