Turn-on Snubber circuits:

- protect switching device from simultaneously high voltage and current during *turn-on*
- modify voltage-current waveforms (switching trajectory) to reduce power loss on the switch during *turn-on*

Example 2-2: Transistor Turn-on Snubber

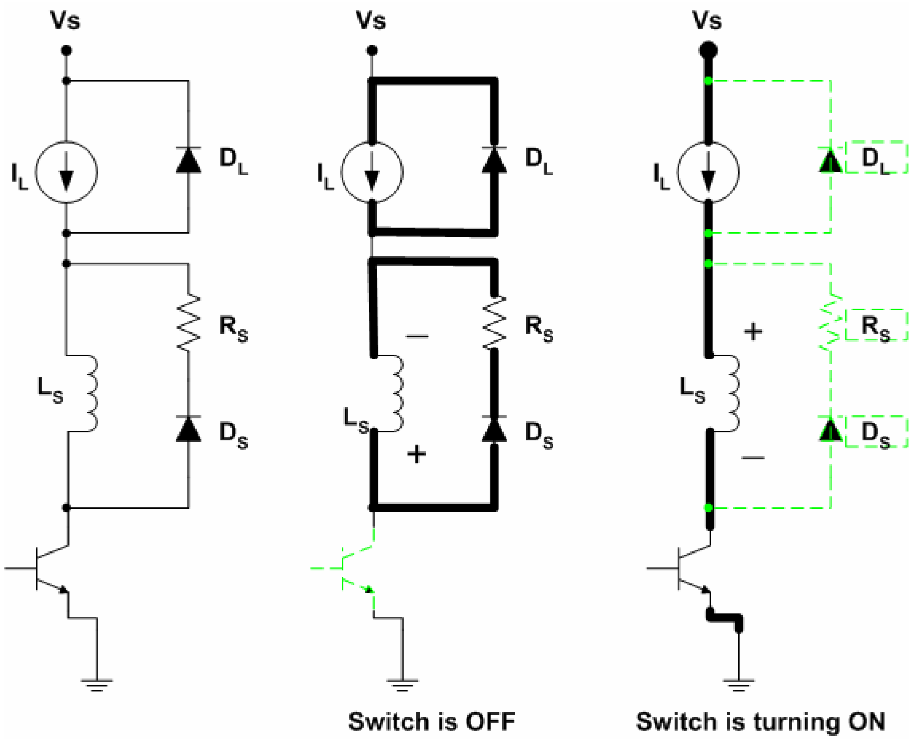


Figure 2-3. Transistor snubber circuit and switching waveforms

- An inductor in series slows the rate of current rise during the turn-on transition
- Snubber diode is OFF during turn on, while D_L is ON
- During turn-off, the energy stored in the turn-on snubber inductor = ½ $L_S I_o^2$ is dissipated in the resistor R
- To choose the values of L_S and R:
    - Recall that the snubber time constant $\tau = L_S/R$
    - The inductor current in the snubber during the *turn-off* state must decay to close to zero, so that the snubber can be effective during the next turn-on

- If say, 3 time constant is necessary for inductor discharge, then:

$$t_{\text{off state}} > 3^* L_s/R$$

Pspice Simulations:

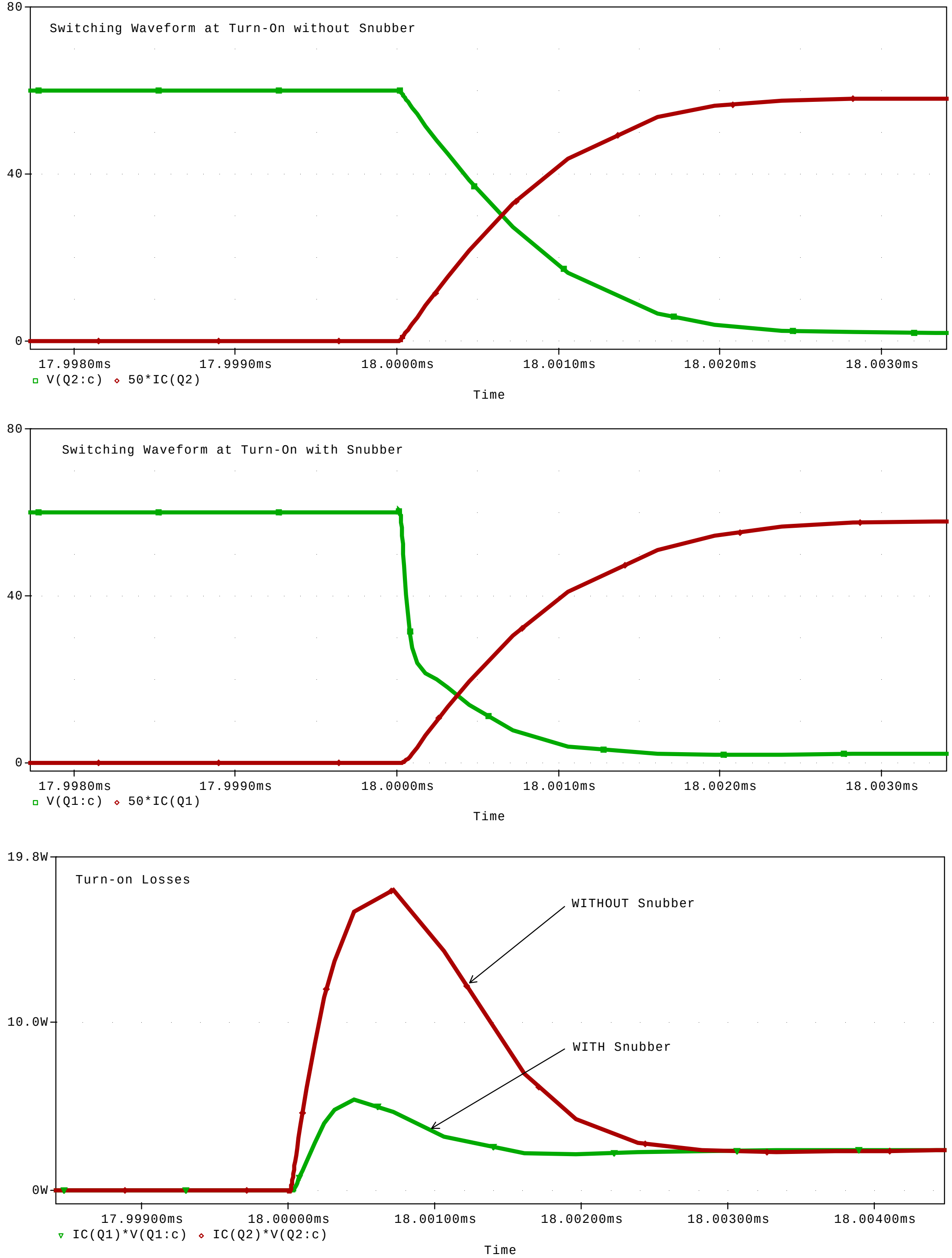


Figure 2-4. Pspice Example to show effect of Snubber

Energy Recovery Snubber circuits:

- With turn-off and turn-on snubbers, the power dissipated in the switching device may be reduced
- At the same time, snubbers transfer the power to the snubber resistor which dissipates power loss as heat
  - Not an energy efficient solution
    1. Need to eliminate the use of snubber resistor
    2. Need to transfer the stored energy in the snubber to the load or back to the source
    3. A method that satisfies (1) and (2) is called the Energy Recovery Snubber circuits
    4. Energy Recovery Snubber is also known as Nondissipative snubber

Advantages of nondissipative snubber:

- Increase operating efficiency
- Can be cost effective in high-power equipment

Disadvantages

- More complex circuit
- More components: reliability issue, added cost, weight

Example 2-3: Transistor Energy Recovery Snubber

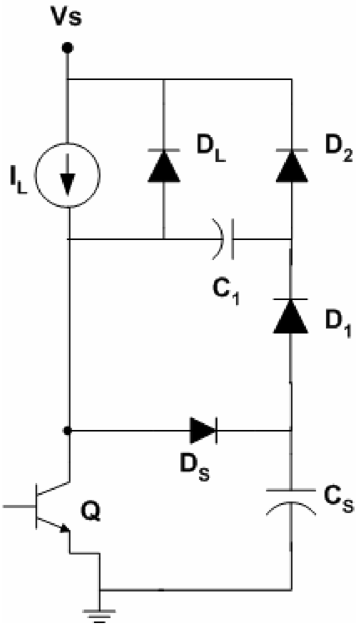
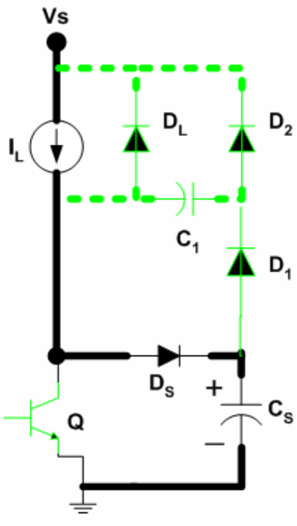
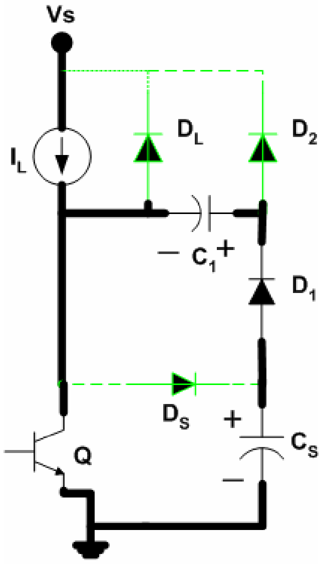


Figure 2-5. Transistor Energy Recovery Snubber Circuit



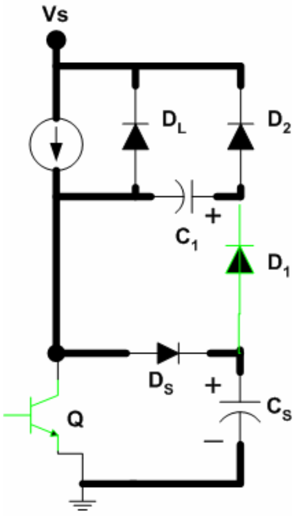
Switch is turning OFF

- When the switch is turning OFF
  - D_s and C_s act like the turn-off snubber
  - During turn-off, C_s charges to V_s and delays the voltage rise across the transistor



Switch is turning ON

- When the switch is turning ON
  - Diodes D_L and D_2 are off
  - A current path C_s, D_1, C_1 and Q is formed, and thus charging capacitor C_1
  - The charge initially stored in C_s is transferred to C_1



Next turning OFF

- At the next turn-off:
  - C_1 discharges through D_2 into the load, while C_s charges again

Example 2-4: Transistor Energy Recovery Snubber

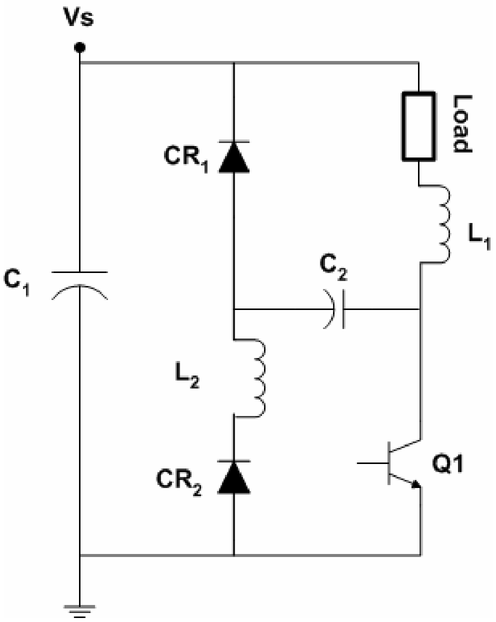


Figure 2-6. Another Transistor Energy Recovery Snubber Circuit

- Assume initially C_2 has been charged to V_s, then when Q_1 turns off energy from L_1 goes to C_2, through path Load-L_1-C_2-CR_1

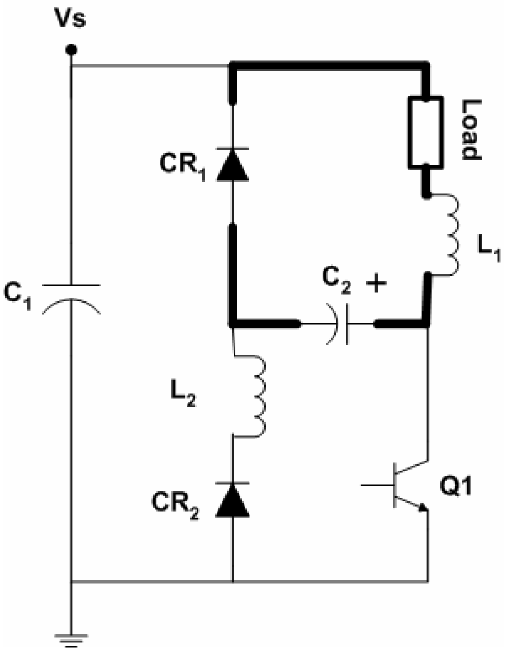


Figure 2-7. Charging C2

- When Q_1 turns on, then current flows through path C_2-Q_1-CR_2-L_2 while charging L_2

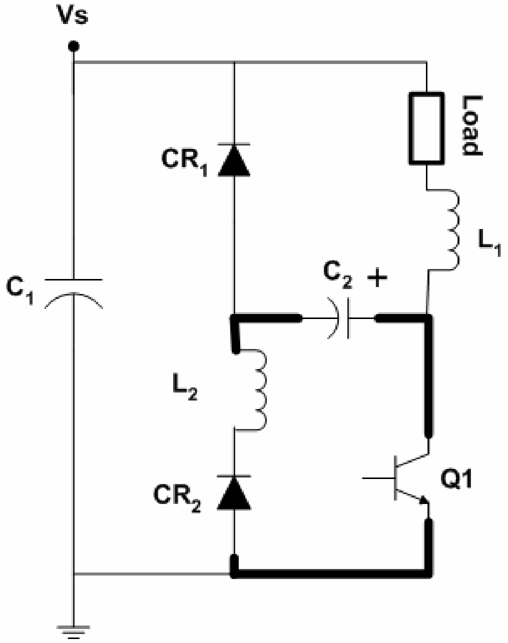


Figure 2-8. Charging L2

- When Q_1 turns off again (CR_1 turns on again), the energy stored in L_2 is now delivered back to C_1, hence to back to the input source, through path L_2-CR_1-C_1-CR_2

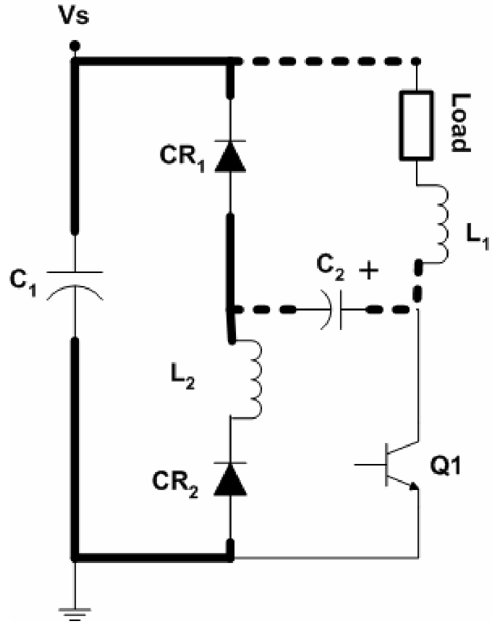


Figure 2-9. Discharging back to C1

Other Snubber Circuits:

- There are wide varieties of Snubber circuits depending on:
  - The semiconductor switches used
  - The purpose of the snubbers (turn-off, turn-on, combined, energy recovery, over-voltage, etc.)
  - Other useful references for various Snubbers:
    - Power Electronic Text-Books
    - Engineering Database such as Applied Science & Technology, Engineering Village 2
    - US Patent search engine: patent.womplex.ibm.com/

Other Examples of Snubbers:

Rectifier Snubbers

- Can reduce voltage transients and EMI

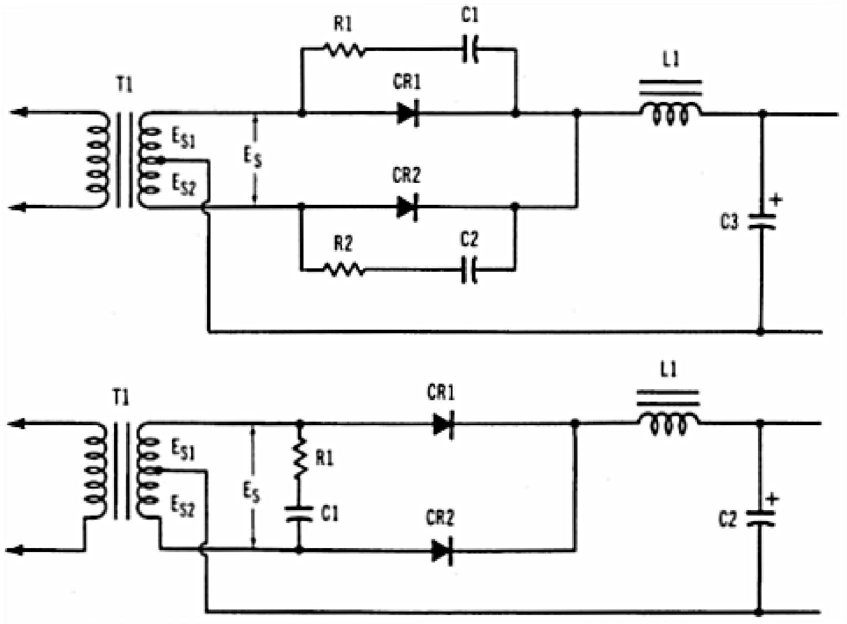


Figure 2-10. Rectifier Snubber Circuit [4]

- Top snubber is recommended for a high output current
- Bottom snubber is recommended for low output currents and/or high-voltage outputs

Triac Snubbers

- For lamp load

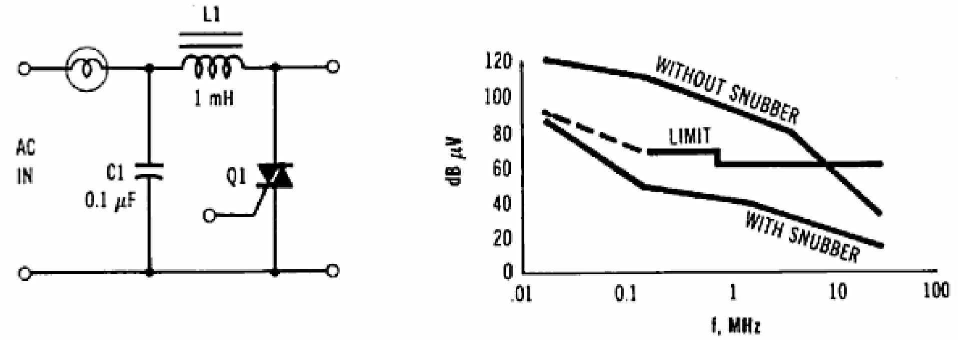


Figure 2-11. TRIAC Snubber Circuit [4]

- For inductive load

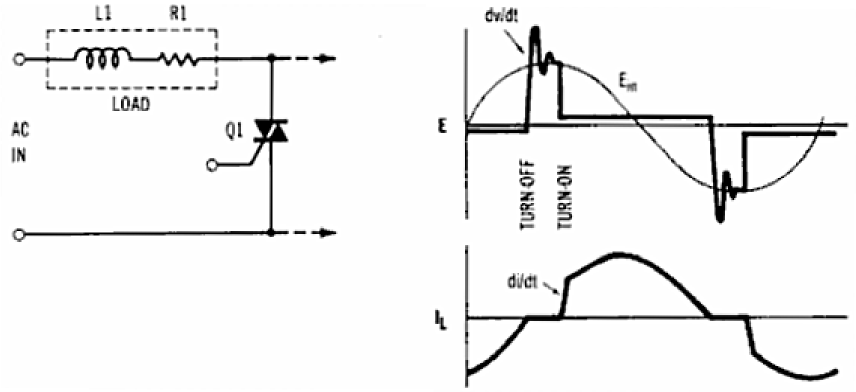


Figure 2-12. TRIAC Snubber Circuit with Inductive Load [4]

- to alleviate di/dt and dv/dt

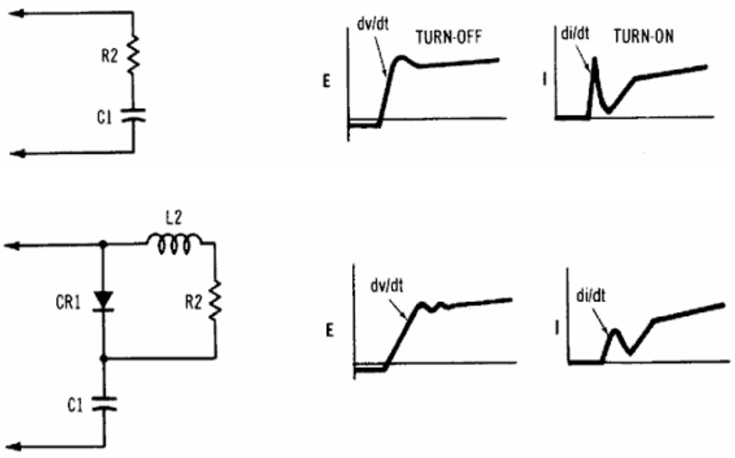


Figure 2-13. TRIAC Snubber Circuit for di/dt and dv/dt [4]

SCR Snubber

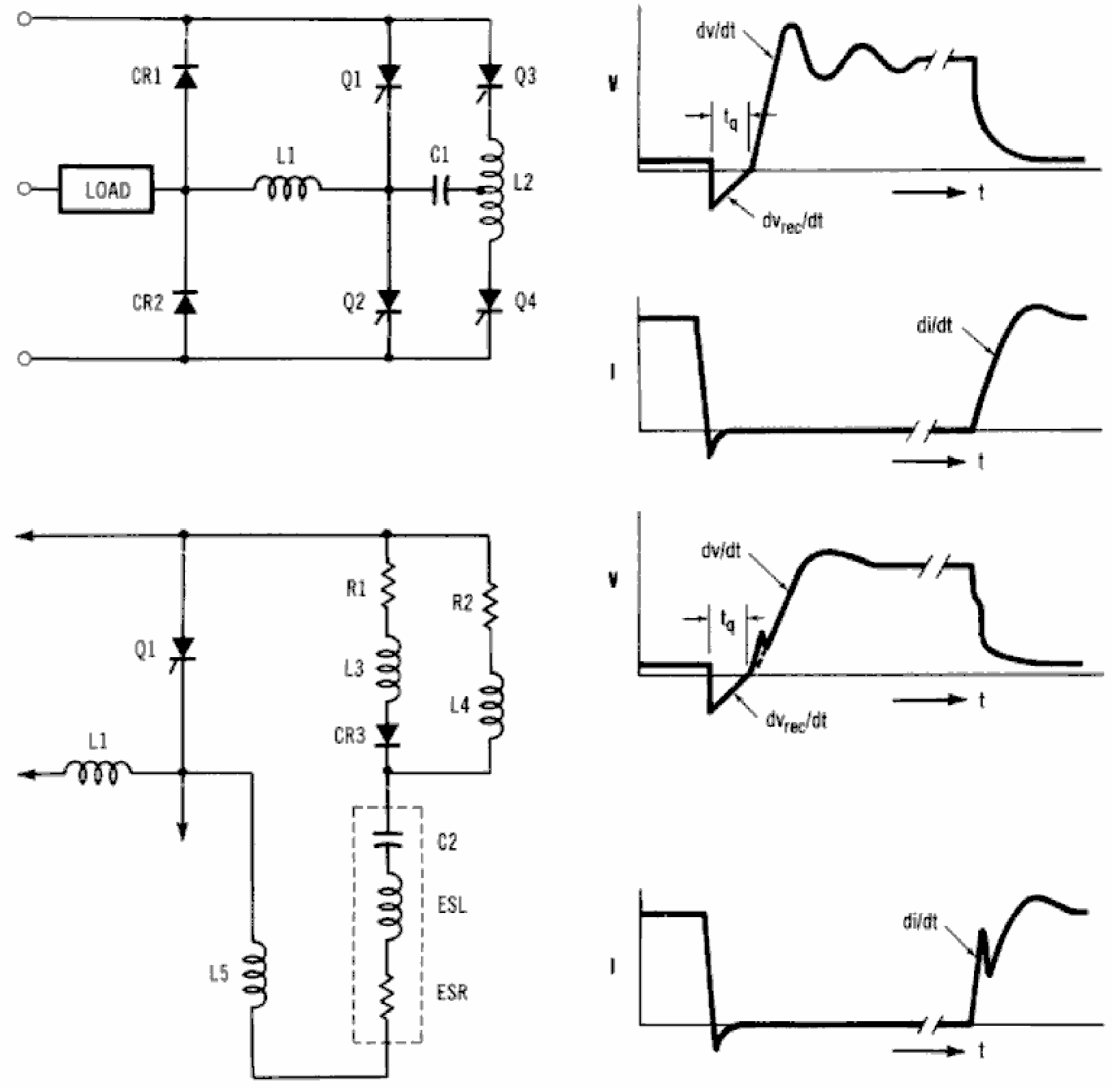


Figure 2-14. SCR Snubber Circuit [4]

MOSFET Snubbers:

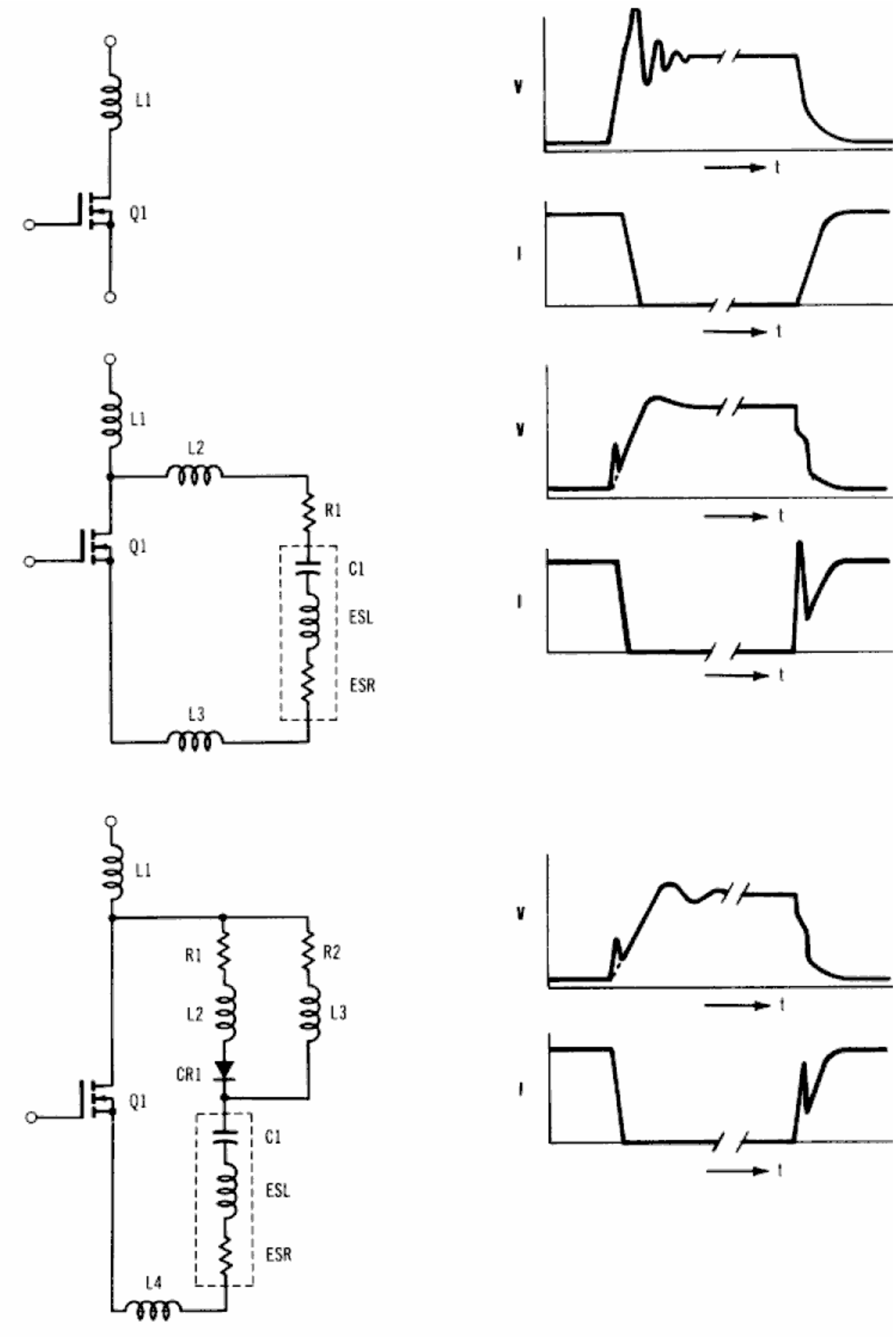


Figure 2-15. MOSFET Snubber Circuit [4]

Alternative to Snubbers

- So far we have discussed switching technique where the switch in the circuit is required to turn on from significantly high voltage and to turn off from significantly high current
  - Called the Square-wave switching or Hard-switching
  - High switching dv/dt and di/dt stresses
  - Associated with EMI (Electro-Magnetic Interference) problem due to large di/dt and dv/dt noises
  - Switching losses since the switch absorbs crucial amount of power loss that increases linearly with the switching frequency

- Snubber Circuits alleviate switching losses:
  - Help by shifting the energy loss from the switching devices to the snubber components
  - Not a good solution since
    - Do not *necessarily* suppress total loss, hence may not improve overall converter's efficiency
    - Limit the operating switching frequency
      - since snubbers slow down the rate of rise and fall times
      - consequently reduce maximum duty cycle
    - Associated with additional components
      - Extra cost
      - More reliability consideration
      - May increase size and weight

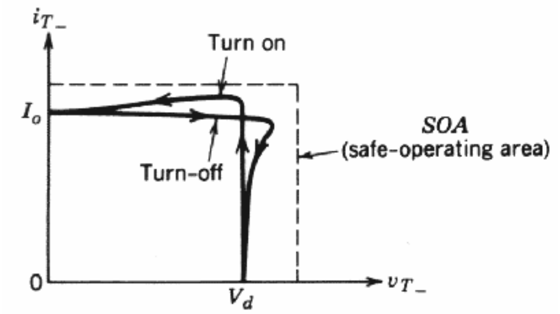
- Theoretically, snubbers won't be needed if
  - The switch is operated in such a way that the voltage across it and/or the current through it is ZERO at the switching instants or transitions
      - No auxiliary circuit added to the switch - cost efficient
      - Switching frequency can be increased, without increasing switching loss and thus total loss
        - reduce filter requirement and thus converter size and weight in general

Converter topology which incorporates either ZERO Voltage or ZERO Current switching or both is called:

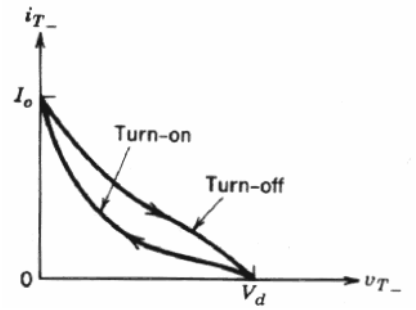
☞ The Soft-switching Topology ☜

- The soft-switching topology can be achieved for example by using resonant circuit
- Examples of switching trajectory using Hard-switching, Hard-switching+Snubber, and Soft-switching in Bridge Converter:

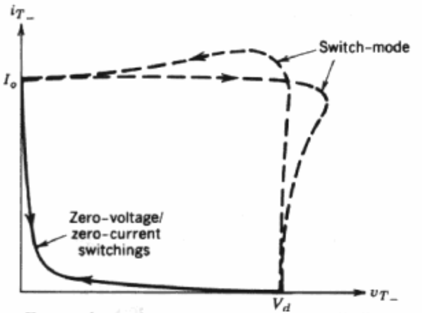
  1. Switch Mode



  2. Switch Mode with Snubbers



  3. ZVS/ZCS Switching



Zero-voltage-/zero-current-switching loci.

Figure 2-16. Examples of Switching Trajectories [5]

Self Assessment Study

1. What are Snubber Circuits?
2. List two uses of Snubber Circuits.
3. Why Snubber Circuits do not always reduce the total loss of converter.
4. How does a turn-off transistor snubber reduce turn-off switching loss?
5. In the turn-off transistor snubber, how do you select the snubber capacitor?
6. How do you select the snubber resistor in the turn-off transistor snubber?
7. What are Energy-recovery Snubbers?
8. List disadvantages of using Snubbers.
9. What is Soft-Switching?
10. What are the advantages of Soft-Switching over the Snubbers?

Chapter 3: Soft-Switching

Review of Resonant Circuits

Basic Resonant Circuit Concepts

Two types of Basic Resonant Circuit

1. Series-Resonant Circuits
    - Undamped Series-Resonant Circuit
    - Series-Resonant Circuit with a Capacitor-Parallel Load
2. Parallel-Resonant Circuits
    - Undamped Parallel Resonant Circuit

Undamped Series-Resonant Circuit

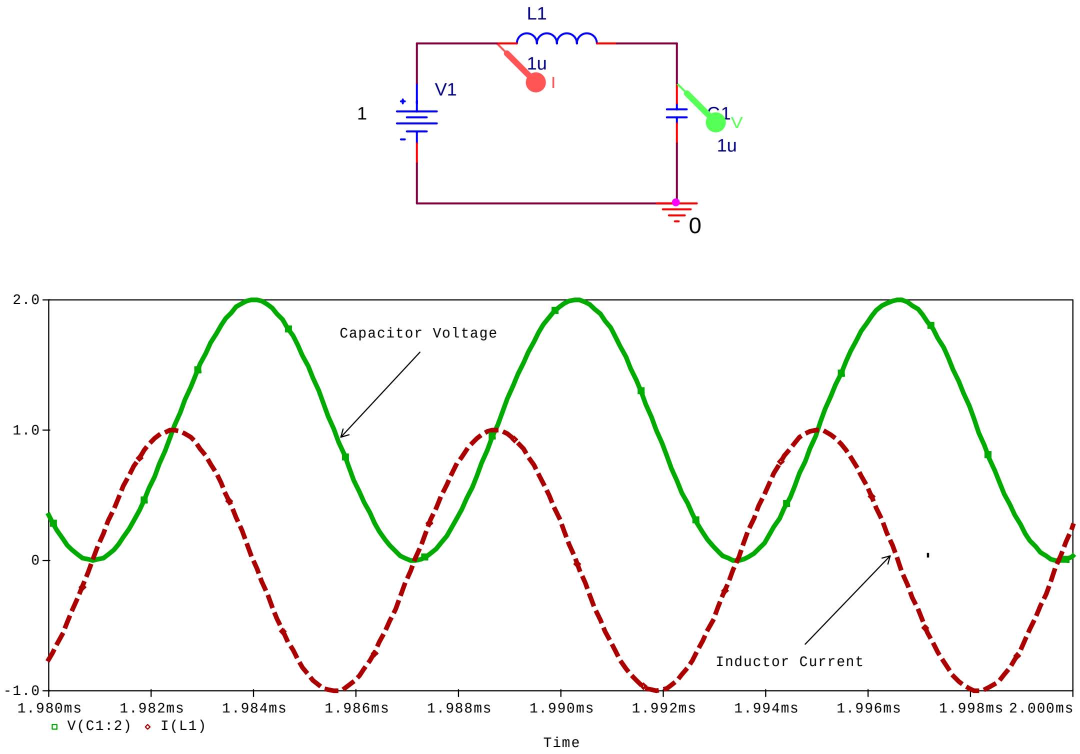


Figure 3-1. Undamped Series-Resonant Circuit and waveforms with no initial conditions

Using KVL:

$$L_r \frac{di_L}{dt} + v_c = V_d \qquad \text{and} \qquad C_r \frac{dv_c}{dt} = i_C = i_L$$

The solution of these differential equations for

$$i_L(t) = I_{L0} \cos\omega_o t + \frac{V_d - V_{c0}}{Z_0} \sin\omega_o t \qquad (1)$$

$$v_c(t) = V_d - (V_d - V_{c0})\cos\omega_o t + Z_0 I_{L0} \sin\omega_o t \qquad (2)$$

where:

I_{L0}	= initial condition of the inductor	[Amps]
V_{c0}	= initial condition of the capacitor	[Volts]
ω_o	= angular resonant frequency $= 2\pi f_o = \frac{1}{\sqrt{L_r C_r}}$	[rad/sec]
Z_o	= characteristic impedance $= \sqrt{\frac{L_r}{C_r}}$	[Ohms]

4 Cases:

1. When no initial conditions (Zero initial conditions) are found in L_1 and C_1

$$i_L(t) = \frac{V_d}{Z_0} \sin\omega_o t$$

$$v_c(t) = V_d - V_d \cos\omega_o t$$

See Figure 3-1 for Inductor and Capacitor waveforms

2. When both L_1 and C_1 posses initial conditions

Equations (1) and (2)

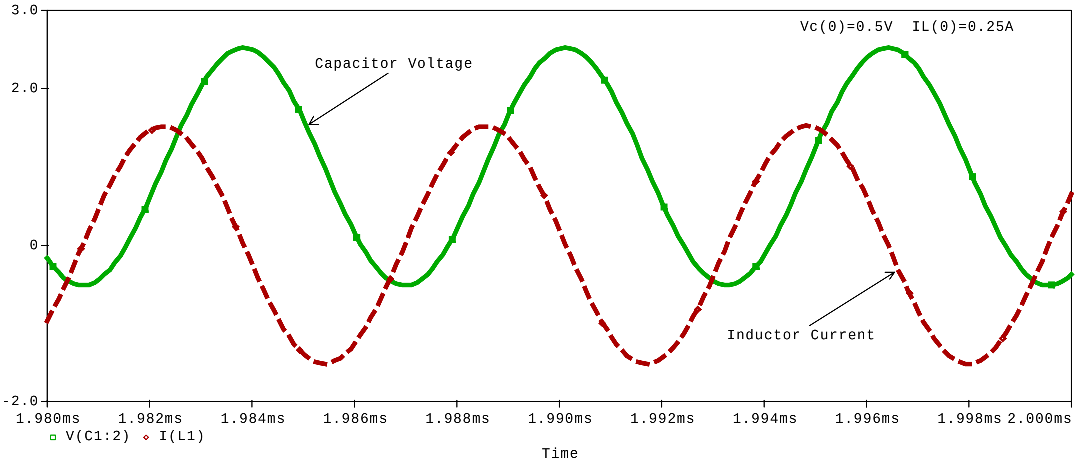


Figure 3-2. Undamped Series-Resonant Circuit and with initial conditions on both L and C

3. When only C_1 has the initial condition

$$i_L(t) = \frac{V_d - V_{c0}}{Z_0} \sin \omega_o t$$

$$v_c(t) = V_d - (V_d - V_{c0}) \cos \omega_o t$$

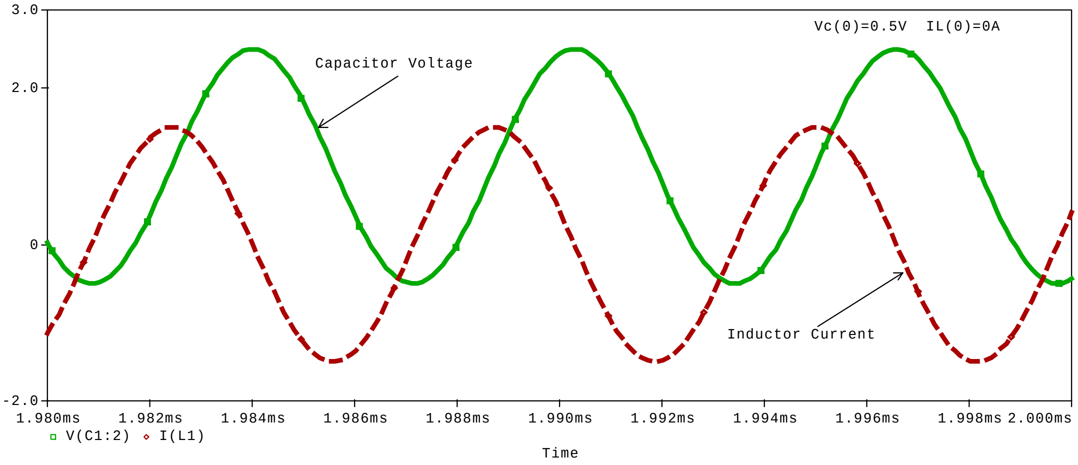


Figure 3-3. Undamped Series-Resonant Circuit and with initial condition on C only

4. When only L_1 has the initial condition

$$i_L(t) = I_{L0} \cos \omega_o t + \frac{V_d}{Z_0} \sin \omega_0 t$$

$$v_c(t) = V_d - V_d \cos\omega_0 t + Z_0 I_{L0} \sin\omega_o t$$

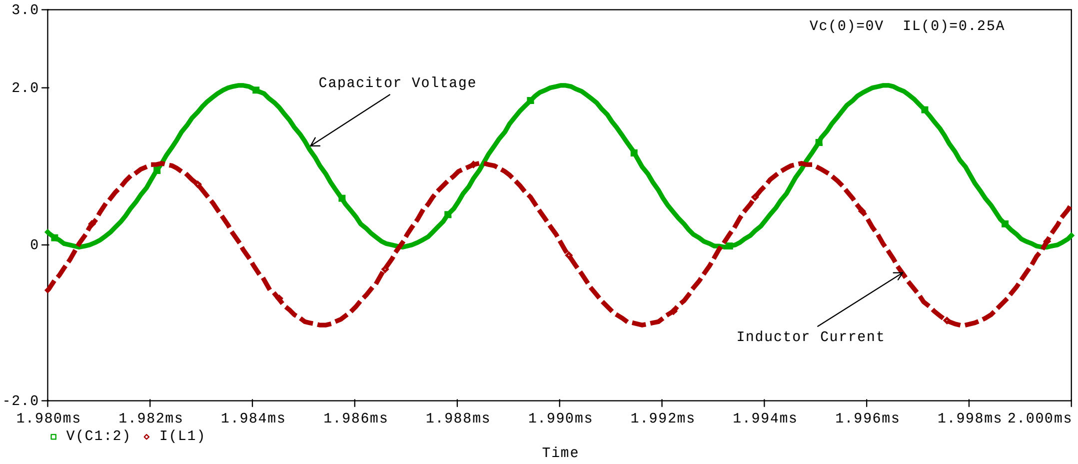


Figure 3-4. Undamped Series-Resonant Circuit and with initial condition on L only