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Linear & Switching Voltage Regulator Handbook

ON Semiconductor™

SECTION 11

SWITCHING REGULATOR COMPONENT DESIGN TIPS

Transistors

The initial selection of a transistor for a switcher is basically a problem of finding the one with voltage and current capabilities that are compatible with the application. For the final choice performance and cost tradeoffs among devices from the same or several manufacturers have to be weighed. Before these devices can be put in the circuit, both protective and drive circuits will have to be designed.

ON Semiconductor's first line of devices for switchers were trademarked "Switchmode" transistors and introduced in the early 70's with data sheets that provided all the information that a designer would need including reverse bias safe operating area (RBSOA) and performance at elevated temperature (100°C). The first series was the 2N6542 through 2N6547, TO–204 (TO–3) and was followed by the MJE13002 through MJE13009 series in a plastic TO–220 package. Finally, high voltage (1.0 kV) requirements were met by the metal MJ8500 thru MJ8505 series and the plastic MJE8500 series. The Switchmode II series is an advanced version of Switchmode I that features faster switching. Switchmode III is a state of the art bipolar with exceptional speed, RBSOA, and up to 1.5 kV blocking capacity. Here, device cost is somewhat higher, but system costs may be lowered because of reduced snubber requirements and higher operating frequencies. A similar argument applies to ON Semiconductor TMOS Power FETs. These devices make it possible to switch efficiently at higher frequencies (200 kHz to 500 kHz) but the main selling point is that they are easier to drive. This latter point is the one most often made to show that systems savings are again quite possible even though the initial device cost is higher.

Table 11–1. ON Semiconductor High Voltage Switching Transistor Technologies

Family	Typical Device	Typical Fall Time	Approximate Switching Frequency
SWITCHMODE I	2N6545 MJE13005 MJE12007	200 ns to 500 ns	20 k
SWITCHMODE II	MJ13081	100 ns	100 k
SWITCHMODE III	MJ16010	50 ns	200 k
TMOS	MTP5N40	20 ns	500 k

Table 11–2 is a chart of the transistor voltage requirements for the various off–line converter circuits. As illustrated, the most stringent requirement for single transistor circuits (flyback and forward) is the blocking or V_{CEV} rating. Bridge circuits, on the other hand, turn on and off from the dc bus and their most critical voltage is the turn–on or $V_{CEO(sus)}$ rating.

Table 11–2. Power Transistor Voltage Chart

Line Voltage	Circuit			
	Flyback, Forward or Push–Pull		Half or Full–Bridge	
	V_{CEV}	$V_{CEO(sus)}$	$V_{CEO(sus)}$	V_{CEV}
220 120	850 kV to 1.0 kV 450	450 250	450 250	450 250

Most switchmode transistor load lines are inductive during turn–on and turn–off. Turn–on is generally inductive because the short circuit created by output rectifier reverse recovery times is isolated by leakage inductance in the transformer. This inductance effectively snubs most turn–on load lines so that the rectifier recovery (or short circuit) current and the input voltage are not applied simultaneously to the transistor. Sometimes primary interwinding capacitance presents a small current spike but usually turn–on transients are not a problem. Turn–off transients due to this same leakage inductance, however, are almost always a problem. In bridge circuits, clamp diodes can be used to limit these voltage spikes. If the resulting inductive load line exceeds the transistor's reverse bias switching capability (RBSOA) then an RC network may also be added across the primary to absorb some of this transient energy. The time constant of this network should equal the anticipated switching time of the transistor (50 ns to 500 ns). Resistance values of 100 Ω to 1000 Ω in this RC network are generally appropriate. Trial and error will indicate how low the resistor has to be to provide the correct amount of snubbing. For single transistor converters, the circuits shown in Figure 11–1 are generally used.

Here slightly different criteria are used to define the R and C snubber values:

$$C = \frac{I\,t_f}{V}$$

where; I = the peak switching current

t_f = the transistor fall time

V = the peak switching voltage (Approximately twice the DC bus)

also, R = t_{on}/C (it is not necessary to completely discharge this capacitor in order to obtain the desired effects of this circuit)

where, t_{on} = the minimum on–time or pulse width

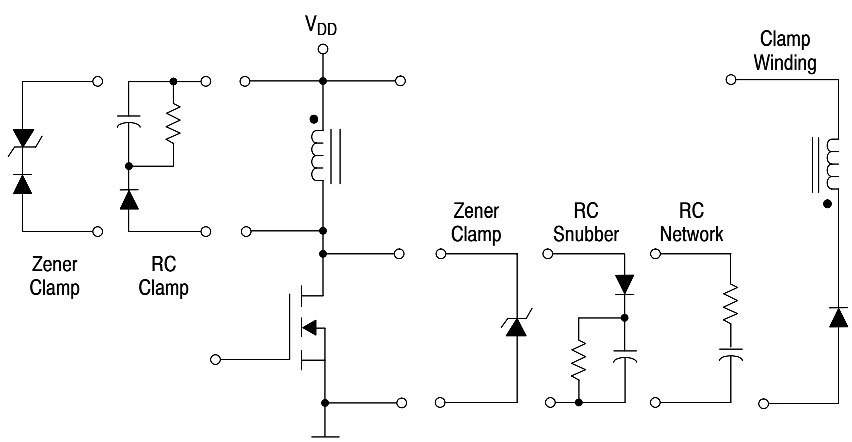
and, $P_R = \dfrac{CV^2f}{2}$

where, P_R = the power rating of the resistor

and, f = the operating frequency.

In most of today's designs snubber elements are small or nonexistent and voltage spikes from energy left in the leakage inductance a more critical problem depending on how good the coupling is between the primary and clamp windings and how fast the clamp diode turns on. FETs often have to be slowed down to prevent self destruction from this spike.

Figure 11–1. Protection Circuits for Switching Transistors



Zener and Mosorb Transient Suppressors

If necessary, protection from voltage spikes may be obtained by adding a zener and rectifier across the primary as shown in Figure 11–1. Here ON Semiconductor’s 5.0 W zener lines with ratings up to 200 V, and 10 W TO–220 Mosorbs with ratings up to 250 V can provide the clamping or spike limiting function. If the zener must handle most of the power, its size can be estimated using:

$$PZ = \frac{L_L I^2 f}{2}$$

where, P_Z = the zener power rating
and, L_L = the leakage inductance (measured with the clamp winding or secondary shorted)
I = peak collector current
f = operating frequency

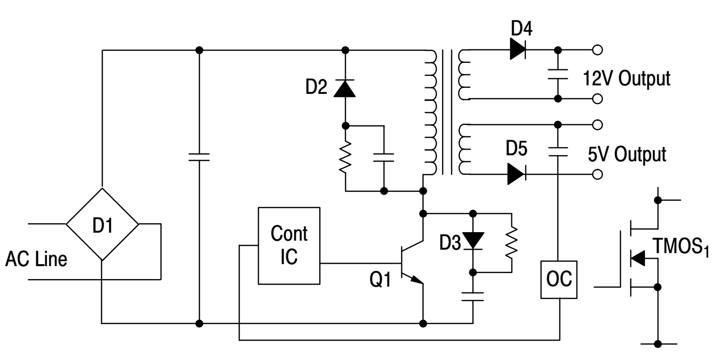
Distinction is sometimes made between devices trademarked Mosorb (by ON Semiconductor, Inc.), and standard zener/avalanche diodes used for reference, low–level regulation and low–level protection purposes. It must be emphasized that Mosorb devices are, in fact, zener diodes. The basic semiconductor technology and processing are identical. The primary difference is in the applications for which they are designed. Mosorb devices are intended specifically for transient protection purposes and are designed, therefore, with a large effective junction area that provides high pulse power capability while minimizing the total silicon use. Thus, Mosorb pulse power ratings begin at 600 W — well in excess of low power conventional zener diodes which in many cases do not even include pulse power ratings among their specifications.

MOVs, like Mosorbs, do have the pulse power capabilities for transient suppression. They are metal oxide varistors (not semiconductors) that exhibit bidirectional avalanche characteristics, similar to those of back–to–back connected zeners. The main attributes of such devices are low manufacturing cost, the ability to absorb high energy surges (up to 600 joules) and symmetrical bidirectional “breakdown” characteristics. Major disadvantages are: high clamping factor, an internal wear–out mechanism and an absence of low–end voltage capability. These limitations restrict the use of MOVs primarily to the protection of insensitive electronic components against high energy transients in applications above 20 V, whereas, Mosorbs are best suited for precise protection of sensitive equipment even in the low voltage range the same range covered by conventional zener diodes.

Rectifiers

Once components for the inverter section of a switcher have been chosen, it is time to determine how to get power into and out of this section. This is where the all–important rectifier comes into play. (See Figure 11–2.) The input rectifier is generally a standard recovery bridge that operates off the ac line and into a capacitive filter. For the output section, most designers use Schottkys for efficient rectification of the low voltage, 5.0 V output windings and for the higher voltage, 12 V to 15 V outputs, the more economical fast recovery or ultrafast diodes are used.

Figure 11–2. Switchmode Power Supply Flyback or Boost Design



D1 — Bridge Rectifier — Line Voltage
D2 — Clamp Diode — HV/Fast–Ultrafast
D3 — Snubber Diode — HV/Fast–Ultrafast
D4 — Output Rectifier — Fast/Ultrafast
D5 — Output Rectifier — Schottky

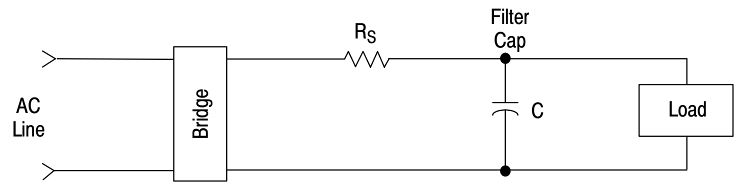
For the process of choosing an input rectifier, it is useful to visualize the circuit shown in Figure 11–3. To reduce cost, most earlier approaches of using choke input filters, soft start relays (Triacs), or SCRs to bypass a large limiting resistor have been abandoned in favor of using small limiting resistors or thermistors and a large bridge. The bridge must be able to withstand the surge currents that exist from repetitive starts at peak line. The procedure for finding the right component and checking its fit is as follows:

1. Choose a rectifier with 2 to 5 times the average I_O required.
2. Estimate the peak surge current (I_p) and time (t) using:

$$I_p = \frac{1.4\ V_{in}}{R_S} \quad t = R_S C$$

Where V_{in} is the RMS input voltage; R_S is the total series resistance; and C is the filter capacitor size.

Figure 11–3. Choosing Input Rectifiers



3. Compare this current pulse to the sub cycle surge current rating (I_S) of the diode itself. If the curve of I_S versus time is not given on the data sheet, the approximate value for I_S at a particular pulse width (t) may be calculated knowing:
   - I_{FSM} — the single cycle (8.3 ms) surge current rating and using.
   - $I^2 \sqrt{t}$ = K, which applies when the diode temperature rise is controlled by its thermal response as well as power (i.e., $T = K'P \sqrt{t}$ for t < 8.0 ms).

   This gives:

$$I_S2 \sqrt{t} = I2_{FSM} \sqrt{8.3\ ms} \quad \text{or,} \quad I_S = I_{FSM} \left(\frac{8.3\ ms}{t}\right)^{1/4}$$, t is in milliseconds.

4. If $I_S < I_P$, consider either increasing the limiting resistor (R_S) or utilizing a larger diode.

In the output section where high frequency rectifiers are needed, there are several types available to the designer. In addition to the Schottky (SBR) and fast recovery (FR), there is also an ultrafast recovery (UFR). Comparative performance for devices with similar current ratings is shown in Table 11–3. The obvious point here is that lower forward voltage improves efficiency and lower recovery times reduce turn–on losses in the switching transistors, but the tradeoff is higher cost. As stated earlier, Schottkys are generally used for 5.0 V outputs and fast recovery and ultrafast devices for 12 V outputs and greater. The ultrafast is competing both with the Schottky where higher breakdown is needed and with the fast recovery in those applications where performance is more important than cost. Ten years ago Schottkys were very fragile and could fail short from either excessive dv/dt (1.0 V to 5.0 V per nanosecond) or reverse avalanche. Since that time, ON Semiconductor has incorporated a “guard ring” or internal zener which minimizes these earlier problems and reduces the need for RC snubbers and other external protective networks.

Table 11–3. ON Semiconductor Rectifier Product Portfolio

Parameter	Schottky	Ultrafast	Fast Recovery	Standard Recovery
Forward Voltage (V_F)	0.5 V to 0.6 V	0.9 V to 1.0 V	1.2 V to 1.4 V	1.2 V to 1.4 V
Reverse Recovery Time (t_{rr})	<10 ns	25 ns to 100 ns	150 ns	1.0 µs
t_{rr} Form	Soft	Soft	Soft	Soft

DC Blocking Voltage (V_R)	20 V to 60 V	50 V to 1000 V	50 V to 1000 V	50 V to 1000 V
Cost Ratio	3:1	3:1	2:1	1:1