MOTOROLA INC.

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Application Note

DRIVE OPTIMIZATION FOR 1.0 kV OFF-LINE CONVERTER TRANSISTORS

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Today's single output transistor topologies are well known for the simplicity they bring to off-line switching power supplies. They are also very popular. Single transistor switchers are also noted for the hefty voltage excursions they place upon the output transistor. In a typical supply, worst case excursions on the order of 800 volts are not unusual.

The bulk of today's off-line transistors have breakdown ratings of 850 volts or less, and do not really have a desirable amount of safety margin for these applications. For this reason, 1500 volt TV deflection transistors are often used. However, the 1500 volt transistors are overkill, resulting in significant gain, speed and, cost penalties.

A new series of transistors, specifically optimized for the single transistor off-line switcher, has recently become available. Designated the MJ16000A series, these devices combine 1000 volt ratings, a liberal dose of reverse safe area, and near FET switching speeds. They are one of the better choices for single transistor off-line switchers.

The purpose here is to take a look at how to optimally use these parts. Both switching time and reverse safe area are examined in several different circuit configurations. The results are intended to save the effort of going through a similar process each time a power supply is designed.

THIRD GENERATION CHARACTERISTICS

The MJ16000A family of off-line converter transistors is a 1.0 kV optimization of third generation (SM III) bipolar technology. The significant difference between these parts and older types is "hollow" emitter finger construction. The difference is illustrated in Figure 1.

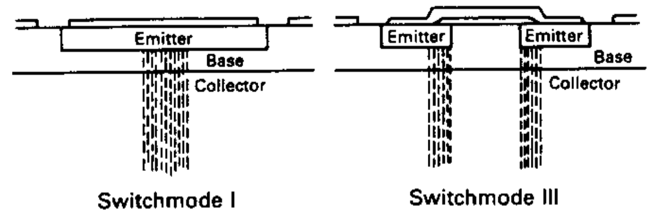

FIGURE 1 — Third Generation Transistor Construction

Two aspects of Figure 1 are highly significant, with respect to dynamic performance. First, the area of peak current density that occurs in the center of the solid finger is split into two parts and separated in the SM III structure. Peak stress is thereby spread over a larger area, explaining the excellent RBSOA results that follow. Second, the area of highest current density is substantially closer to the base finger metalization in the SM III design. Closer proximity reduces base spreading resistance, and gives the base fingers better control over reverse current flow. The result is near FET switching times.

Both switching and RBSOA for the 1.0 kV SM III structure are illustrated in Table 1. The data was taken on the MJH16006A, a part that is optimally sized for 100 watt off-line switchers. Five different test circuits are examined, each one with and without a Baker clamp. The test circuits were plugged into non-destructive test equipment, enabling RBSOA limits in each circuit to be determined for the same group of test transistors. In addition, transistors were chosen from the slower half of the switching distribution, giving a relatively conservative view of expected results.

Turning to the numbers in Table 1, there are several observations worth noting. First, performance is heavily dependent upon drive optimization. Choosing a third generation transistor, by itself, is not enough to guarantee state of the art performance. It is also necessary to optimize base drive.

TABLE 1
Test Results

Test Circuit	t_{sv} (μs)	t_c (ns)	1.0 kV RBSOA (Amps)
Fixed I_{B2} = 1.0 A			
I_{B1} = 1.0 A	3.0	160	2.6
I_{B1} Baker Clamped	1.3	160	2.9
Fixed I_{B2} = 2.0 A			
I_{B1} = 1.0 A	1.9	100	4.2
I_{B1} Baker Clamped	0.8	80	4.4
Fixed $V_{BE(off)}$ = 2.0 V			
I_{B1} = 1.0 A	0.86	300	6.0
I_{B1} Baker Clamped	0.53	75	5.6
Fixed $V_{BE(off)}$ = 5.0 V			
I_{B1} = 1.0 A	0.59	320	7.0
I_{B1} Baker Clamped	0.28	80	6.8
Series Base Inductor			
I_{B1} = 1.0 A	2.4	110	5.4
I_{B1} Baker Clamped	1.6	80	4.5
Single Ended Push Pull			
I_{B1} = 1.0 A	2.5	100	2.0
I_{B1} Baker Clamped	0.9	80	1.8
Emitter Switched			
I_{B1} = 1.0 A	0.41	175	6.4
I_{B1} Baker Clamped	0.22	90	6.2
Test Conditions Switching: $I_{c(pk)}$ = 5.0 A, $V_{Cl(pk)}$ = 250 V, L = 100 μH, T_C = 25°C RBSOA: $V_{CE(pk)}$ = 1000 V, L = 200 μH, T_L = 25°C			

Second, a common theme pervades the switching time data. Baker clamps tend to optimize switching performance. This is no surprise. Conductivity modulation theory predicts the same results. Baker clamps, by reducing excess stored charge, tend to minimize switching times.

Third, Reverse Bias Safe Operating Area is much better than most people realize. Properly driven, the third generation devices will comfortably exceed 4.0 amps at 1000 volts. This is enough capability to compete head to head with FETs, and eliminate snubbers from many off-line switchers.

CIRCUIT DESIGN

Given the need for drive optimization, performance is looked at from a circuit design point of view. A discussion begins with the fixed I_{B2} approach, and touches briefly on each of the circuits that were used to obtain the data in Table 1. The first three circuits (Figures 3, 4 and 5) need some sort of an up-down driver for test purposes. An example is shown in Figure 2.

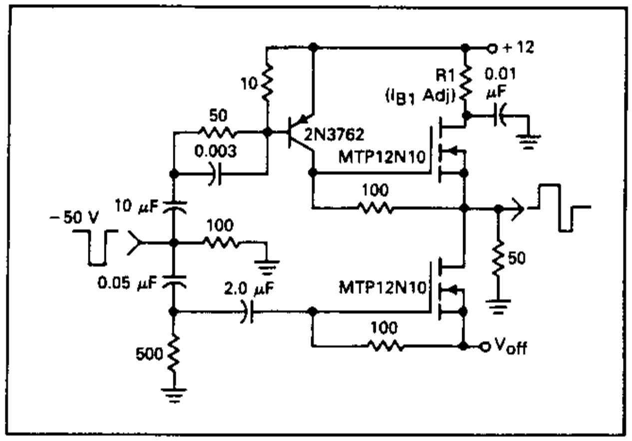

FIGURE 2 — Driver

FIXED I_{B2}

The I_{B1} = I_{B2} method of driving power transistors is both time honored and straightforward. A modern version of this approach, with ULTRAFAST Baker clamp diodes, is illustrated in Figure 3. In addition, I_{B2} = 2.0 amps is considered.

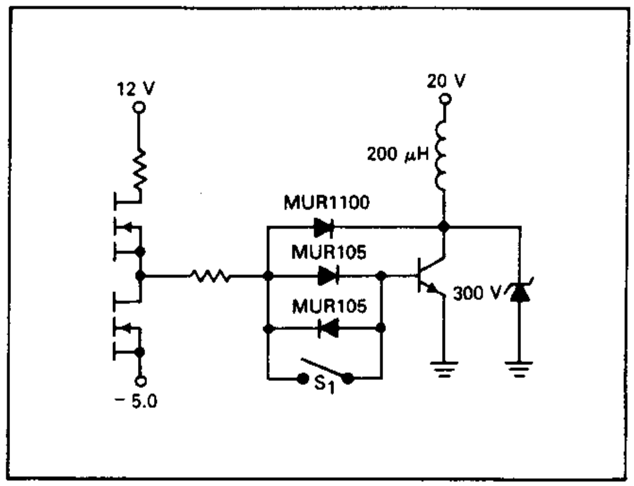

FIGURE 3 — Fixed Reverse Base Current

When I_{B2} is set at 1.0 amp, neither switching nor RBSOA performance are particularly optimum. However, as I_{B2} is increased to 2.0 amps, the results change substantially. Crossover times are among the fastest recorded, particularly in the unclamped condition. RBSOA also improves with the increased reverse current, but not by as much. The I_{B2} = 2.0 A RBSOA results, although improved, are still mediocre compared to some of the other test circuits.

FIXED $V_{BE(off)}$

$V_{BE(off)}$ was also investigated at two levels, 2.0 volts and 5.0 volts. The applicable test circuit is illustrated in Figure 4. In this circuit, V_{off} closely approximates $V_{BE(off)}$ when the Baker clamp diodes are switched out. In these experiments, V_{off} was held constant. Therefore, actual Baker clamped $V_{BE(off)}$ is approximately 0.8 volts less than the unclamped value.

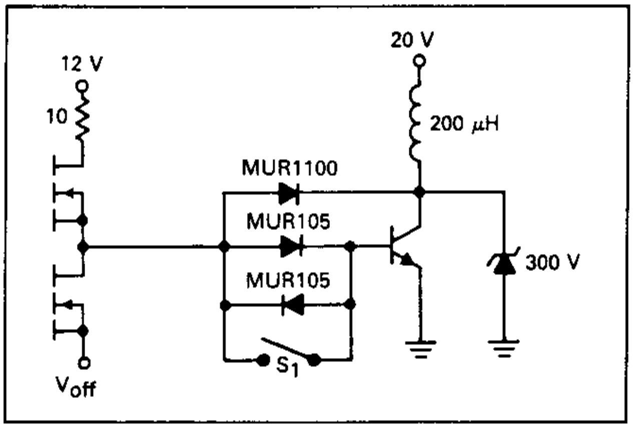

FIGURE 4 — Fixed Reverse Base Voltage

The fixed $V_{BE(off)}$ approach gives both the best and the worst results. Consider switching time — the best crossover times were obtained with fixed off voltage and Baker clamps. However, the worst crossover times were obtained with fixed $V_{BE(off)}$ and no Baker clamp. From a switching point of view, fixed off drive is an optimal approach if and only if a Baker clamp is used.

The situation is a little different for reverse safe area. Optimum results are obtained with a fixed 5.0 volt off drive with or without the Baker clamp. Turning in an impressive 7.0 amp performance at 1000 volts, the 5.0 volt off drive scored the highest reverse safe area. The Baker clamp made little difference, showing a 6.8 amp capability with the diodes in place.

Varying the off voltage from 2.0 volts to 5.0 volts did not make much difference in crossover time. The lower off bias gives the best result, but only by a thin margin. The most pronounced effect is on storage time, where the 530 ns 2.0 volt Baker clamped value is reduced to 280 ns, with a 5.0 volt bias. RBSOA also benefits from the higher level of off drive, improving by roughly 1.0 amp as off drive is increased from 2.0 volts to 5.0 volts. All things considered, 5.0 volts of $V_{BE(off)}$ seems to be the more optimum of the two drive levels.

SERIES BASE INDUCTOR

The series base inductor is a traditional drive method that is used by the TV industry. It is noted for significant improvements in fall time, with a corresponding sacrifice in storage time. The results obtained with the circuit of Figure 5 do not entirely fit this pattern.

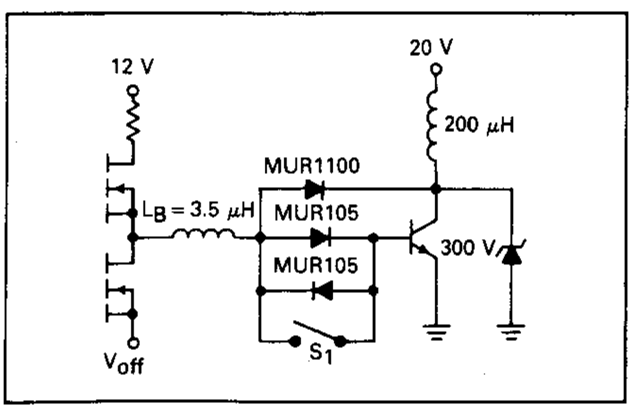

FIGURE 5 — Series Base Inductor

Crossover time is among the best, but not the best recorded. Fixed $V_{BE(off)}$ does better with a Baker clamp. Single ended push-pull and fixed I_{B2} do better without the clamp. Similarly, the highest storage time was obtained with fixed I_{B2}, and not the series base inductor. RBSOA results are at the median of the group, three are better and three are worse.

Although the series base inductor circuit tends to optimize crossover time for 1500 volt deflection transistors, it appears to offer little advantage for these 1000 volt off-line converter parts. Several of the other drive methods offer similar crossover times with definite improvements in both storage time and RBSOA.

SINGLE ENDED PUSH-PULL

Single ended push-pull was chosen for its ability to avalanche the test transistor's base emitter junction. The circuit shown in Figure 6 provides an avalanche condition for approximately 10 μs, with a reverse current that is limited by the turn-on base current I_{B1}.

In a similar study of 1500 volt transistors, this circuit produced the best switching results. Switching times were good here, also, but not the best. Looking at RBSOA, the results are not so encouraging. Single ended push-pull gave the worst RBSOA performance of all. For the 1000 volt transistor, this is not an optimum drive technique.

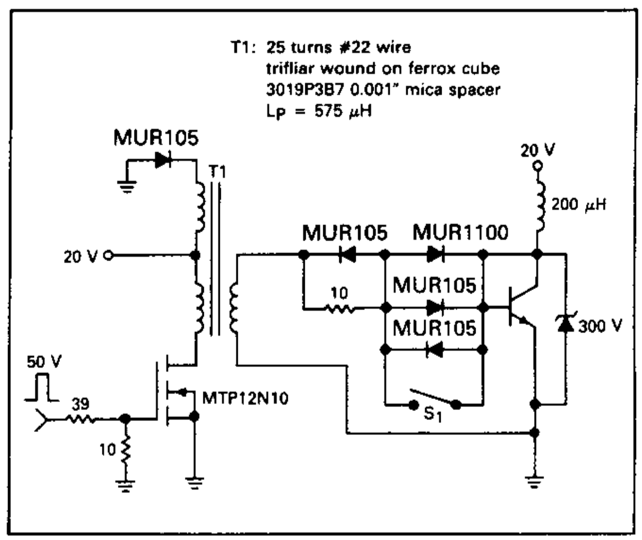

FIGURE 6 — Single Ended Push Pull

EMITTER SWITCHED

Emitter switching has been much touted as a technique for achieving dramatic improvements in switching time and reverse safe area. However, there is a catch. This technique is effective only for transistors with collector-base breakdown voltages less than roughly 800 volts. As breakdown voltage is increased above 800 volts, emitter switching becomes less and less effective. Since the MJH16006's median collector-base breakdown voltage is between 1100 and 1200 volts, one might expect that emitter switching is not the optimum drive technique.

Test data from the circuit in Figure 7 supports this prediction. Although emitter switching is far from the worst drive technique, it is not the best for either crossover time or RBSOA. However, when Baker clamped, crossover time and RBSOA are close enough to optimum that this technique could conceivably be used for other reasons, such as drive simplicity.

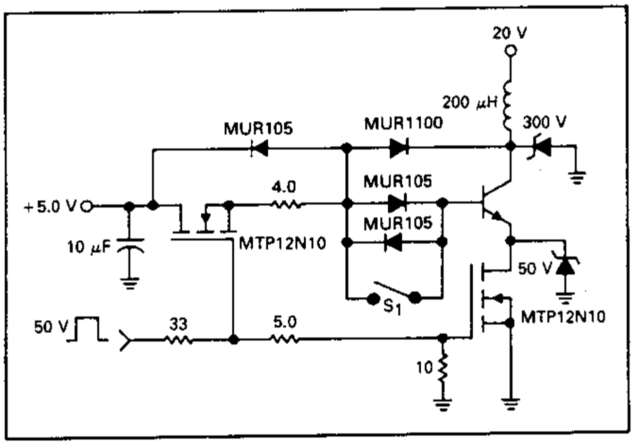

FIGURE 7 — Emitter Switching

BAKER CLAMPS

A common thread runs through the drive circuit experiments described here. That commonality is the Baker clamp. Regardless of the type of drive circuit, use of the Baker clamp improves performance.

Baker clamps also have another important attribute. They make the optimization job easier. This idea is illustrated by the curves in Figure 8. These curves show crossover time plotted versus I_{B2} for both clamped and unclamped operation. Note that the unclamped curve has a much narrower trough, indicating a much higher sensitivity to small changes in off-bias.

The clamped response is inherently nicer to work with, giving a little more freedom to maneuver. It also suggests minimized risks. Baker clamped performance is less affected by unanticipated changes in component characteristics. The Baker clamp builds in the kind of forgiveness that may seem unnecessary on paper, but often proves its worth in the field.

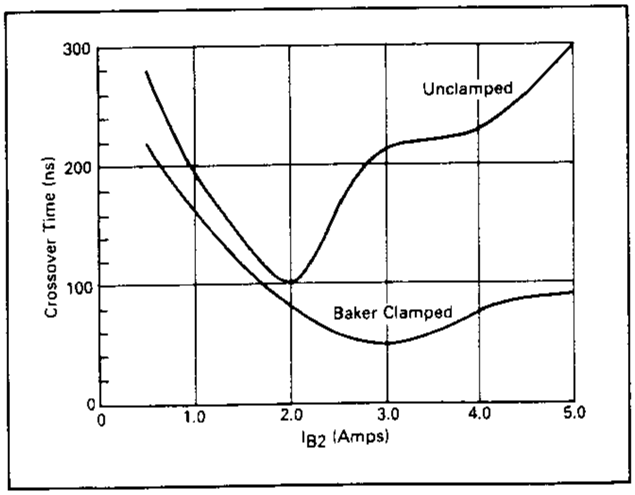

FIGURE 8 — Baker Clamped Performance

REVERSE BASE SAFE OPERATING AREA

The preceeding experiments have focused on RBSOA at 1000 volts. It is assumed that this is the point of most interest for off-line converter applications. Just in case this is a bad assumption, a look at the complete RBSOA curve, for two values of off-bias, are included in Figure 9.

These curves differ from their data sheet counterparts in one important respect. They show actual failure points, not guaranteed limits. These curves show the expected crossover, with the 5.0 volt off-bias superior at high voltages and the 2.0 amp off-bias superior at high currents. They also show an RBSOA capability, which is dramatically better than what is indicated on the MJ16006A data sheet. The data sheet is being revised to show a more realistic capability, and will guarantee 4.0 amps at 1000 volts.

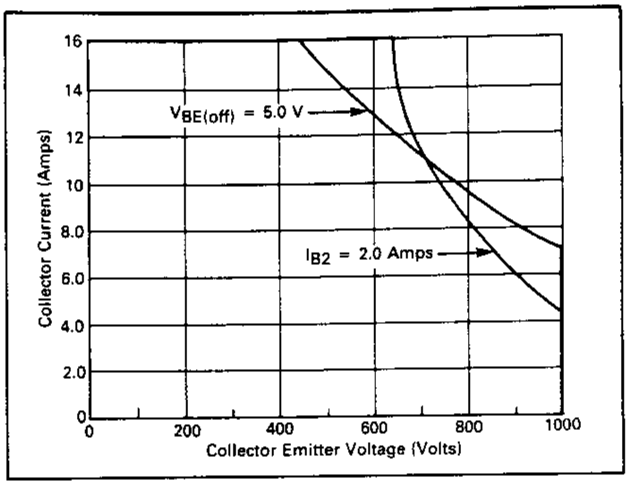

FIGURE 9 — RBSOA

PRACTICAL REALIZATION

Fortunately, choosing an optimum drive technique from the foregoing data is not nearly as difficult as it can be with some transistors. There are no troublesome tradeoffs between crossover time, storage time, and reverse safe area. Near optimum performance in all three areas is readily obtained with a Baker clamped 5.0 volt off drive.

Although the test results are fairly clear, the 5.0 volt off drive that was used for making accurate measurements is not terribly practical for use in a switching power supply. The question remains as to how close a simple practical circuit can come to the test results. The circuit described in Figure 10 is designed to answer this question.

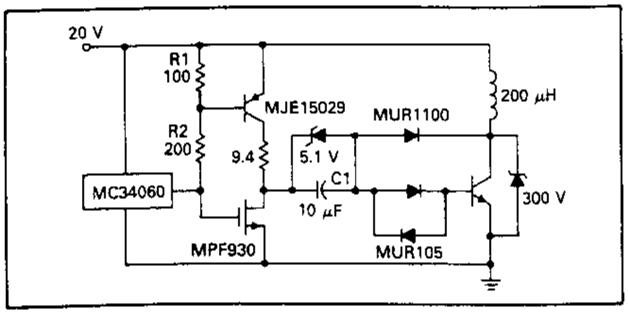

FIGURE 10 — Practical Realization

This circuit is based upon the popular MC34060 switching power supply control IC. It develops a 5.0 volt off drive by first charging C1 up to 5.1 volts during the transistor's on time. When Q1 then pulls the input side of C1 to ground, the Baker clamp's input is pulled down 5.1 volts, less the on-voltage of Q2. This is not quite as stiff as the original test circuit; however, the results are quite good. They are summarized in Table 2.

TABLE 2

Parameter	Test Circuit	Applications Circuit
Storage Time (ns)	280	380
Crossover Time (ns)	80	100
RBSOA (Amps)	6.8	7.4

Switching times are almost as good, but not quite. The slightly slower times are the result of a compromise that was made in choosing R1 and R2. Higher values minimize the power dissipation in these resistors, lower values improve switching time. This tradeoff is relatively straightforward. The applications circuit places a higher premium on drive power, and trades off a small amount of switching time to do so.

What is not straightforward is the reverse safe area results. The applications circuit gives a better result for reasons which are not readily apparent. Like many successful experiments, this one has generated questions as well as answers.

CONCLUSION

A number of conclusions can be drawn from the test results presented here. First, it is evident that bias optimization is an important part of switching power supply design. One kilovolt third generation power transistors are intended to facilitate an optimum power supply design, but proper choice of transistors is not enough. Bias optimization is crucial. Second, Baker clamps make the design job easier. They not only contribute to significantly improved performance, but also reduce the risks associated with component variations.

The best results were obtained with on-drive Baker clamped, and off-drive supplied by a 5.0 volt source. Biased in this way, 80 ns crossover times and 6.8 amps of RBSOA at 1000 volts were achieved. This kind of performance can appreciably affect the competitiveness and reliability of today's off-line switcher designs. In particular, the reverse safe area is so good that snubbers can be minimized and safety margin improved. Coupled with excellent switching, these benefits inevitably translate into higher reliability, more competitive, switchers.

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