

Snubber Circuits: Theory, Design and Application

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Introduction

Snubbers are an essential part of power electronics. Snubbers are small networks of parts in the power switching circuits whose function is to control the effects of circuit reactances.

Snubbers enhance the performance of the switching circuits and result in higher reliability, higher efficiency, higher switching frequency, smaller size, lower weight, and lower EMI. The basic intent of a snubber is to absorb energy from the reactive elements in the circuit. The benefits of this may include circuit damping, controlling the rate of change of voltage or current, or clamping voltage overshoot. In performing these functions a snubber limits the amount of stress which the switch must endure and this increases the reliability of the switch. When a snubber is properly designed and implemented the switch will have lower average power dissipation, much lower peak power dissipation, lower peak operating voltage and lower peak operating current. This article describes some of the various types of snubbers, where they are used, how they function, how they are designed and what their limitations are.

Snubbers may be either passive or active networks. This article is limited to the main types of passive snubbers. Passive snubber network elements are limited to resistors, capacitors, inductors and diodes. Active snubbers include transistors or other active switches, often entail a significant amount of extra circuitry and introduce another level of parasitics which must be dealt with (usually with a passive snubber). However, active snubbers are appropriate in some applications. A good example of an active snub is what you would like to say to your boss when he or she decides not to give you a raise.

Passive Snubber Types

The basic function of a snubber is to absorb energy from the reactances in the power circuit. The first classification of snubber circuits is whether they absorb energy in controlling a voltage or a current. A capacitor placed in parallel with other circuit elements will control the voltage across those elements. An inductor placed in series with other circuit elements will control the current through those elements. Figure 1 shows this concept. A voltage snubber (Fig. 1a) has energy storage capacitors in it and a current snubber (Fig. 1b) has inductors for energy storage. The networks associated with the inductor and capacitor shown in Figure 1 determine how energy is passed to the storage element and how the energy is removed from it.

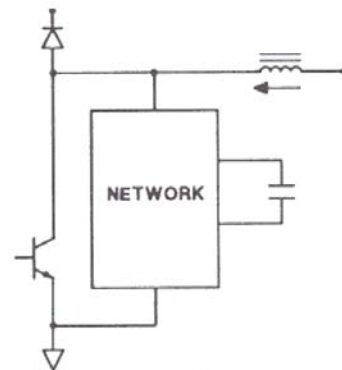


Fig. 1a

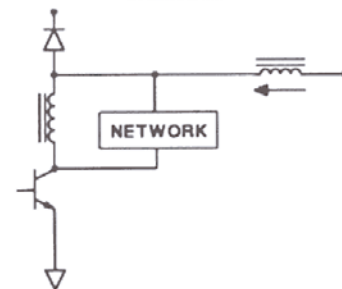


Fig. 1b

All of the other classifications of snubbers relate to the ways in which the energy is transferred to and from the snubber. If the energy stored in the snubber is dissipated in a resistor the snubber is classed as dissipative but if the energy is moved back to the input or ahead to the output the snubber is classed as non-dissipative even though there may be some small losses. A snubber is classed as polarized or non-polarized depending on

whether energy moves in or out of the snubber on one edge of the switching waveform or both. The last classification for snubber circuits is rate of rise of voltage or voltage clamping. Current snubbers are all rate of rise control types as there is no passive current limiting device available yet. Voltage snubbers may clamp a voltage to a fixed or variable level or may control the dV/dt of the voltage.

Snubbers are often used in combinations and a given application may have two or three snubbers merged into one network to control both the current and voltage of the switch.

Table 1 is an applications guide and it gives a breakdown of the basic snubber types and their uses. The simple damping snubbers are dissipative by definition. Rate of rise control and voltage clamp snubbers may be either dissipative or non-dissipative. Non-dissipative snubbers are more complex than dissipative snubbers but this complexity is justified when the power dissipation is too high or the efficiency is too low.

Table I - QUICK GUIDE TO SNUBBER CIRCUIT USAGE

RATE OF RISE CONTROL SNUBBERS

Voltage

- reduce power dissipation and stress in switch at turn-off
- prevent overshoot and ringing by not exciting resonance
- reduce EMI by reducing high frequency noise

Current

- reduce power dissipation and stress in switch at turn-on
- reduce diode reverse recovery current

VOLTAGE CLAMP

- reduce peak switch voltage
- reduce peak switch power dissipation at turn-off
- reduce ringing at switch turn-off

DAMPING

Voltage

- reduce overshoot and ringing at switch turn-off
- reduce switch power dissipation
- reduce EMI

Current

- reduce overshoot and ringing at switch turn-on
- reduce power dissipation in switch
- reduce EMI

Rate of rise control snubbers and voltage clamp snubbers may be either dissipative or non-dissipative. Non-dissipative snubbers reduce the power dissipation of the snubber and increase the efficiency of the system.

Table 2 is an index to the snubber circuits described in this article and gives the page number that the description of that snubber begins on.

Duality in Snubber Operation

Snubbers have a duality which is a drawback in some applications. A snubber which controls the switch voltage at turn off will create a current pulse in the switch at turn on. A snubber which controls the switch current at turn on will create a voltage pulse across the switch at turn off.

Converters with alternating switches, such as a push-pull converter, with a voltage snubber on one switch to control the voltage at turn off will have a current spike in the other switch when it turns on. The same is true for snubbers on the output diodes of a converter. Some diodes are driven off by the switches and others are driven on so if a snubber is not properly designed it will present a low impedance to the switches when they are turning on and result in a large current spike.

Snubber Fundamentals

Each snubber in this discussion will be shown in an example circuit which is as generic as possible. Figure 2 shows the basic buck, boost and flyback converter circuits drawn so that the switch is always grounded. The figures which follow will generally show a snubber in relation to a generic grounded switch so Figure 2 may be used to apply the snubber to most other topologies. In this approach the switch and the snubber may be thought of as a single unit, a snubbed switch, which may be used

Table II - INDEX TO SNUBBER CIRCUITS

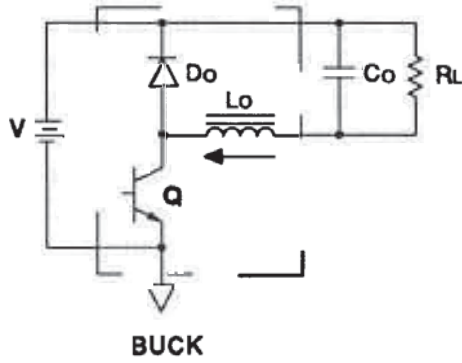
Dissipative Snubbers	3
Simple RC Voltage Snubber	3
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Two Terminal 3D-2C-1L Voltage Snubber	10
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in almost any switching regulator topology.

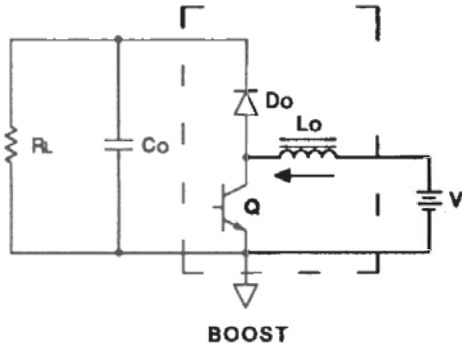
Not all snubbers are applicable to a particular problem. The circuits in Figure 2 are all clamped inductive loads and these circuits do not need voltage clamp snubbers since that function is inherent in the topology. The snubbers which are appropriate in these topologies are voltage and current rate of rise control snubbers.

Controlling the rate of rise of voltage and current and clamping the voltage and controlling resonances reduces the stress on the switch. Snubbers can control the voltage and current to the point where switching occurs at zero voltage and zero current and this raises the reliability of the power stage significantly. Taken to the extreme, zero voltage and current switching becomes resonant power conversion. This becomes necessary when the circuit parasitics become large relative to the power level. High voltage outputs are one example. In most cases, however, the optimum efficiency level is reached with small snubbers long before a full resonant approach is necessary.

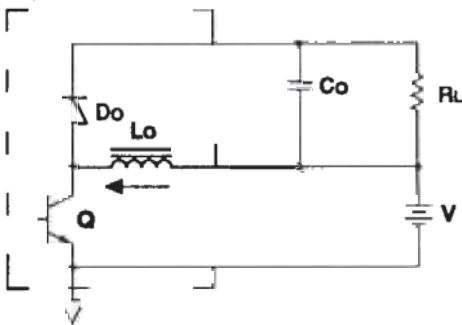
The effect of a snubber on the switch may be viewed as changing, or shaping, the load line on the



BUCK



BOOST



FLYBACK

Fig 2a, b, c

switch for a particular purpose. An inductor in series with the switch, a current snubber, presents the switch with an inductive load at turn-on so that it switches on with zero current. This is a modification of the load which would typically be somewhat capacitive at turn-on. The same is true at turn-off with a voltage snubber. At turn-off the load on the switch will typically look inductive so a capacitor in shunt with the switch, a voltage snubber, will change the load line to be capacitive so that the switch can turn off at zero voltage.

Dissipative Voltage Snubbers

Dissipative snubbers are those which dissipate the energy they absorb in a resistor. Dissipative snubbers may be either voltage or current snubbers and may be either polarized or non-polarized. Dissipative snubbers may be designed to control the rate of rise of voltage or current or be designed to clamp the voltage.

Simple RC Voltage Snubber: The simple RC snubber shown in Figure 3A provides damping of the parasitic resonances in the power stage and is probably the most widely used of all snubber circuits. It is used on output inductors and the secondaries of transformers as well as across diodes and switches. It is applicable both to rate of rise control and to damping. The simple RC snubber is one of few snubbers which is effective in the classic push-pull switch configuration.

Figure 3B shows the RC snubber applied to the generic switch circuit. As discussed above the generic switch circuit is a clamped inductive load so in the idealized form shown here there are no parasitic resonances to damp. In this case the RC snubber may be used to reduce the peak power dissipation in the switch. If the values of R and C are chosen correctly the switching losses can be reduced by up to 40% including both the loss in the switch and the loss in the resistor over the complete switching cycle[1].

The main application of an RC snubber is damping the resonance of parasitic elements in the power circuit. In applications where damping is required the value of the resistor must be close to the impedance of the parasitic resonance which it is intended to damp. The snubber capacitance must be

larger than the resonant circuit capacitance but must be small enough so that the power dissipation of the resistor is kept to a minimum. The power dissipation in the resistor increases with the value of capacitance.

Figure 3C shows an application which has an extra unclamped inductance. This could be leakage inductance in an isolated flyback converter, a forward converter or a push-pull converter. It might also be the inductance from a current snubber. In these cases there is an unclamped inductance and a resonating capacitance, the switch output capacitance. When the switch turns off, the energy stored in the inductance will ring with the capacitance if there is no snubber. For simplicity we assume the switch withstands the extra voltage. There is typically very little loss in a parasitic resonant circuit so many cycles of ringing normally occur.

The RC snubber will damp the ringing and if the snubber resistance is equal to the characteristic impedance of the resonant circuit $[(L/C)^{1/2}]$ then the resonant circuit will be critically damped and have no overshoot. The capacitor in series with the resistor must be larger than the circuit parasitic capacitance to reduce overshoot and ringing.

The value of the capacitor and resistor can often be estimated from the other circuit components. The dominant circuit capacitance is the output capacitance of the switching transistor and its value can be obtained from the data sheet. The snubber capacitance will generally be two to four times this value. The snubber resistor value can be estimated

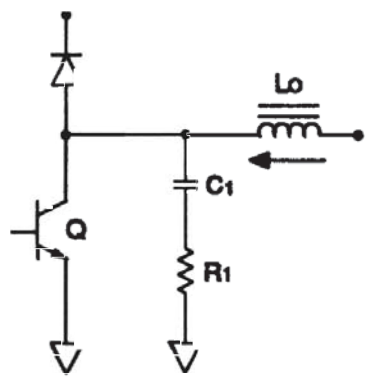
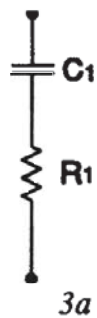


Fig 3b

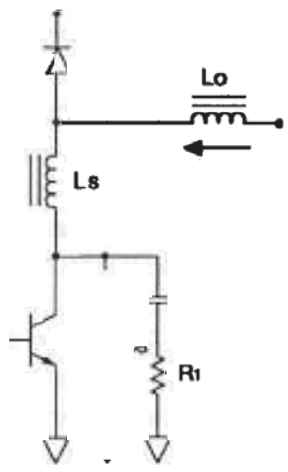


Fig. 3c

if the impedance of the parasitic resonant circuit is known. The value of inductance is usually the leakage inductance of the transformer and can be estimated with some effort. The resistor value is set equal to the resulting characteristic impedance.

It is always good practice to estimate the values needed first since a calculated value which is grossly in error indicates that either the circuit is not built as designed or was not designed as built.

Once the circuit has been built and is operating, the values of the snubber components may be optimized experimentally. Start with a small value of capacitor and place it in the circuit in the snubber position, often this is directly across the switch, and then observe the voltage waveform with and without the capacitor in the circuit. Increase the value of the capacitor until the frequency of the ringing to be damped has been halved. At this point the circuit capacitance is four times the original value so the additional capacitance is three times the original circuit value. This is a near optimum value for the capacitor since it allows damping very near $Q = 1$. The circuit inductance may be calculated from the two resonant frequencies and the two values of capacitance. The characteristic impedance of the parasitic resonant circuit may be calculated from the original circuit capacitance and the inductance and the value of the snubber resistance is equal to this impedance. These calculated values of resistance and capacitance may be added to the circuit to form the snubber.

Example: Assume that the primary of a forward converter transformer has an unclamped leakage inductance of 2 μ H and the power mosfet has an output capacitance of 330 pF. One ampere flowing in the switch at turn off will produce a voltage spike of 78 volts above V_{cc} if there is no damping in the circuit. The ringing frequency will be 6.2 MHz. The characteristic impedance of the LC tank is 78 ohms. If a 1000pF capacitor is added in parallel with the switch the ringing frequency will decrease to 3.1 MHz. If 78 ohms are added in series with the new capacitor the ringing will disappear.

Power Dissipation of Simple RC Voltage Snubber: The power dissipation of the resistor must be found also. Finding an exact expression for the power dissipation is a mathematically difficult task but it may be estimated. The assumption is that the time constant of the snubber ($t=RC$) is short compared to the switching period but is long compared to the voltage rise time. If the time constant is on the same order as the rise time the power dissipation estimate will be too high. If the time constant is too long the equations are not valid and the estimated power will again be too high.

The capacitor in a snubber stores energy. In a simple RC snubber the capacitor charges and discharges. By the principle of conservation of charge an amount of energy equal to that stored will be dissipated for each charge and discharge cycle. This amount of power dissipation is independent of the value of the resistor. The power dissipation may be calculated from the capacitance, the charging voltage and the switching frequency. The equation evolves as follows:

$$P = 2f(\frac{1}{2} C V^2) = f C V^2$$

Where P is the power dissipation, F is the switch frequency, C is the value of the snubber capacitor and V is the voltage that the capacitor charges to on each switching transition. This is a handy equation and is quite useful when designing the power circuit. The dominant value of capacitance is usually the switch output capacitance so three times that is the snubber capacitance. The voltage that the capacitor charges to is generally known so the maximum power dissipation of the snubber resistor can be calculated. This allows the selection of a resistor wattage which will not flame at the first application of power. Note that the frequency chosen is the switch frequency. In some single ended converters the output frequency is half of the clock frequency. In a push-pull converter the switch frequency will be equal to the clock frequency.

It is also possible to calculate a minimum power dissipation which is based on the average current through the snubber resistor. The actual dissipation will be greater than this. The equation is derived from averaging the absolute value of the charge and discharge currents over the time period. The current

may be found from the capacitance and the voltage.

$$= \Delta Q \cdot 2f \text{ and } \Delta Q = CV \text{ so } = 2CVf$$

and

$$P = I^2R, \text{ so } P = 4C^2V^2f^2R$$

This calculation is especially useful when the time constant of the snubber is on the order of the rise time of the voltage. In that case the power dissipation will be at least equal to the I^2R loss calculated above.

Example: The inductance is 2 μ H and the capacitance is 330pF as above. The snubber capacitor is 1000pF and the resistor is 78 ohms. The voltage across the switch is 400V and the switching frequency is 100KHz. The power dissipation will be 16.0 watts. The resistor selected must be non-inductive since it must handle very high frequencies. In general, even a non-inductive wire wound resistor will have too much inductance to be effective. The minimum power dissipation will be 0.5 watts.

Polarized Voltage Snubbers

The objective of a polarized voltage snubber is different from that of a non-polarized snubber. The polarized voltage snubber does not necessarily provide damping since is disconnected from the circuit over much of the cycle. Its main functions are rate of rise control or clamping.

The RCD Voltage Snubber: The circuit in Figure 4A applicable to either rate of rise control or clamping. The circuit variation shown in Figure 4B is applicable only to the clamp operation.

A typical application of a resistor-capacitor-diode snubber is to control the rate of rise of voltage on the drain or collector of a switching transistor in a forward, flyback or boost converter. At turn-off, the snubber will carry a major portion of the switch current (if not all of it) and this transfers the power dissipation of the switch into the snubber. The reliability of the switch increases since its peak power dissipation is reduced and the controlled rate of rise of voltage also lowers the high frequency EMI which the uncontrolled switching generates.

When the resistor-capacitor-diode snubber is used to control the rate of rise of voltage, the RC time constant must be short compared to the switching

frequency because the capacitor must be charged and discharged on each cycle. The circuit in Figure 4C shows how the snubber would be connected in the generic switch circuit. When the switch turns off, the current from the inductor is diverted through the snubber diode to the snubber capacitor until the capacitor is charged to the rail voltage and the main diode turns on to carry the inductor current. The snubber is active only during the switching transition. When the switch turns on the snubber capacitor is discharged through the resistor and the switch. It must be almost fully discharged on each cycle to control the rate of rise of voltage on the switch.

The design of the snubber begins with the choice of the rise time at maximum inductor current and the supply voltage or the peak voltage the capacitor will charge to. The relationship between the voltage and current in a capacitor allows the calculation of the necessary capacitor value.

$$I = C \Delta V / \Delta t$$

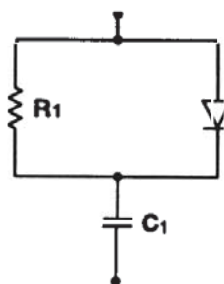


Fig 4a

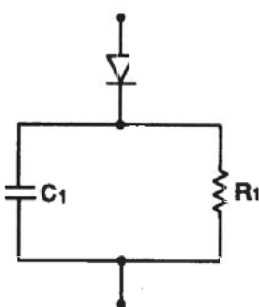


Fig 4b

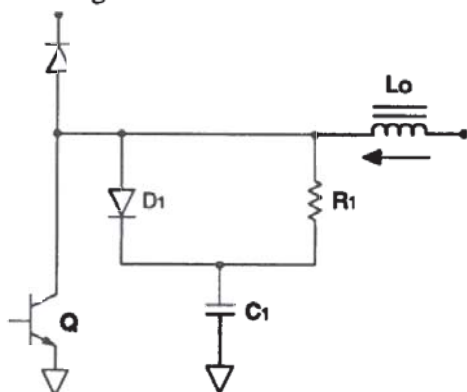


Fig 4c

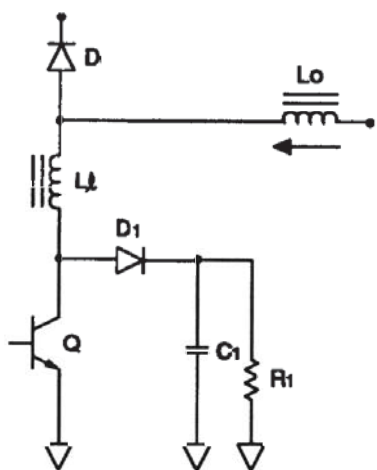


Fig 4d

Where I is the maximum peak switch current, ΔV is the peak voltage the capacitor will charge to, Δt is the rise time of the voltage and C is the value of the capacitor. The resistor is then chosen to have a time constant which is small compared to the switching period. A typical value for the time constant would be one tenth of the switch maximum on time.

The power dissipation of the resistor is determined by the size of the capacitor since the time constant is short compared to the switching period. All of the energy stored in the capacitor is dissipated on each cycle but there is only one transition (the capacitor discharge) so the power dissipated by the resistor is given by:

$$P = \frac{1}{2} C V^2 f$$

Where P is the power dissipated, C is the capacitance value, V is the peak voltage the capacitor charges to, and F is the number of discharge cycles per second. Again, note that the power dissipated by the resistor is independent of its value as long as the time constant is short compared to the switching period. If the time constant is longer than this, the snubber is functioning in a different mode and different equations apply.

A point to keep in mind about this kind of snubber is that when the switch turns on, the current which is discharging the snubber is flowing through the switch. This current will add to the spike on the leading edge of the current waveform. Another point is that the discharge is sensitive to the pulse width. If the pulse width becomes very narrow, the capacitor will not be fully discharged. This usually happens only during an overcurrent condition. When this happens the peak stress on the switch will go way up but the average power dissipation on the switch is generally reasonable because the duty factor is quite low.

Example: The switch current is 1.0 amps and the maximum voltage is 400v. The voltage rise time is to be 400ns. The capacitance necessary is 1000pF. The time constant to discharge the capacitance is chosen to be 500ns, which is compatible with a 100KHz switching frequency. The discharge resistor value is 500 ohms. The power dissipated in

the resistor is 8.0 watts. A wire wound resistor may be used in this case since the time constant is relatively long and the self inductance of the resistor will not be important.

The RCD Voltage Snubber in Clamp Mode: The purpose of a resistor-capacitor-diode (RCD) snubber used in clamp mode is different from one used in the rate of rise mode. In clamp mode the objective is to keep the switch from exceeding some maximum voltage. The switch itself will have to sustain the peak power dissipation of turning off. Only the peak voltage will be limited. The prime characteristic of the snubber which distinguishes the clamp mode from the rate of rise mode is the RC time constant which is much longer than the switching period in the clamp mode.

The circuit shown in Figure 4A and 4C will work for clamp mode but the clamp level will be a function of the duty factor since the discharge time, which is long compared to the switch on time, changes as a function of duty factor. To remove the same amount of charge on each switching cycle with a fixed resistance the clamp voltage must change with the duty factor. The clamp voltage will be high when the duty factor is small and low when the duty factor is large. This is normal for this topology but is not always desirable.

The circuit variation shown in Figure 4B and 4D is a better choice for the clamp mode RCD snubber. It cannot be used for rate of rise control since there is a DC path through the snubber. To function properly the resistor value must be large. As shown in Figure 4D the clamp mode RCD snubber has the resistor going to ground but it is often used where the voltage to be clamped goes above the DC bus and then the resistor may be returned to the DC bus. By returning the resistor to this bus the total power dissipation is reduced.

The value of the capacitor is based on the amount of energy stored in the parasitic inductance. The maximum stored energy must make only a relatively small change in the voltage on the capacitor since the capacitor voltage is the clamp level. The parasitic inductance, the leakage inductance in a flyback converter or the magnetizing inductance in a forward converter, must be discharged into the capacitor on each switching cycle. We can write a

simple equation to define this relationship.

$$W_L + W_{C1} = W_{C2}$$

Where W_L is the energy stored in the parasitic inductance, W_{C1} is the initial energy stored on the capacitor and W_{C2} is the final energy stored on the capacitor. This equation may be expanded as follows:

$$\frac{1}{2}LI^2 + \frac{1}{2}CV^2 = \frac{1}{2}C(V+\Delta V)^2$$

This can be rearranged to solve for C:

$$C = \frac{LI^2}{\Delta V(\Delta V + 2V)}$$

Where ΔV is the change of voltage on the capacitor and V is the initial voltage. L is the inductance to be discharged and I is the peak current in the inductor at the time the switch turns off. This gives the minimum value for the capacitance. The value may be larger without compromising performance and this may be desirable. The value of V is determined by the voltage to which the discharge resistor is connected. V is the difference between the this voltage and the average capacitor voltage. The resistor may be connected to some voltage in the circuit rather than ground since that will lower the power dissipation.

In a flyback converter, the capacitor will charge to a voltage proportional to the turns ratio and the output voltage plus the input voltage. The energy stored in the leakage inductance will add to this level. The energy that the resistance must dissipate is equal to $\frac{1}{2}LI^2$ plus the dissipation from the voltage due to the output voltage and transformer turns ratio.

Example: The unclamped inductance is $2\mu\text{H}$ and the current is 1.0A. The switching frequency is 100KHz. The change of the voltage on the capacitor is to be less than 2.0V so the capacitor will be $0.5\mu\text{F}$ (the initial voltage is 0). A $0.1\mu\text{F}$ capacitor will have a voltage change of 4.5V. The power dissipation of the resistor will be 0.1 watt if the resistor is returned to the output of a boost or a flyback converter or the input of a buck converter. The time constant of the resistor and capacitor must be quite long compared to the switching frequency. 200 ohms would be a reasonable value for the

resistor with the 0.5 μ F capacitor. This gives a 100 μ s time constant. The average voltage across the resistor is 0.5V and the average current is 2.5mA. The capacitor must have low inductance to handle the relatively high peak currents at switch turn-off.

Clamping may also be performed by zener diodes. The advantage of a zener is that it clamps at an absolute level. The zener must be rated for high peak power dissipation as well as the average power dissipation. The zener is not necessarily a high speed device when the package inductance is taken into account so care must be taken with the circuit layout to insure that the stray inductance is kept low to avoid overshoot. If the zener is large then it may not be possible to keep the inductance low and it may be necessary to add a small high frequency capacitor in parallel with the zener and to put a diode in series with both of them. The capacitor handles the very high frequency currents. A zener clamp may also be integrated into an RCD snubber and the snubber handles the high frequency currents and the zener clamps the voltage on the snubber capacitor and thereby the voltage across the switch.

The simple flyback regulator shown in Figure 5 is from Unitrode Application Note U-96A. C8, D5, and R11 form a rate of rise control voltage snubber and C9, D4 and R12 form a clamp to limit the drain voltage. This is an example of using two snubber circuits to accomplish different objectives and control the voltage across the switch.

Dissipative Current Snubbers

The purpose of a current snubber is to control the rate of rise of current in the switch and, conversely, it is often used to control the rate of decrease of current in, and therefore turn-off of, the output diodes. The series inductance allows the switch to be fully turned on by the time the current reaches its operating value. This greatly reduces the peak power dissipation in the switch, it reduces the average dissipation in the switch and it increases the reliability.

The current snubber for the switch also benefits the turn off of the diode on the output. In PWM converters one of the output diodes is driven off by the switch and high reverse currents result. The current snubber on the switch provides a controlled

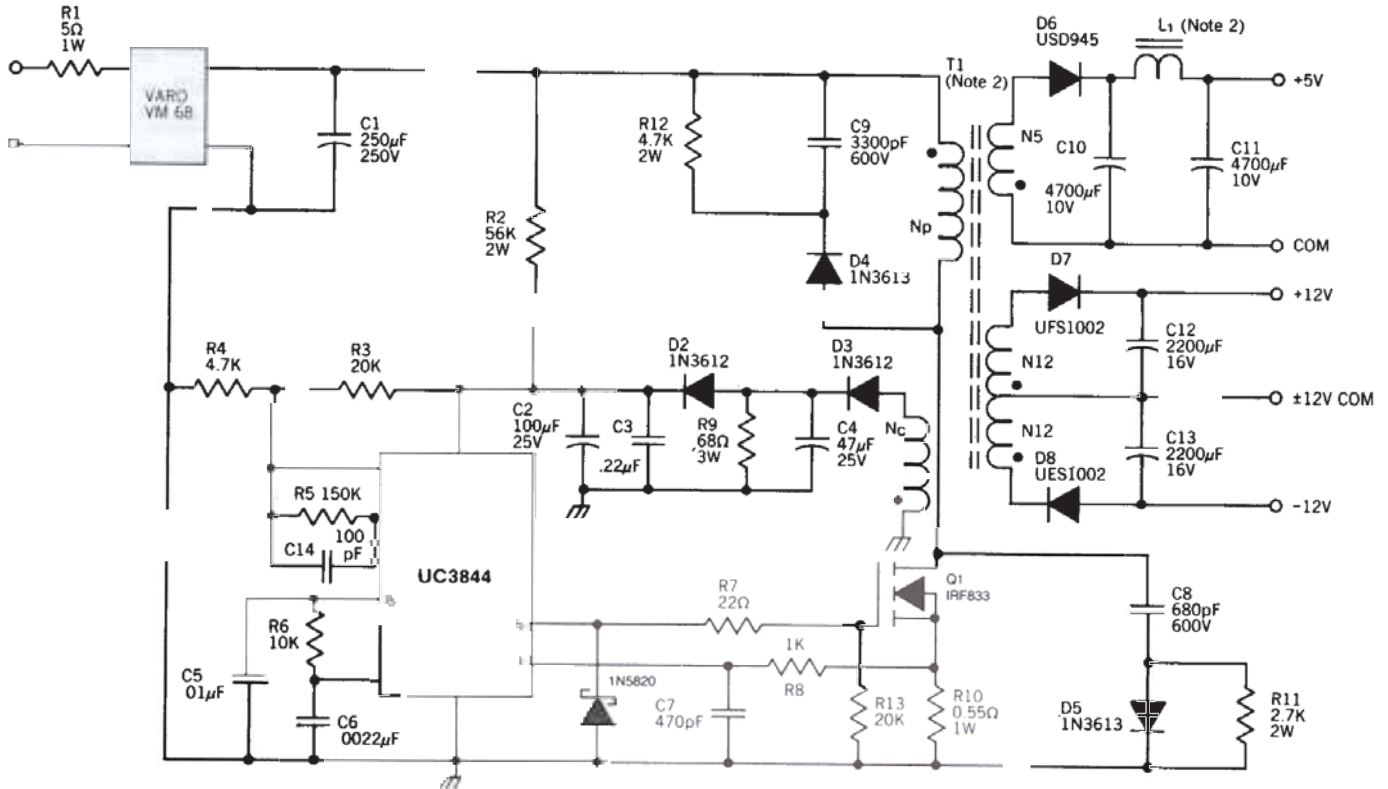


Fig 5 - 25 W Off-Line Flyback Regulator

rate of change of current in the diode and the low di/dt lowers the dissipation in the diode and reduces the peak reverse current.

The Simple RL Current Snubber: The simple RL circuit shown in Figure 6A. This is the dual of the simple RC snubber circuit. It is not often used in switching circuits in this form because from a practical standpoint the value of resistance tends to be small for good damping of the circuit. In a switching circuit this will have high power dissipation. This circuit is rather common in input and output filters where the AC component of the current is relatively small and the resistor provides damping necessary to control the Q of the filter transfer function^[2]. Other variations of this snubber with lower loss are useful for switching circuits.

A ferrite bead is actually a simple RL circuit with both the inductance and resistance incorporated into a single device. It can be very effective in low power situations but the beads have only a very limited power dissipation capability. In switching circuits the bead will have high power dissipation and this generally makes it unusable in all but the lowest power situations.

Square loop cores are sometimes used for current snubbers so that the resistor may be eliminated. The square loop core will allow the switch to turn on with low loss but it will not benefit the output diodes

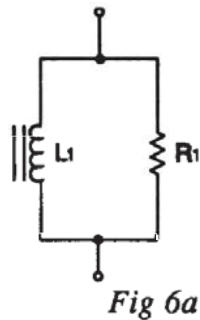


Fig 6a

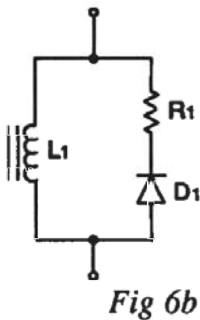


Fig 6b

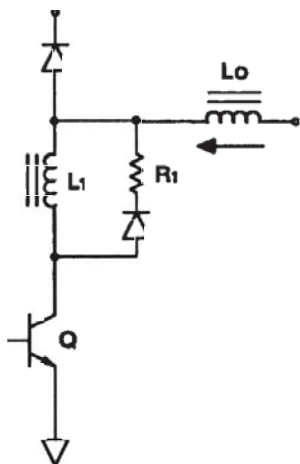


Fig 6c

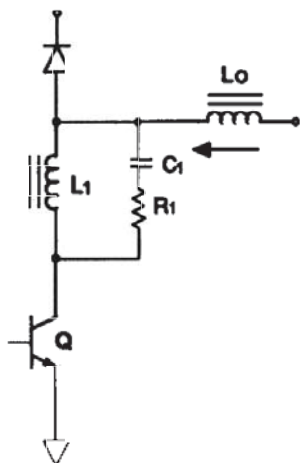


Fig 6d

since the square loop core functions as a switch and does not provide a controlled di/dt for the diode. However, in situations where the diode is not a consideration the square loop cores can be effective.

Variations of the Simple RL Snubber: One way to reduce the power dissipation of the resistor in a simple RL snubber circuit is to add a diode in series with the resistor. This makes it a polarized snubber which is often a desirable characteristic. This is shown in Figure 6B and a simple application is shown in Figure 6C. The inductor functions normally when the switch turns on and current only flows through the resistor when it is needed to dissipate the energy which is stored in the inductor. The amount of power dissipated by the resistor is equal to $\frac{1}{2}LI^2F$ where I is the peak current in the inductor and it includes the diode reverse recovery current as well as the load current. This snubber can be very effective in increasing the overall efficiency of the circuit and in increasing the reliability.

The variation shown in Figure 6D is actually a combination of the simple RC snubber and the inductor and has the lowest loss of the RL dissipative snubbers. The capacitor eliminates DC losses in the resistor, which are the major contributor to power loss in switching circuit applications, and allows the resistor value to be optimized for damping. This configuration is especially useful in non-dissipative energy recovery networks because there are usually low energy, high frequency resonances which must be damped.

Example: A switch is turning on into 400V such as in a boost converter. The circuit is Figure 6C. Switch current is 1.0A. An inductor of 40 μ H will give the diode 100ns to turn off. The inductor will store 20 μ J of energy. The power dissipation of the resistor is 2.0 watts with a 100KHz switching frequency. 80 ohms will give a 500ns reset time constant which should be reasonable at 100KHz. There will also be an 80V spike across the switch when it turns off which must be taken into account. A lower value of resistance would lower this peak voltage.

Non-dissipative Snubbers

Non-dissipative snubbers are sometimes called resonant snubbers although the class is more extensive than just resonant energy recovery. Non-dissipative snubbers are the class of snubbers which recycle the energy they collect either to the input or the output or they circulate it to prepare for the next cycle. They include both current and voltage snubbers and both rate of rise and clamp types of voltage snubbers. The basic principles of non-dissipative snubbers are the same as for dissipative snubbers but in general non-dissipative snubbers do not provide damping. Damping is by definition a dissipative function and small resistors are often necessary in non-dissipative snubbers to control tertiary resonances. All non-dissipative snubbers are polarized snubbers.

Non-dissipative Voltage Snubbers

A voltage snubber controls voltage by transferring energy into a capacitor and in a dissipative snubber this energy is removed from the capacitor and turned into heat but in a non-dissipative snubber a way is found to transfer the energy either back into the source or forward into the load or to cycle it back and forth within the snubber. There are only a few basic types of non-dissipative or resonant energy recovery voltage snubbers. They are all polarized and they operate on only one edge of the switching waveform and are reset on the other edge. In some applications they can become very complex, especially when combined with current snubbers.

Two Terminal Voltage Snubber: One of the basic circuits is a three diode, two capacitor, one inductor (3D-2C-1L) circuit which is configured as a two terminal network. There are two versions of 3D-2C-1L networks, the first of which is a two terminal network. This network is shown in Figure 7A and the connection to the generic switch circuit is shown in Figure 7B. Note that this snubber is applicable to all three converters, buck, boost and buck-boost. This is a rate of rise control snubber and cannot be used as a clamp. The two capacitors generally have equal values and the resonant frequency of the two capacitors and the inductor is much higher than the switching frequency.

To understand the operation of the snubber assume that the switch in Figure 7B is off, the inductor is conducting through the main diode and that the two capacitors are discharged. The snubber must be reset when the switch turns on. As the switch is

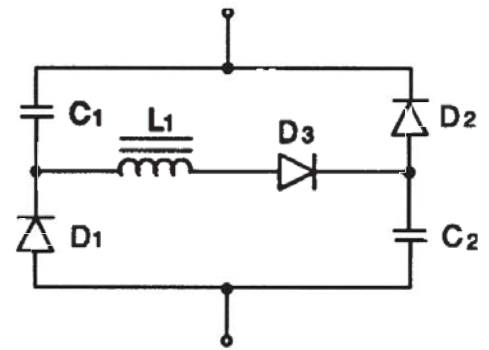


Fig 7a

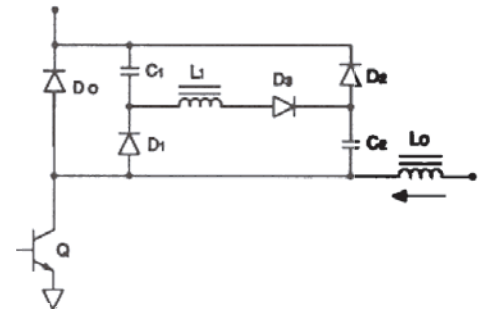


Fig 7b

turning on, diodes D1 and D2 will turn off and the capacitors will apply V_{cc} across the snubber inductor because they are discharged. Current will flow through the inductor and it will ring with the capacitors until the current reaches zero and the diode in series with the inductor turns off. At this point both capacitors are charged to V_{cc} and the snubber is ready for the switch turn-off. When the switch turns off all of the current from the main inductor will flow into the two capacitors. The two diodes in series with the capacitors now conduct so that the capacitors are effectively in parallel. The two capacitors control the rate of change of voltage across the switch. The turn off dissipation of the switch is very small since the capacitors take the full inductor current. The main diode clamps the snubber voltage when the capacitors are fully discharged and the cycle is ready to begin again.

The first step in the design process is knowing what the peak switch current is to be, what the maximum value of V_{cc} is and what the desired switch voltage rise time is. The value of the two capacitors in parallel is found from the equation for a capacitor which has been rearranged into the following form:

$$2C = I \cdot t_r / V_{cc}$$

Where C is the value of one of the capacitors, I is the peak current in the switch, t_r is the desired maximum rise time and V_{cc} is the maximum supply voltage.

The length of time it takes to charge the capacitors is half of one complete resonant period of the two capacitors in series with the inductor. This time period must be less than the smallest expected switch on time. If the on time becomes less than this, the snubber will not be fully reset and the switch dissipation will go up. Note that this normally happens only when the power supply is in current limit. Under a short circuit condition the snubber will be completely ineffective and care must be taken to see that the switch will survive during this condition. Once the reset time is known the value of inductance may be calculated from the following equation:

$$L = \frac{2t^2}{C\pi^2}$$

Where L is the value of the inductance, t is the reset time and C is the value of one of the snubber capacitors.

The peak current in the inductor must be found so that the inductor and the diode in series with it can be sized to handle the current. The peak current is found by equating the inductive and capacitive energy when each is at its peak during the cycle. The equation reduces to the following:

$$I^2 = \frac{CV_{cc}^2}{2L}$$

Where I is the peak current in the inductor, C is the value of one of the snubber capacitors, L is the value of the snubber inductor and V_{cc} is the maximum supply voltage. An important consideration is that the half sine current pulse which resets the snubber when the switch is on must flow through the switch. The switch must be able to handle this current in addition to the load current. The snubber current should not flow through the current sense mechanism when the switch turns on.

Some designers make one of the two capacitors 10-20% larger than the other to insure that at least one of the two capacitors will be completely charged to V_{cc} . They feel that this gives the lowest

stress and power dissipation in the switch.

Example: The current in the switch is 1.0A and the switch voltage is 400V. The rise time is to be 400ns. The value of the capacitors is 500pF each. A 1.0µs recovery time gives an inductor value of 400µH. The peak current in the inductor will be 316mA. Note that with this small a capacitance the recovered charge of the diodes becomes significant. The diodes must be very fast and have a very low recovered charge. The average current through them is very small so they do not have to be large. If the recovered charge in the diodes is too large the voltage stored on the capacitors will not be sufficient to reset them for the next cycle.

Three Terminal Voltage Snubber: Another configuration of the three diode, two capacitor, one inductor non-dissipative voltage snubber has three terminals rather than two. In operation it is similar to the two terminal circuit. The three terminal snubber is shown in Figure 8A. Figure 8B is the same circuit with the top and bottom terminals reversed. The circuit in Figure 8C shows the snubber connected to the generic converter of Figure 2. This snubber may be used with either buck, boost or flyback configurations. The snubber is a rate of rise control type.

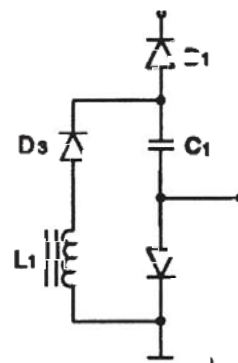


Fig 8a

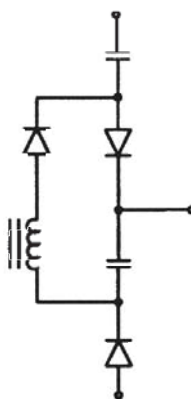


Fig 8b

or flyback configurations. The snubber is a rate of rise control type.

Referring to Figure 8C, the operation of the circuit begins with the switch off, the upper capacitor, C1, discharged and the lower capacitor, C2, charged to V_{cc} . The main diode, D0, is conducting the current in the main inductor, L0. When the switch turns on,

the diodes in series with the snubber capacitors turn off and V_{cc} is applied across the snubber inductor, L1, because C1 is discharged and C2 is charged to V_{cc} . Current flows from C2 through L1 and D3 to charge C1. When the lower capacitor is discharged, the upper capacitor, C1, is charged to V_{cc} , the inductor current is zero, and diode D3, in series with the induc-

tor, is off. The switch turns off some time later and the current through the main inductor, L_0 , flows into the snubber. This current discharges the upper capacitor through D_1 and charges the lower capacitor through D_2 . This controls the rate of rise of voltage across the switch. The two capacitors are effectively operating in parallel even though one is charging and the other is discharging.

The design of this snubber is exactly the same as for the two terminal snubber discussed previously.

Voltage Snubber With Intermediate Voltage: The voltage snubber shown in Figure 9A requires an intermediate voltage which makes this snubber especially useful in forward and flyback converters.

This is a three terminal network and it may be used as either a rate of rise control snubber or as a clamp mode snubber. Figure 9B shows how the snubber connects to the generic converters of Figure 2 and in this application it is operating as a rate of rise control snubber. In clamp mode of operation the circuit is the same but the values of the components are different. This mode is normally used in association with a current snubber for resonant energy recovery so discussion of this mode of operation will be discussed later.

The operation of the snubber begins with the switch off and the capacitor charged to some voltage which is the difference between the diode anode voltage (V_1) and the right inductor terminal (V_2). In a buck or flyback converter this will be the output volt-

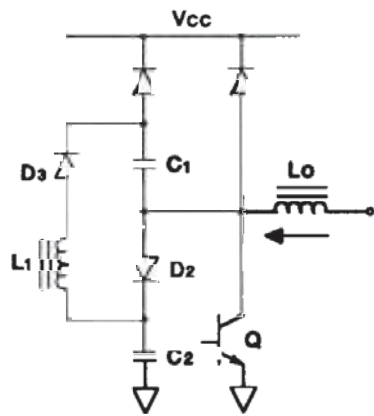


Fig 8c



Fig 9a

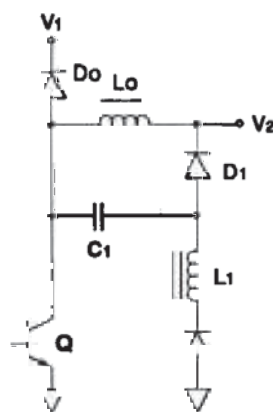


Fig 9b

age, while in a boost converter this will be the difference between the input and the output voltages. When the switch turns on the capacitor will force the voltage on the snubber inductor negative which will ring with the capacitor until the current through the snubber reaches zero or until the diode D_1 conducts to clamp the voltage. The capacitor voltage will have reversed sign but will not be larger than V_2 in Figure 9B. When the switch turns off, the current from the main inductor will flow into the capacitor, through diode D_1 and back to V_2 , and this controls the rate of rise of voltage across the switch. When the voltage is high enough to turn on, the main diode and capacitor will be charged to the initial state (V_1-V_2).

If V_1-V_2 in Figure 9B is less than V_2 , the charge on the snubber capacitor at the end of the reset period will not be equal to V_2 . When this happens, the switch will not turn off at zero voltage but instead will turn off at some intermediate voltage which is determined by the point at which D_1 is conducting. This is still a dramatic improvement over not having a snubber at all but it must be considered in switch selection and heat sinking.

The design procedure for this snubber is similar to the procedure given above for the two terminal non-dissipative snubber. The capacitor value, C , is found from:

$$I = C \, dV/dt$$

Where I is the maximum switch current and dV/dt is the maximum rate of change of voltage desired across the switch. The inductor value, L , is found from the length of time available for the reset and the capacitor value. The equation is:

$$L = \frac{4t^2}{C\pi^2}$$

Where t is the length of time available for resetting the capacitor and it is shorter than the smallest pulse width under normal operation. The peak current in the inductor is given by:

$$I^2 = \frac{CV^2}{L}$$

Where I is the peak inductor current and V is the initial voltage on the capacitor and is equal to (V_1-V_2) in Figure 9B.

Non-dissipative Current Snubbers

The basic principle of a current snubber is that energy is collected in an inductor as part of its function of controlling the rate of rise of current in the switch. Non-dissipative current snubbers are very similar to their dissipative counterparts. The basic functionality is the same, an inductor is placed in series with the switch to control the rate of rise of current. In a non-dissipative current snubber the energy stored in the inductor on each cycle is transferred back to the input or ahead to the output instead of being dissipated. There are several methods for removing the energy from the inductor on each cycle and some of the more common methods are discussed in this section.

Flyback Reset Current Snubber: One of the most obvious ways to get the energy out of the inductor is to put an extra winding on it. This allows the energy to be directed anywhere and provides a controlled overvoltage condition on the switch set by the turns ratio and the recovery voltage. Figure 10A shows the basic snubber and Figure 10B and Figure 10C show two ways of hooking the snubber to the generic converter of Figure 2. The configuration chosen depends on whether it is a buck, flyback (Figure 10B) or boost (Figure 10C) converter. In all cases the energy is transferred to the load although other connections could transfer the energy back to the input.

The design of this type of snubber is rather simple. The value of the primary inductance is the same as it would be for a dissipative snubber and the voltage which is added to the switch during reset is determined by the

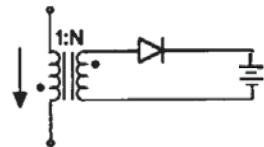


Fig 10a

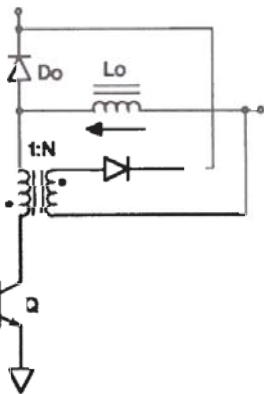


Fig 10b

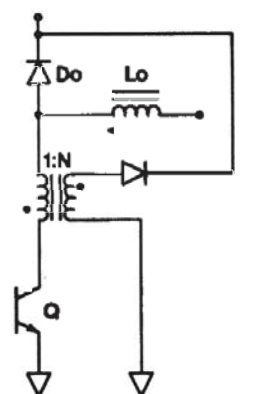


Fig 10c

turns ratio and either the source or load voltage.

The major problem with this type of snubber is the leakage inductance between the primary and secondary of the inductor. This leakage inductance can cause a large voltage spike across the switch. This type of snubber has been used effectively but it is generally used with high power converters where the rise and fall times are slow or where rate of rise voltage snubbers are also used. Simple RC damping networks are usually needed across both the primary and secondary of the inductor.

Resonant Recovery Current Snubbers: Figure 11A shows the generic converter of Figure 2 with a current snubber where the energy is being returned to one of the converter voltages. The energy recovery in this snubber is being handled in the clamp mode and the energy is recovered when the switch turns off. The voltage across the switch is clamped to the highest voltage in the converter whether it is an input or an output voltage. Obviously, a single diode could have been used in place of the RLD network so there must be some justification for using the network. The object of the network is to reduce the current in the snubber inductor to zero as rapidly as is practical. If a single diode were used the switch would be clamped but there would be no voltage across the snubber inductor so it would continue conducting until the switch turned on again and it would therefore be ineffective as a current snubber.

The purpose of the snubber in Figure 11A is to provide voltage to reset the snubber inductor to zero current on each cycle. The clamping of the switch voltage at turn off is a secondary benefit. The snubber capacitor needs to be small so that it has a significant voltage change due to the energy from the snubber inductor. The voltage change on the capacitor

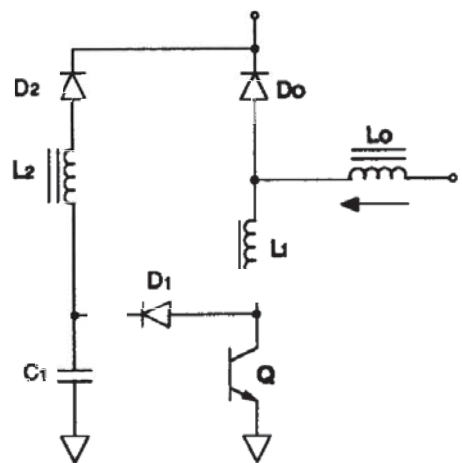


Fig 11a

is what allows the inductor to reset to zero current. Again, the simple relationship between the energy stored in the inductor and the energy in the capacitor is used to calculate the size of the capacitor.

$$W_L = W_C \quad \text{or} \quad \frac{1}{2}LI^2 = \frac{1}{2}CV^2$$

This equation may be rearranged to solve for the capacitance:

$$C = \frac{LI^2}{V^2}$$

Where C is the capacitance in the snubber, L is the inductance of the snubber, I is the current in the switch at turn-off and V is the change of voltage on the capacitor. Note that the smaller the capacitor is, the greater the voltage will be and the faster the inductor will reset. The reset time is approximately one quarter resonant cycle and is given by:

$$t = \frac{\pi\sqrt{LC}}{2}$$

Where t is the reset time, L is the snubber inductor and C is the snubber capacitance.

The inductor which is used to discharge the capacitor may be large or small. If the value is small, that is, the resonant frequency is smaller than the switching frequency, the diode in series is necessary to limit the resonance to a single half cycle. The L and C will resonate to discharge the capacitor and at the end of the discharge cycle the capacitor will be as far below the nominal as it was above at the beginning. A small series resistor or a large parallel resistor may be necessary to eliminate ringing when the diode turns off. If the value of the inductor is large, that is, the resonant frequency is much greater than the switching frequency, the diode is not necessary since the inductor will be in continuous conduction. The voltage waveform on the capacitor will be similar but the discharge will be a straight line. This is the most efficient configuration of the snubber. The only problem to watch out for is that the resonant frequency of the discharge inductor and capacitor must be high enough so that under transient conditions the peak voltage on the switch will not exceed its specifications. If the resonant frequency of the capacitor and reset

inductor is larger than the switching frequency the voltage on the capacitor can change with the load current. Care must be taken to insure that the voltage does not exceed the switch rating.

Example: The circuit is shown in Figure 11A. The switch current is 1.0A and the series inductor is 40μH as was given in the example for dissipative current snubbers. The reset time of the inductor is chosen to be 1.0μs for a 100KHz switching frequency. The capacitor will be 0.01μF. The change of voltage across the capacitor will be 63V. The inductor in the recovery network may be either large or small as discussed above.

The snubber circuit shown in Figure 11B is intended to solve a somewhat different problem from that of Figure 11A. Both snubber circuits control the current in the switch when it turns on but the energy recovery circuit shown in Figure 11B recovers the diode turn off energy. The snubber inductor stores the reverse recovery charge from the diode and it could drive the diode into an overvoltage condition. The snubber in Figure 11B recycles this energy.

The energy recovery part of the snubber in Figure 11B is the same as the voltage snubber in Figure 9B except that it is operating in the clamp mode. The operation of the snubber in Figure 11B begins with the switch off and the main diode carrying the inductor current. When the switch turns on the current in snubber inductor L1 will ramp up and the current through the main diode will ramp down. The diode current will eventually reach zero and it will begin to turn off. The voltage across the diode will not change until it is completely turned off. The diode reverse recovery current as it turns off must flow into the snubber inductor since the main inductor current will not change significantly in that short a time. Once the diode is fully turned

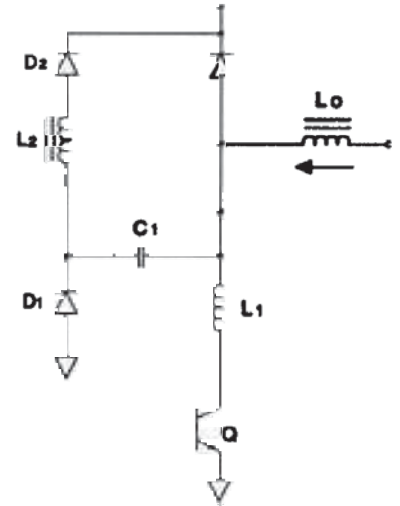


Fig 11b

off the snubber inductor will drive the voltage to ground since its current is higher than the current in the main inductor. The energy which was needed to turn off the diode is now stored in the snubber inductor. The energy which was needed to turn off the diode is now stored in the snubber inductor. The snubber network in Figure 11B is designed to recycle the extra energy stored in the inductor. After the diode turns off and the voltage has dropped to zero, the snubber capacitor begins charging through diode D1. The excess energy in the snubber inductor will transfer into the capacitor and the diode will hold the energy on the capacitor. When the switch turns off the main diode will conduct again and the snubber discharge inductor L2 will reverse the charge on the snubber capacitor so that it is ready for the next cycle. Since the energy recovery network is operating in clamp mode the capacitor is relatively large and the voltage across it will be small.

Example: The same example as above. The circuit is Figure 11B. The diode reverse recovery current is assumed to be 0.5A peak and the snubber inductor is 40 μ H. The energy will be transferred into the capacitor in 1.0 μ s so the capacitor is 0.01 μ F. The extra voltage across the diode will be 32V peak. The reset inductor may be small with a reset time of 2 μ s. Note that the reset requires a full half cycle so the equation is $t = \pi\sqrt{LC}$. The reset inductor is 40 μ H but it only carries 0.5A peak.

Transformer Reset Non-dissipative Voltage Clamp

There is one circuit which deserves special mention and which is not particularly easy to classify since it requires a transformer for operation. It is a voltage snubber and it operates in clamp mode. It is particularly applicable to forward converters and push-pull converters, both of which are notoriously difficult to snub. The forward converter version of the circuit is shown in Figure 12.

Winding N1 on the transformer in Figure 12 is the primary power winding. Winding N2 is the reset winding and it controls the voltage on the capacitor and provides the core reset that the forward converter needs. Note that the two windings have the same number of turns and that this limits the maximum duty factor of the forward con-

verter to 50%. The circuit operation begins with the switch on and the capacitor charged to Vcc by the reset winding. When the switch turns off, both the transformer leakage inductance and the magnetizing inductance will drive the voltage on the switch above Vcc.

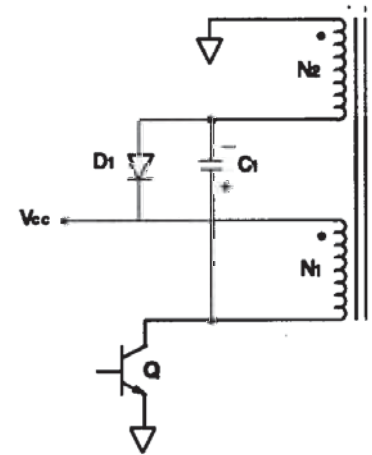


Fig 12

When the voltage across the switch reaches twice Vcc the diode will turn on and the current in the transformer leakage inductance will be clamped by the capacitor and diode. The reset winding will then conduct the magnetizing current through the diode to reset the transformer core. When the switch turns on, the capacitor, which is still holding the energy from the leakage inductance, will discharge into the reset winding and its voltage will again be equal to Vcc. A small resistor may be needed in series with the reset winding of the transformer to damp the resonances which may occur between the capacitor and the windings. The capacitor must be large enough to absorb the energy from the leakage inductance with only a small voltage change and the diode must handle the peak current from the spike and must be rated for at least twice Vcc.

Snubbing Diodes

Some diodes are driven off by the switch and others are driven on. Those driven off are usually turned on naturally by the energy storage elements in the output circuit and those driven on are usually turned off by the energy storage elements. Some care must be taken to insure that adding a snubber to the diodes will not add to the stress on the switch. For example, adding a simple RC snubber to the output of a forward converter will add to the current spike in the switch at turn-on. And yet, the snubber may be needed to control ringing which results from the reverse recovery current of the shunt diode and the transformer leakage inductance.

Figure 13 shows a forward converter with two simple RC snubbers and the transformer leakage inductance is shown explicitly. There are two resonances in this output which must be damped. The first is the resonant circuit formed by the transformer leakage inductance and diode D1's capacitance in parallel with the output inductor capacitance and the stray circuit capacitance. This circuit is excited by the recovery current in D1 as it turns off. This occurs when the switch turns on so it is important to minimize the value of C1. In general, this resonant frequency will be the lowest one in the output section because the stray capacitance is largest. Snubbing this resonance with C1 and R1 will result in minimum loss since the voltage swing is smallest at this point.

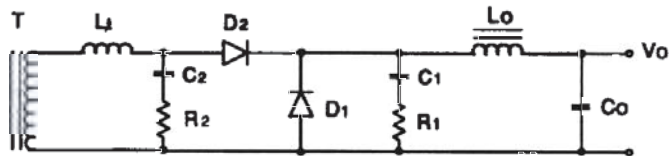


Fig 13

The other resonance in the forward converter output is due to the transformer leakage inductance and the capacitance of D2. The anode of D2 will ring due to the reverse recovery current. This resonance will be higher in frequency than the other one because the capacitance is smaller. This requires a smaller capacitor for C2 so the power dissipation will be minimized in R2. This circuit is excited when the switch turns off.

It is possible to use a current snubber in series with D1 to control the turn-off of the diode. The snubber energy may be recovered using both of the recovery networks shown in Figure 11 or dissipative networks may be used but two networks are required.

Component Problems

The characteristics of the components used in snubbers are very important and this is especially true in clamping snubbers. The rate of change of current in a snubber is very large and very small parasitics can make it almost completely ineffective. The author recalls a clamp snubber in a boost converter which had one inch of track on the PWB over a ground plane. That provided enough induc-

tance to cause high amplitude ringing at 50 MHz.

Good layout practices are extremely important. A ground plane is a necessity and tracks which carry high frequency currents must be kept wide relative to the board thickness to keep the inductance down.

The diodes used in snubbers generally do not have to be large diodes. They must handle relatively large peak currents but only low average currents. They need low recovered charge, especially in non-dissipative snubbers as was mentioned in the examples above. Small diodes are often the best choice and may need small heat sinks.

Inductors have parallel capacitance which must be minimized. The bandwidth of the inductor must be as high as possible for good snubber operation. The inductor itself may go into parallel resonance and this cannot be damped electronically since it is a field resonance. It must be eliminated by changing the winding configuration. Progressive winding and bank winding techniques will minimize the winding capacitance. Layer winding will maximize the capacitance and random winding will have a random distribution of values.

Capacitors have series inductance which must be minimized. Capacitors are often paralleled to reduce the circuit inductance and this is effective up to a point. The series inductance of a large capacitor is quite capable of resonating with a small capacitor placed in parallel with it and the resonant circuit will have high Q. This is especially true for the output capacitor in a boost converter, the input capacitor in a buck converter and all capacitors in a flyback converter.

The resistors used in RC damping networks must be low inductance types. Non-inductive wire wound resistors generally have too much inductance and will cause ringing and overshoot at high frequencies instead of providing damping. If there is no other alternative it is sometimes possible to parallel a wire wound resistor with a series RC network to damp the inductance of the wire wound resistor.

General Approach to Snubbing Switching Regulators

The first step in snubbing a switching regulator takes place when the design is still on paper. Formulate an overall snubbing strategy and calcu-

late the values for each snubber. Where is the greatest need in the circuit. How important is efficiency? How important is cost?

In the laboratory there is a general approach to snubbing and trouble shooting which is effective. We should point out here that it is sudden death to a project to snub your technician and we strongly recommend that you not even try. Statements of appreciation are usually much more effective at preventing spiking and flaming.

The switches are the most vulnerable part of the system and must be treated gently until the circuit is well behaved. The power stage can be observed with only a small fraction of the rated voltage and current so that measurements can be made without the possibility of switch damage. In this mode the effect of each snubber can be ascertained and its effectiveness determined. Snubbing generally proceeds from the input to the output of the circuit not only because the switches are the most vulnerable part of the circuit but also because the problems in a switching power supply are staggered in time.

When a switch is on there is no need for a voltage snubber to control the switch voltage. The switch is connecting the output network of the supply directly to a voltage source. When the switch turns off, however, there may be some reactances which are not controlled and which will ring. In a forward converter, for example, when the switch turns off the leakage inductance on the primary will drive a spike across the switch. The leakage inductance on the secondary will continue to supply current through the diode. The leakage inductance on the secondary will prevent the diode from turning off for a few tens of nanoseconds after the switch voltage has reached its clamp level. This time displacement is observable. This allows the individual parasitic elements to be separated and each one can be dealt an appropriate snubber. It usually requires an oscilloscope with matched and properly adjusted probes.

Once a point has been identified as needing a snubber the objective of the snubber must be considered. Is the objective to provide damping of a resonant circuit, to clamp an overshoot, to control a rise or fall time or to increase efficiency. This determines the type of snubber to add. Always

remember that more than one snubber may be required for any particular location.

Conclusion

A properly snubbed circuit enhances system reliability, is more efficient, and is quieter than an unsnubbed circuit. A properly snubbed circuit performs well over time, temperature and production tolerances. It is well worth the time to understand and use snubber circuits.

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