9

Switching-aid Circuits with Energy Recovery

Turn-on and turn-off snubber circuits for the IGBT transistor and the GTO thyristor have been considered in chapter 7. These snubber circuits modify the device *I-V* switching trajectory and in so doing reduce the device transient losses. Snubber circuit action involves temporary energy stored in either an inductor or capacitor. In resetting these passive components it is usual to dissipate the stored energy in a resistor as heat. At high frequencies these losses may become a limiting factor because of the difficulties associated with equipment cooling. Instead of dissipating the switching-aid circuit stored energy, it may be viable to recover the energy either back into the supply or into the load. Two classifications of energy recovery circuits exist, either passive or active. A passive recovery circuit involves only passive components such as *L* and *C* while active recovery techniques involve switching devices, as in a switched-mode power supply.

9.1 Energy recovery for turn-on snubber circuits

Figure 9.1 shows the conventional turn-on snubber circuit for a simple IGBT transistor switching circuit. Equally the switch may be a GTO thyristor or a GCT, for which an inductive turn-on snubber is mandatory.
At switch turn-on the snubber inductance controls the rate of rise of current as the collector voltage falls to zero. The switch turns on without the stressful condition of simultaneous maximum voltage and current being experienced. At turn-off the inductor current is diverted through the diode and resistor network and the stored inductor energy $\frac{1}{2}LI^2$ is dissipated in the resistance of the *L-R-D* circuit as heat. The power loss is determined by the switching frequency and is given by $\frac{1}{2}LI^2f_s$. Full design and operational aspects have been considered in section 8.3.3.

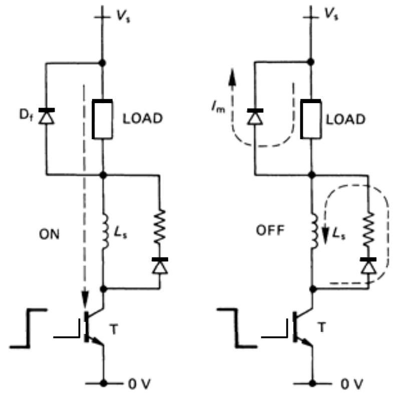

Figure 9.1. *Conventional inductive turn-on snubber principal currents at: (a) turn-on and (b) turn-off.*

9.1.1 *Passive recovery*

Figure 9.2 shows a simple passive technique for recovering the turn-on snubber stored energy back into the supply. The inductor is bifilar-wound with a catch winding. The primary winding is designed to give the required inductance based on core dimensions, properties, and number of turns. At switch turn-off the current in the coupled inductor primary is diverted to the secondary so as to maintain core flux. The windings are arranged so that the transferred current flows back into the supply via a diode which prevents reverse current flow.
The operating principles of this turn-on snubber recovery scheme are simple but a number of important circuit characteristics are exhibited. Let the coupled inductor have a primary-to-secondary turns ratio of 1*:N*. At turn-off the catch winding conducts and is thereby clamped to the supply rail V_s. The primary winding therefore has an induced voltage specified by the turns ratio. That is

$$V_{\ell p} = \tfrac{1}{N} V_s \qquad \text{(V)} \qquad (9.1)$$

The switch collector voltage at turn-off is increased by this component, to

$$V_c = \left(1 + \tfrac{1}{N}\right) V_s \qquad \text{(V)} \qquad (9.2)$$

The turns ratio *N* should be large so as to minimise the switch voltage rating.

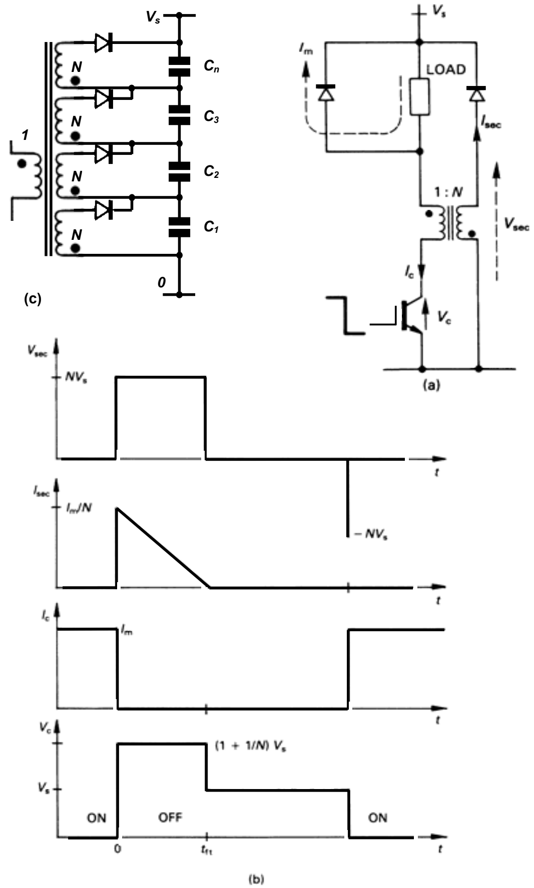

Figure 9.2. *Turn-on snubber with snubber energy recovery via a catch winding: (a) circuit diagram; (b) circuit waveforms; and (c) multilevel recovery.*

At turn-on the inductor supports the full rail voltage and, by transformer action, the induced secondary voltage is NV_s. The reverse-blocking voltage seen by the secondary blocking diode is

$$V_c = (1+N)V_s \quad \text{(V)} \qquad (9.3)$$

Thus by decreasing the switch voltage requirement with large *N*, the blocking diode reverse voltage rating is increased, and vice versa when *N* is decreased.

One further design compromise involving the turns ratio is necessary. The higher the effective pull-down voltage, the quicker the stored energy is returned to the supply. The secondary voltage during the recovery is fixed at V_s; hence from $v = L\,di/dt$ the current will decrease linearly from I_m/N to zero in time t_{fi}. By equating the magnetically stored energy with the energy pumped back to the rail

$$½L_p I_m^2 = V_s \frac{I_m}{N} ½t_{fi} \quad \text{(J)} \qquad (9.4)$$

the core reset time, that is the time for the core energy to be returned to the supply, is given by

$$t_{fi} = L_p \frac{I_m}{V_s} N \quad \text{(s)} \qquad (9.5)$$

Thus the lower the turns ratio *N*, the shorter the core reset time and the higher the upper switching frequency limit. This analysis assumes that the collector current fall time is short compared with the core reset time.

Primary leakage inductance results in a small portion of the core stored energy remaining at turn-off. This energy, in the form of primary current, can usually be absorbed by the turn-off snubber circuit across the switch.

Figure 11.2c shows a recovery arrangement with multiple secondary windings, for a multilevel inverter. The reflected voltage, $(1+N/n)\,V_s$, on to the switch is significantly reduced as the number of secondary windings, *n*, increases. Auto balancing and regulation of the capacitor voltages is achieved since only the lowest charged capacitor has energy transferred to it.

9.1.2 Active recovery

Figure 9.3 shows an inductive turn-on snubber energy recovery scheme which utilises a switched-mode power supply (smps) based on the boost converter in 15.4, as shown in figure 9.4a.

At switch turn-off the energy stored in the snubber inductor L_s is transferred to the storage capacitor *C* via the blocking diode, D_b. The smps is then used to convert the relatively low capacitor voltage into a higher voltage suitable for feeding energy back into a supply. The capacitor charging rate is dependent on load current magnitude. The smps can be controlled so as to maintain the capacitor voltage constant, thereby fixing the maximum switch collector off-state voltage, or varied with current so as to maintain a constant snubber inductor reset time. One smps and storage capacitor can be utilised by a number of switching circuits, each with a blocking diode as indicated in figure 9.3. The diode and switch are rated at V_s+V_{Co}.

If the load and turn-on snubber are re-arranged to be in the cathode circuit, then the smps in figure 9.4b can be used to recover the snubber energy from capacitor C_o.

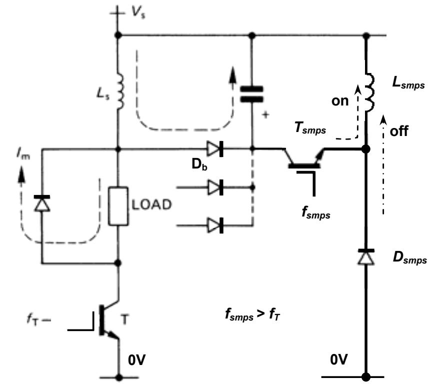

Figure 9.3. *Turn-on snubber with active snubber inductor energy recovery.*

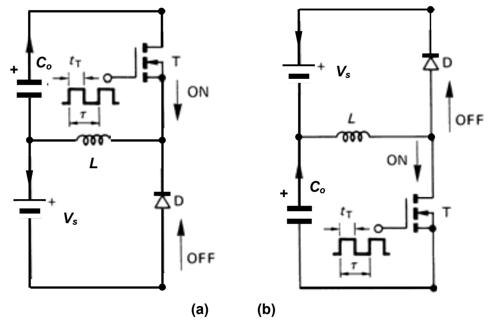

Figure 9.4. *Underlying energy recovery circuits for when energy in C_o is stored: (a) above V_s and (b) below 0V.*

9.2 Energy recovery for turn-off snubber circuits

Figure 9.5 shows the conventional turn-off snubber circuit used with both the GTO thyristor and the IGBT transistor. At turn-off, collector current is diverted into the snubber capacitor *C* via D. The switch turns off clamped to the capacitor voltage which increases quadratically from zero. At the subsequent switch turn-on the energy stored in *C,* $\frac{1}{2}CV_s^2$ is dissipated as heat, mainly in the resistor *R*. A full functional description and design procedure for the turn-off snubber circuit is to be found in section 8.3.1.

At high voltages and switching frequencies, with slow switching devices, snubber losses $(\frac{1}{2}CV_s^2 f_s)$ may be too high to be dissipated easily. An alternative is to recover this energy, using either passive or active recovery techniques.

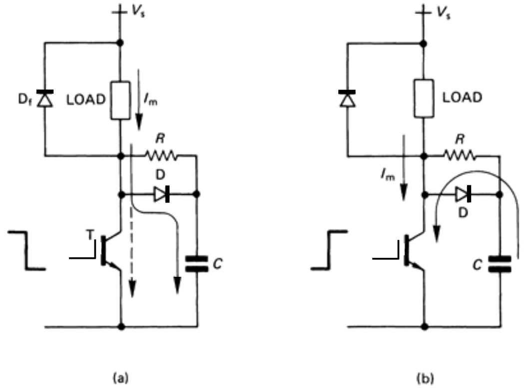

Figure 9.5. *Conventional capacitive turn-off snubber showing currents at: (a) turn-off and (b) IGBT transistor turn-on.*

9.2.1 Passive recovery

Figure 9.6 illustrates a passive, lossless, turn-off snubber energy recovery scheme which dumps the snubber energy, $\frac{1}{2}CV_s^2 f_s$, into the load. The turn-off protection is that of the conventional capacitive snubber circuit. At turn-off the snubber capacitor C_s charges to the voltage rail V_s as shown in figure 9.7a.

At subsequent switch turn-on, the load current diverts from the freewheeling diode to the switch. Simultaneously the snubber capacitor resonates its charge to capacitor C_o through the path shown in figure 9.7b.

When the switch next turns off, the snubber capacitor C_s charges and the capacitor C_o discharges into the load. When C_o is discharged the freewheeling diode conducts. During turn-off C_o and C_s act effectively in parallel across the switching device.

A convenient starting point for the analysis of the recovery scheme is at switch turn-on when snubber energy is transferred from C_s to C_o. The active portions of figure 9.7b are shown in figure 9.8a.

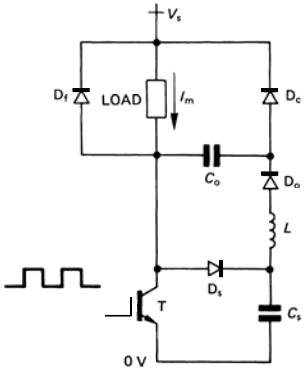

Figure 9.6. *A capacitive turn-off snubber with passive capacitor energy recovery into the load.*

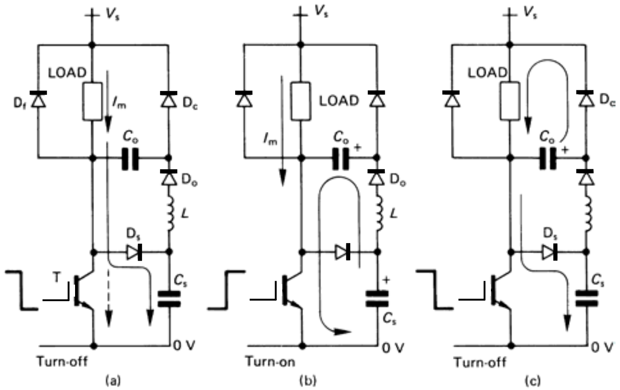

Figure 9.7. *Energy recovery turn-off snubber showing the energy recovery stages: (a) conventional snubber action at turn-off; (b) intermediate energy transfer at subsequent switch turn-on; and (c) transferred energy dumped into the load at subsequent switch turn-off.*

Analysis of the *L-C* resonant circuit with the initial conditions shown yields the following capacitor voltage and current equations. The resonant current is given by

$$i(\omega t) = \frac{V_s}{Z}\sin\omega t \quad \text{(A)} \qquad (9.6)$$

where
$$Z = \omega L = Z_o\sqrt{1 + 1/n} \quad \text{(ohms)}$$
$$\omega = \omega_o\sqrt{1 + 1/n} \quad \text{(rad/s)}$$
$$\omega_o = 1/\sqrt{LC_o} \quad \text{(rad/s)}$$
$$n = C_s / C_o$$
$$Z_o = \sqrt{L/C_o} \quad \text{(ohms)}$$

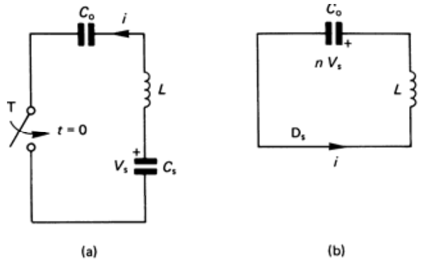

Figure 9.8. *Equivalent circuit for the intermediate energy transfer phase of snubber energy recover, occurring via: (a) the main switch T and (b) then via the snubber diode D_s.*

The snubber capacitor voltage decreases according to

$$V_{Cs} = V_s\left\{1 - \frac{1}{1+n}\cos\omega t\right\} \quad \text{(V)} \qquad (9.7)$$

while the transfer capacitor voltage charges according to

$$V_{Co} = V_s\frac{n}{1+n}\left(1 + \cos\omega t\right) \quad \text{(V)} \qquad (9.8)$$

Examination of equation (9.7) shows that if $n > 1$, the final snubber capacitor voltage at $\omega t = \pi$ will be positive. It is required that C_s retains no charge, ready for subsequent switch turn-off; thus $n \le 1$, that is $C_o \ge C_s$. If C_o is greater than C_s equation (9.7) predicts C_s will retain a negative voltage. Within the practical circuit of figure 9.6, C_s will be clamped to zero volts by diode D_s conducting and allowing the stored energy in L to be transferred to C_o. The new equivalent circuit for $\omega t = \cos^{-1}(-n)$ is shown in figure 9.8b. The resonant current is given by

$$i(\omega t) = \frac{V_s}{Z}\sin\left(\omega_o t + \phi\right) \quad \text{(A)} \qquad (9.9)$$

where $t \ge 0$ and $\phi = -\tan^{-1}\sqrt{\frac{1-n^2}{n}}$.

The final voltage on C_o is $\sqrt{n}\,V_s$ and C_s retains no charge. The voltage and current waveforms for the resonant energy transfer stage are shown in figure 9.9.

Energy dumping from C_o into the load and snubber action occur in parallel and commence when the switch is turned off. As the collector current falls to zero in time t_{fi} a number of serial phases occur. These phases, depicted by capacitor voltage and current waveforms, are shown in figure 9.10.

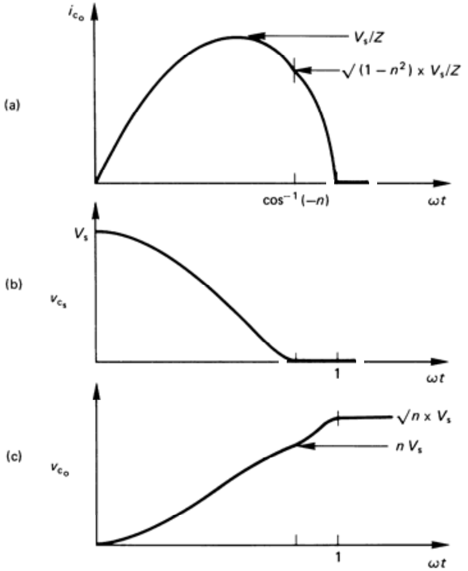

Figure 9.9. *Circuit waveforms during intermediate energy transfer phase of snubber energy recovery: (a) transfer capacitor C_0 current; (b) snubber capacitor voltage; and (c) transfer capacitor voltage.*

Phase one

Capacitor C_o is charged to $\sqrt{n}\,V_s$, so until the snubber capacitor C_s charges to $\left(1-\sqrt{n}\right)V_s$, C_o takes no part. Conventional snubber turn-off action occurs as discussed in section 8.3.1. The snubber capacitor voltage increases according to

$$V_{Cs} = \tfrac{1}{2}\frac{I_m}{C_s t_{fi}} t^2 \qquad \text{(V)} \qquad (9.10)$$

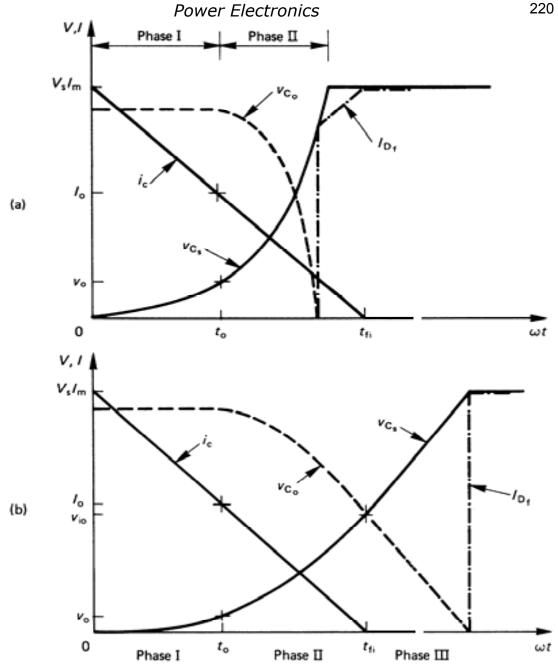

Figure 9.10. *Circuit waveforms at switch turn-off with turn-off snubber energy recovery when: (a) the snubber C_s is fully charged before the switch current at turn-off reaches zero and (b) the switch collector current has fallen to zero before the snubber capacitor has charged to the rail voltage.*

while C_o remains charged with a constant voltage of $\sqrt{n}\,V_s$. This first phase is complete at t_o when

$$V_{Cs} = v_o = \tfrac{1}{2}\frac{I_m t_o^2}{C_s t_{fi}} = \left(1-\sqrt{n}\right)V_s \qquad \text{(V)} \qquad (9.11)$$

whence

$$t_o = \sqrt{\frac{2\left(1-\sqrt{n}V_s C_s t_{fi}\right)}{I_m}} \qquad \text{(s)} \qquad (9.12)$$

and the collector current

$$I_o = \mathrm{I_m}\left(1 - {}^{t_o}\!/_{t_{fi}}\right) \qquad \text{(A)} \qquad (9.13)$$

Phase two

When C_s charges to $\left(1-\sqrt{n}\right)V_s$, the capacitor C_o begins to discharge into the load. The equivalent circuit is shown in figure 9.11a, where the load current is assumed constant while the collector current fall is assumed linear. The following conditions must be satisfied

$$V_s = V_{Cs} + V_{Co} \qquad \text{(V)} \qquad (9.14)$$

$$I_m = i_{Co} + i_{Cs} + I_o(1 - t/t_{fi}) \qquad \text{(A)} \qquad (9.15)$$

for $0 \le t \le t_{fi} - t_o$

Under these conditions, the snubber capacitor voltage increases according to

$$V_{Cs} = \frac{n}{1+n}\frac{1}{C_s}\left[\left(I_m - I_o\right)t + ½t^2/t_o\right] + \left(1-\sqrt{n}\right)V_s \qquad \text{(V)} \qquad (9.16)$$

with a current

$$i_{Cs} = \frac{1}{1+n}\left\{I_m - I_o(1 - t/t_o)\right\} \qquad \text{(A)} \qquad (9.17)$$

The transfer dump capacitor C_o discharges with a current given by

$$i_{Co} = i_{Cs}/n \qquad (9.18)$$

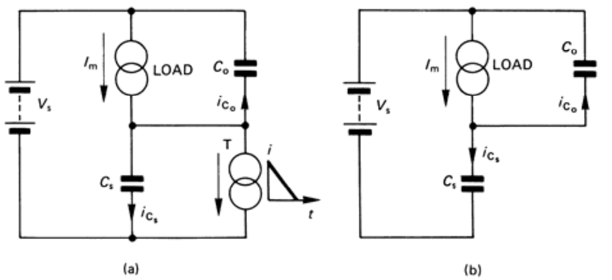

Figure 9.11. *Turn-off snubber equivalent circuit during energy recovery into the load when: (a) C_o begins to conduct and (b) after the switch has turned off.*

Phase three

If the snubber capacitor has not charged to the supply rail voltage before the switch collector current has reached zero, phase three will occur as shown in figure 9.10b. The equivalent circuit to be analysed is shown in figure 9.11b. The Kirchhoff equations describing this phase are similar to equations (9.14) and (9.15) except that in equation (9.15) the component $I_o(1 - t/t_0)$ is zero.

The capacitor C_s, charging current is given by

$$i_{Cs} = \frac{n}{1+n}I_m \qquad \text{(A)} \qquad (9.19)$$

while the dumping capacitor C_o current is

$$i_{Co} = i_{Cs}/n \qquad \text{(A)} \qquad (9.20)$$

The snubber capacitor charges linearly, according to

$$V_{Cs} = v_{io} + \frac{n}{1+n}\frac{I_m}{C_s}t \qquad \text{(V)} \qquad (9.21)$$

When C_s is charged to the rail voltage V_s, C_o is discharged and the load freewheeling diode conducts the full load current I_m.
Since the snubber capacitor energy is recovered there is no energy loss penalty for using a large snubber capacitance and the larger the capacitance, the lower the switch turn-off switching loss. The energy to be recovered into the load is fixed, $½C_sV_s^2$ and at low load current levels the long discharge time of C_o may inhibit proper snubber circuit action. This is generally not critical since switching losses are small at low load current levels.

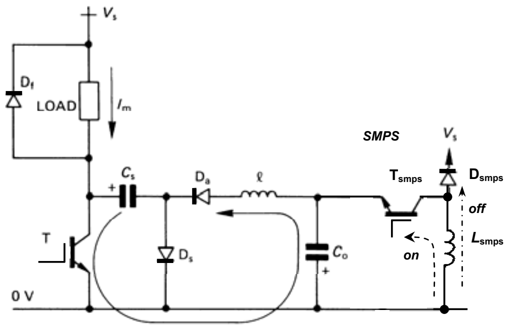

Figure 9.12. *Switching circuit for recovering turn-off snubber capacitor energy, and for providing either a negative voltage rail or transferring to V_s, via an smps.*

9.2.2 Active recovery

Active energy recovery methods for the turn-off snubber are simpler than the technique needed for active recovery of turn-on snubber circuit stored energy. The energy to be recovered from the turn-off snubber is fixed at $½C_sV_s^2$ and is independent of load current. In the case of the turn-on snubber, the energy to be recovered is load current magnitude dependent (αI_L^2) which complicates active recovery.
At turn-on the snubber capacitor stored energy is resonated into a large intermediate storage capacitor C_o as shown in figure 9.12. It is possible to use the energy in C_o as a negative low-voltage rail supply. This passive recovery technique

suffers from the problem that energy $\frac{1}{2}C_sV_s^2$ may represent more energy than the low-voltage supply requires. An smps can convert energy stored in C_o to a more useful voltage level.
It may be noticed that the 'Cuk' converter is in fact the snubber energy recovery circuit in figure 9.12, controlled in a different mode.

9.3 Unified turn-on and turn-off snubber circuit energy recovery

9.3.1 Passive recovery

Conventional turn on and turn off snubber circuits can be incorporated on a switching device as shown in figure 8.20. The stored energy is dissipated as heat in the reset resistor. Figure 9.13 shows turn-on and turn-off snubber circuits which allow energy recovery for both the snubber capacitor and inductor.
The snubber capacitor energy is recovered by the transfer process outlined in section 9.2.1. Figure 9.13a shows the energy transfer paths at switch turn-off. The capacitor C_o and inductor ℓ_s transfer their stored energy to the load in parallel, such that the inductor voltage is clamped to the capacitor voltage V_{Co}.

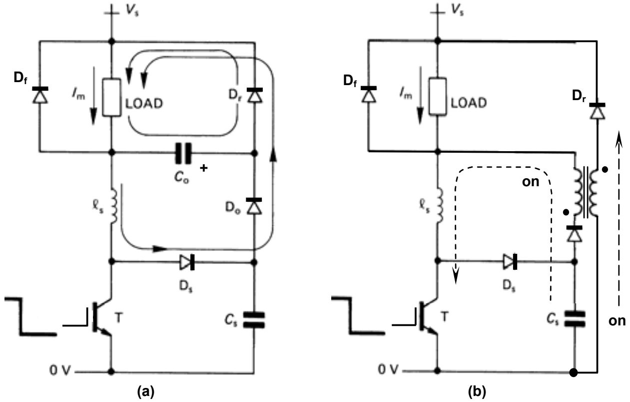

Figure 9.13. *Switching circuits incorporating unified turn-on and turn-off snubber, showing recovery path of energy (a) in C_o and ℓ_s and (b) in C_s and ℓ_s through D_r.*

As C_o discharges, the voltage across ℓ_s decreases to zero, at which time the load freewheel diode conducts. Any remaining inductor energy is dissipated as unwanted heat in circuit resistance. Proper selection of ℓ_s and C_s $(\frac{1}{2}L_sI_m^2 \le \frac{1}{2}C_sV_s^2)$ can minimise the energy that is lost although all the snubber capacitor energy is recovered, neglecting diode and stray resistance losses.

Aspects of the mathematical analysis of this unified recovery circuit are derived in the answer to the problem set at the end of this chapter.
Figure 9.13b shows a dual snubber energy recovery technique where resonance energy is transferred back to the supply at switch turn-on, through a coupled circuit.
Figure 9.14 shows an inverter bridge leg where both switches have turn-on and turn-off snubbers and passive recovery circuits. The circuit also recovers the energy associated with freewheel diode reverse recovery. Both the turn-on energy and turn-off energy are recovered back into the dc supply, V_s. Although this decreases the energy transfer efficiency, recovery into the load gives poor regulation at low load current levels where the capacitor turn-off energy, which is fixed, may exceed the load requirements. Energy recovery involves a coupled circuit which can induce high voltage stresses. Such conditions can be readily avoided if a split capacitor (multilevel) voltage rail is used, as shown in figure 9.2c.

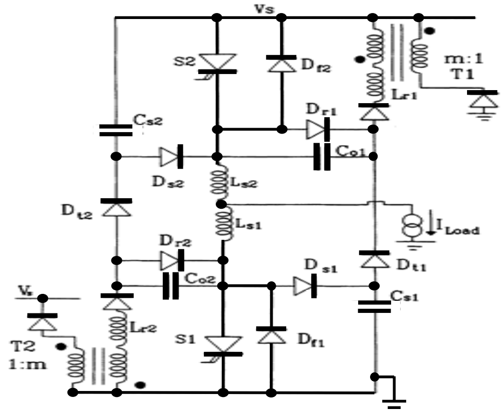

Figure 9.14. *Unified, passive snubber energy recovery circuit for inverter bridge legs.*

9.3.2 Active recovery

Figure 9.15 shows two similar turn-on and turn-off snubber, active energy recovery circuits, which are particularly suitable for bridge leg configurations. In figure 9.15a the turn-on snubber section is similar in operation to that shown in figure 9.3 while the turn-off snubber section is similar in operation to that shown in figure 9.12. A common smps is used for each turn-on and turn-off snubber pair. This arrangement is particularly useful when the two power switches and associated freewheel diodes are available in a single isolated package.

The active recovery circuit in figure 9.15b shows the turn-on snubbers relocated. The smps inputs are cross-coupled, serving the turn-on snubber of one switch and the turn-off snubber of the other switch.
The interaction of turn-off snubbers in both circuits can create high *L-C* resonant currents as discussed in section 8.4. In each case two smps can serve numerous bridge legs. The circuit in figure 9.15a is readily reduced for single-ended operation.

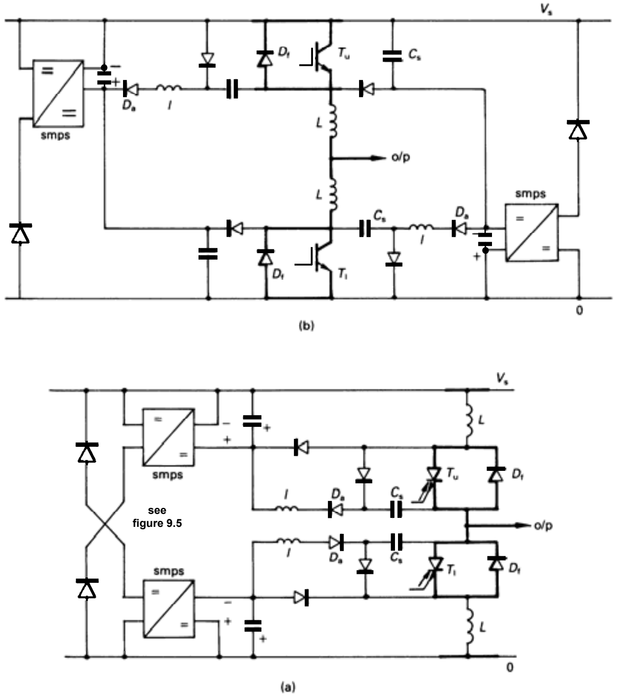

Figure 9.15. *Unified, active snubber energy recovery circuits:*
(a) multiple single-ended circuit and (b) cross-coupled high frequency circuit.

Reading list

Boehringer, A. *et al.,* 'Transistorschatter im Bereich hoher Leistungen und Frequenzen', *ETZ,* Bd. 100 (1979) pp. 664-670.

Peter, J. M., *The Power Transistor in its Environment,* Thomson-CSF, Sescosem, 1978.

Williams, B. W., *et al*., (2000) 'Passive snubber energy recovery for a GTO thyristor inverter bridge leg', *Trans. IE lEEE,* Vol. 47, No. 1, Feb. (2000) pp. 2-8.

Problems

9.1. Derive expressions for the snubber capacitor C_s and transfer capacitor C_o voltage and currents at switch turn-off for the unified snubber circuit energy recovery scheme shown in figure 9.13. The energy transfer process from C_s to C_o at switch turn-on is identical to that in the recovery scheme shown in figure 9.6 and analysed in section 9.2.1.
During recovery, the inductor current is of the form

$$i_1 = a - bt + c\sin(\omega t + \phi)$$

9.2. For the circuit in Figure 9.13a show that the upper current limit for total energy recovery is given by $\frac{1}{2} L_s I_m^2 \le \frac{1}{2} C_s V_s^2$.

9.3. Derive capacitor C_s voltage and current equations which describe the operation of the turn-off snubber energy recovery circuit in figure 9.12. Assume the storage capacitor C_o to be an ideal voltage source with polarity as shown.