MOTOROLA
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Application Note

POWER TRANSISTOR SAFE OPERATING AREA — SPECIAL CONSIDERATIONS FOR MOTOR DRIVES

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Motor drives present a unique set of safe operating area conditions to power output transistors. Starting with the basics of forward and reverse safe operating area, considerations unique to motor drives are discussed.

The industrial motor drive application is significantly enough different from the electronic uses of power transistors, that a new safe operating area specification has been developed. It is called overload safe operating area (OLSOA). The concept and the data sheet curves that go with it are presented.

INTRODUCTION

Power transistors are being used routinely in today's motor control systems. Most often these transistors have been designed for electronic applications. All of the safe operating area (SOA) conditions which typically occur in motor drives are not necessarily addressed.

The emergence of new transistors designed specifically for motor controls is bringing SOA specifications and capabilities that are more closely matched to actual operating conditions. The information presented here describes the new specifications, and reviews the considerable amount of standard SOA information which is of use to the motor drive designer.

REVIEW OF FORWARD BIAS SAFE OPERATING AREA (FBSOA)

Forward bias safe operating area measures the ability of the transistor to handle stress when its base is forward biased. The FBSOA curve contains maximum limits for both steady state dissipation and turn-on load lines. Both aspects are examined.

Definition

Forward bias safe operating area is defined for conditions in which the base is forward biased. Since it is possible to have a positive base-emitter voltage and negative base current during storage time, forward bias is defined in terms of base current. The FBSOA curve applies when turn-on base current (I_{B1}) is flowing, or when the base is open circuited. When turn-off base current is flowing, even if the source is merely a resistor from base to emitter, reverse bias safe operating area applies.

The short pulsewidth FBSOA curve is the load line boundary for turn-on switching. The typical transistor data sheet shows a 5 to 10 microsecond curve. The shorter of the two makes a practical boundary for the turn-on load line.

To complete the definition, it is appropriate to specify a means of measurement. Forward bias safe operating area is measured in a common base test circuit. A simplified schematic is illustrated in Figure 1. This type of circuit allows reasonable precision in defining the three FBSOA variables: collector-emitter voltage, collector current, and time, without having to change input conditions for each transistor.

Voltage Sensitivity

Power transistors are a great deal more sensitive to voltage stress than they are to stress imposed by large collector currents. This is particularly true of bipolar transistors, and shows up readily on the FBSOA curve. Using the curve in Figure 2 as an example, it is easy to show just how significant this voltage sensitivity is.

At Point A, allowable power dissipation is 150 amps x 3.33 volts = 500 watts. As the thermal limit portion of the curve is traversed to Point B, there is no change in power dissipation, 50 amps x 10 volts = 500 watts. However, when a point on the second breakdown portion of the curve is chosen at point C, allowable power dissipation is reduced dramatically to 30 watts.

By definition, the second breakdown portion of the FBSOA curve is that portion in which allowable power dissipation is decreasing with increased voltage. The physics behind this phenomenon is explained with the aid of Figure 3.

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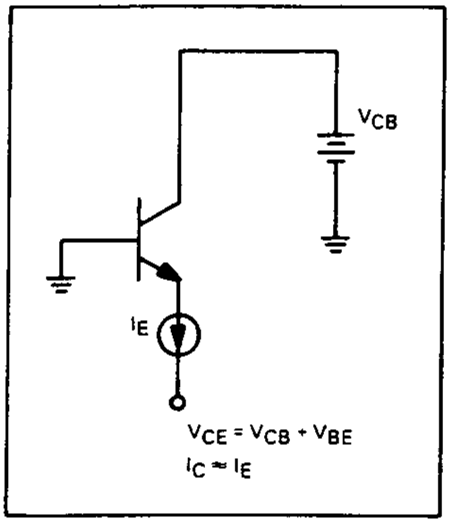

FIGURE 1 — FBSOA Test Circuit

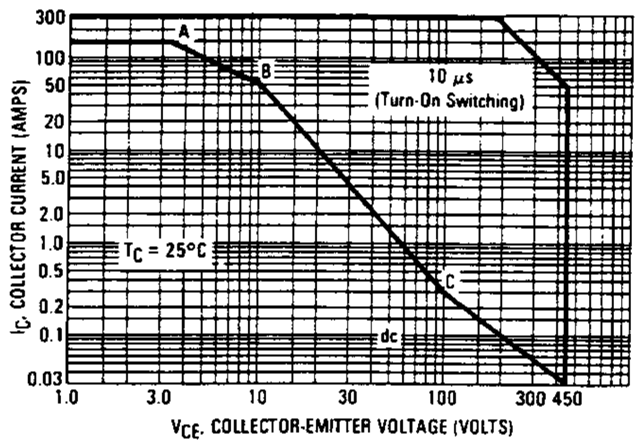

FIGURE 2 — FBSOA Curve (MJ10100)

Current density is superimposed upon the cross section of an emitter finger for two values of collector-emitter voltage, V_{CE} = 10 volts, and V_{CE} = 100 volts.

It is evident from the figure, that current density increases dramatically as voltage rises. As the current density increases, the area in which power dissipation occurs decreases. In other words, the effective size of the transistor becomes smaller and smaller as its collector-emitter voltage is raised.

Looking one step further, increasing current density with collector voltage can be explained by collector-base depletion. As collector voltage is increased, depletion into the metallurgical base increases. The electrical base width is thereby narrowed, causing an increase in the lateral resistance of the base underneath the emitter. In turn, base current to the center of the emitter finger is choked off, limiting the amount of current that will flow through the center of the finger. With very little current flowing through the center, current flow is restricted to the edges. This restriction results in a higher current density at the edge, which gets higher as collector voltage is increased.

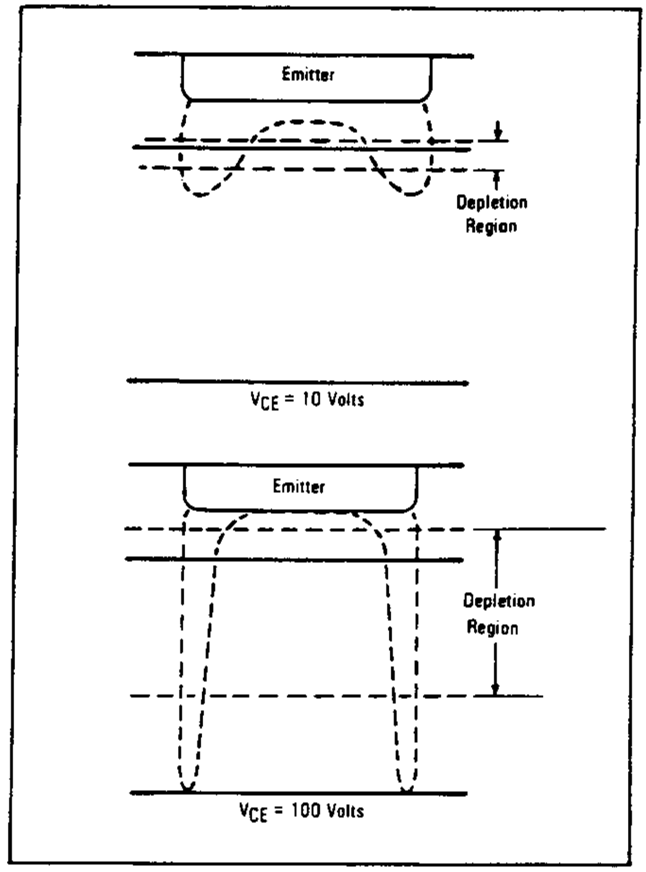

FIGURE 3 — Current Density Comparison

Before ending the discussion of voltage sensitivity, it is worth spending a few moments to consider $V_{CEO(sus)}$, the limit at the right-hand side of the FBSOA curve. There is a point worthy of emphasis. Namely, that $V_{CEO(sus)}$ is an instantaneous limitation. Any excursion of the turn-on load line beyond $V_{CEO(sus)}$, or any condition where $V_{CE} > V_{CEO(sus)}$ with forward bias base current applied, invites failure of the transistor.

Temperature Derating

Temperature derating of FBSOA is a fairly straightforward procedure. However, keeping in mind the preceding discussion on voltage sensitivity, there is a right way and a wrong way to do it.

In the thermally limited region of the FBSOA curve, temperature derating is quite simple. Allowable power dissipation can be found at any case temperature according to the following equation:

---$P_D = (T_J \text{ Max} - T_C)/R_{\theta JC}$

---where: P_D = Maximum Allowable Power Dissipation

T_J = Maximum Specified Junction Temperature

T_C = Case Temperature

$R_{\theta JC}$ = Junction to Case Thermal Resistance

If you prefer to use a curve, a derating factor may be obtained from Figure 4. This derating factor multiplied by the maximum power dissipation limit will yield the same result as the equation.

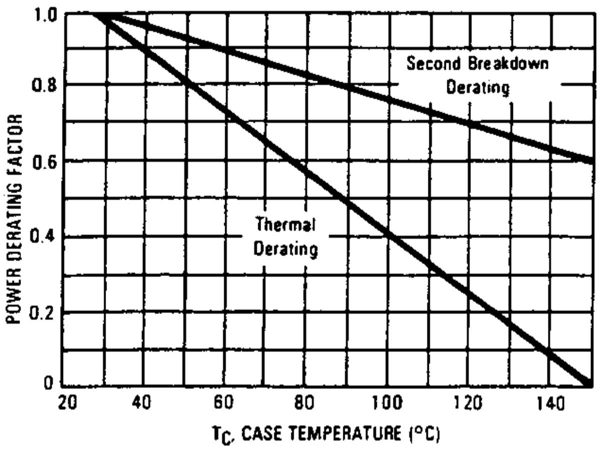

FIGURE 4 — Power Derating

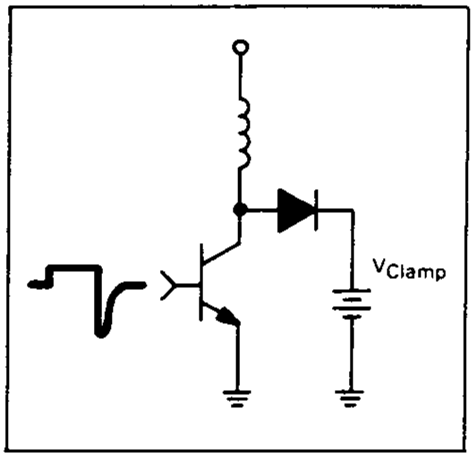

FIGURE 5 — RBSOA Test Circuit

It is in the second breakdown limited portion of the FBSOA curve that the right way, and the wrong way come into the picture. Due to the greater voltage sensitivity of the transistor, derating first starts with voltage and proceeds according to the following steps:

1) At any given voltage, determine maximum allowable power by reading current off the FBSOA curve and multiplying by the voltage.
2) Derate maximum allowable power at temperature, by applying the appropriate derating factor from the second breakdown derating curve in Figure 4.
3) Convert maximum allowable power into maximum allowable current by dividing the voltage into maximum allowable power.
4) Check to make sure that the thermal limit is not exceeded, it applies also.

This procedure is equally applicable to both the pulsed and dc forward bias SOA curves. It, therefore, applies to turn-on load lines as well as conditions of steady state power dissipation.

REVERSE BIAS SAFE OPERATING AREA (RBSOA)

Reverse bias safe operating area is a measure of the transistor's ability to handle stress with its base reverse biased. The RBSOA curve represents the outer boundary for allowable turn-off load lines.

Definition

Reverse bias safe operating area is defined for conditions in which the base is reverse biased. Again, the definition is in terms of current. Reverse bias safe operating area applies to situations in which turn-off base current (I_{B2}) is flowing.

It is measured in the simple flyback circuit shown in Figure 5. The RBSOA curve is a measure of the simultaneous peak collector current and peak clamp voltage that the transistor can withstand in this circuit.

Forward and reverse bias safe operating area are analogous in many respects. One of these is voltage sensitivity. Bipolar power transistors exhibit the same sensitivity to voltage stress in the RBSOA mode that they do in forward bias conditions. It is easy to see from the RBSOA curve in Figure 6, that allowable peak instantaneous power decreases dramatically as voltage is increased.

There is a voltage limit beyond which the transistor will accept no stress. This limit is the collector-base breakdown voltage, commonly referred to in power transistor data sheets as V_{CEV}. Any excursion beyond V_{CEV} will cause device failure.

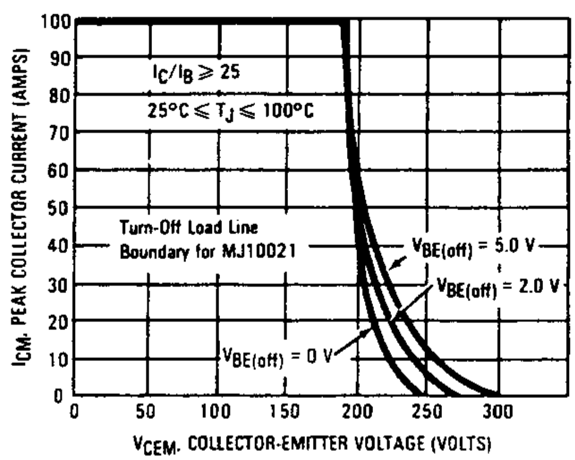

FIGURE 6 — RBSOA Curve (MJ10021)

Temperature Derating

The analogy between forward and reverse bias safe operating area breaks down when it comes to temperature derating. Whereas forward bias SOA requires considerable derating with temperature, reverse bias SOA is essentially independent of temperature. In fact, over the temperature range of 25°C to 100°C, RBSOA of the most commonly used motor control output transistors increases with increasing temperature.

This seemingly contradictory behavior is caused by a strong dependency of RBSOA upon collector resistivity. As temperature goes up, the effect of increasing collector resistivity with temperature predominates over the thermal effects. The result is RBSOA performance which is flat to slightly improving with temperature.

Time

The variables associated with an RBSOA curve are peak collector-emitter voltage (V_{CEM}), peak collector current (I_{CM}), and off-bias. Time does not appear in an RBSOA specification. It is an instantaneous limitation. The turn-off load line is not safe if it goes outside the RBSOA curve even for a brief instant. In fact it is the very short voltage spikes, associated with unclamped inductance, that are most likely to kill transistors at turnoff.

Obviously, in any SOA limit, time has to be factored in somehow. The off-bias variable in RBSOA specs indirectly establishes a time constraint. With a given off-bias, the crossover time of the transistor will be limited to some maximum amount. This amount of time is built into the RBSOA curve.

Off-Bias

Off-bias has a very significant effect upon RBSOA performance. It has a large influence for the following two reasons:

1) Crossover time, and therefore, the amount of energy that the transistor sees, is heavily dependent upon off-bias.
2) Current crowding at turn-off is directly related to off-bias.

These concepts are illustrated in Figures 7 and 8.

From Figure 7 it is readily apparent that as off-bias is increased, the amount of energy in any given RBSOA condition decreases. This effect tends to improve RBSOA performance with increasing off-bias. On the other hand, Figure 8 shows how increasing off-bias increases current density during RBSOA stress. A lateral electric field associated with the off-bias increasingly constricts current flow to the center of the emitter finger, as off-bias is increased. This is very similar to the second breakdown effect in forward bias SOA, and tends to limit RBSOA performance.

With these two factors working against each other, it is possible to design power transistors such that RBSOA will either increase or decrease with increasing off-bias. The fact that different manufacturers advertise RBSOA performance going in opposite directions, represents no real conflict. The divergent RBSOA performance merely reflects differences in transistor design.

SPECIAL CONSIDERATIONS FOR MOTOR DRIVES

There are a number of conditions which frequently occur in motor drives that are not directly addressed by standard concepts of forward and reverse bias safe operating area. Parallel operation, large currents through collector-emitter diodes, and phase-to-phase shorts are among these conditions. A discussion in relation to survivability of the power transistor begins with parallel operation.

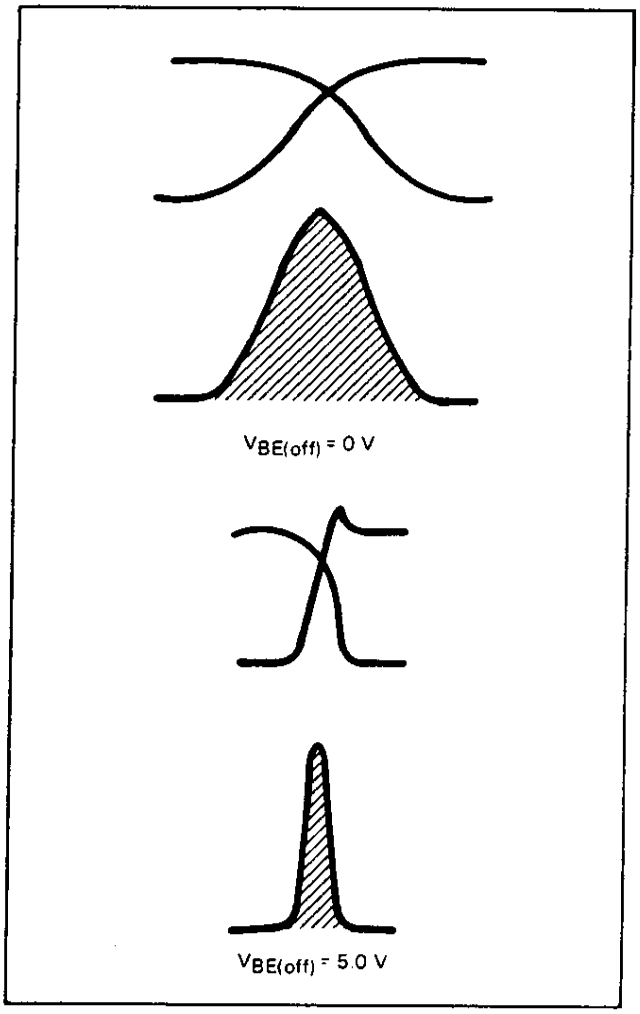

FIGURE 7 — RBSOA Energy Relationships

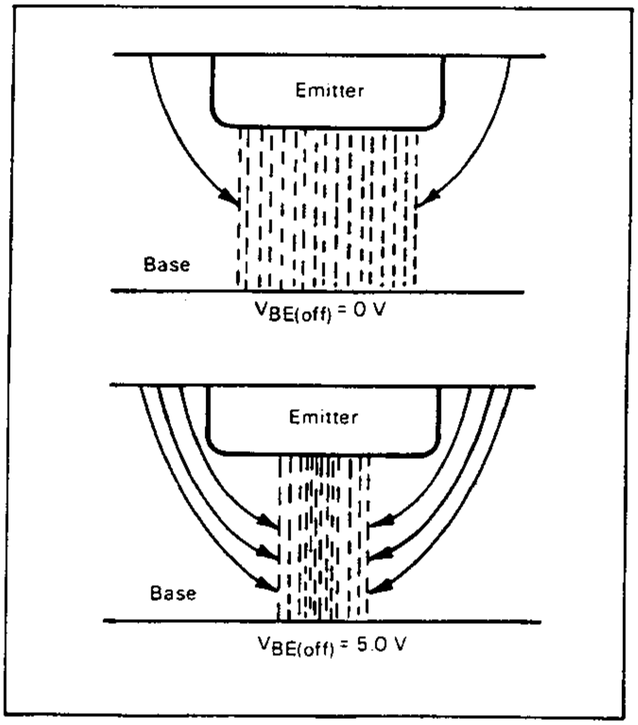

FIGURE 8 — RBSOA Current Crowding

Parallel Operation

Motor drives are one of the better examples of systems which frequently have need for parallel output transistors. With paralleling always comes the question of sharing. The degree to which the power transistors share load current has a significant bearing upon SOA limits, and the reliability of the drive.

This problem can be broken down into three areas: turn-on sharing, saturated sharing, and turn-off sharing.

Turn-on and saturation are usually not a problem. The transistors will turn-on and remain saturated in such a way as to maximize the gain of the combination. This is not an entirely bad situation, considering the desirability of high gain. Also, since the gain of high voltage transistors falls off rapidly with increasing collector current, it is generally difficult for one transistor to take an unreasonable share of the total load current. Turn-on and saturated sharing normally cause very few problems in motor drives.

The challenge comes along when it is time for the transistors to turn off. Due primarily to storage time, it is entirely possible for the slowest transistor to absorb the full RBSOA stress of the combination. This possibility is illustrated in Figure 9.

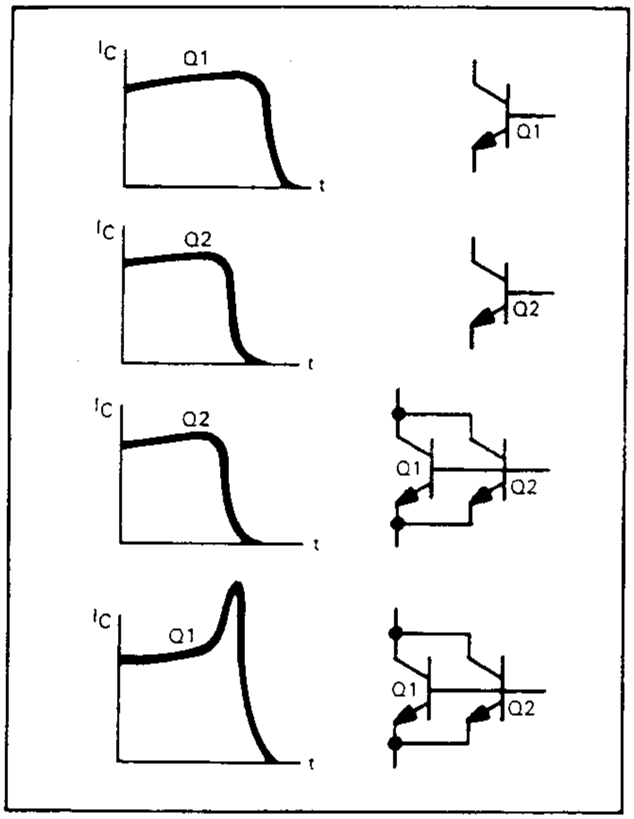

FIGURE 9 — Turn-Off Sharing

In this example, Q2 turns off faster than Q1. Since the load current has not changed, Q1 takes a spike equal to the full load. It sees this spike for approximately the amount of time corresponding to the difference between its storge time and Q2's storage time.

One way to get around this problem is to take advantage of the transistor's characteristics. Just as power transistors are very sensitive to voltage stress, conversely they are very insensitive to current stress, if the voltage is held to a moderate value.

In terms of circuit design, what this means is snubbing the load line. Large spikes of collector current at turn-off will not harm the transistor, provided that the load line is adequately shaped.

The question of how much snubbing is adequate can be somewhat of a thorny issue. Semiconductor manufacturers have seen slow to recognize the need for specifying RBSOA at very high currents, and to recognize the very considerable capabilities of the transistors.

This problem is being solved with some of the newer transistors that are designed specifically for motor control applications. As an example, the MJ10100 data sheet specifies RBSOA out to three times rated collector current. Implicit on this specification is the ability to operate three devices in parallel, at full rated current, without regard to turn-off sharing. Of course, this is only true provided that collector-emitter voltage is snubbed to within limits set by the RBSOA curve.

The waters are considerably more muddy when a transistor with a typical RBSOA specification is being used. Perhaps a rule of thumb will be of some help. Such a rule can be stated as follows: If the load line is snubbed to within 1/2 $V_{CEO(sus)}$ at the point of peak collector current, then the transistor will usually run out of gain before it runs out of RBSOA capability.

It should be kept in mind that this is only a rule of thumb. It is included here to communicate something of what the real capabilities of the output transistor are, and to open an avenue of discussion with transistor manufacturers. In no way is the rule of thumb intended to replace an adequate RBSOA specification.

Whether in terms of guaranteed RBSOA, or transistor characteristics in general, the bottom line is that power output transistors can be safely and simply paralleled. Elaborate schemes to insure current sharing are not necessarily needed; what is needed, is a well snubbed turn-off load line.

Collector-Emitter Diode

In addition to being a good example for parallel output transistors, motor drives are also a good example of systems which significantly stress the collector-emitter diode. In most instances the diode has to have the same forward current capability as the transistor. In PWM systems, a requirement for fast reverse recovery is added to the need for high average current.

The potential for safe operating area related overstress can be appreciated when it is realized that the collector-emitter (freewheeling) diode has been largely neglected by the semiconductor industry. In the typical general purpose high voltage darlington transistor, this diode is parasitic. The parasitic nature of the diode can give rise to three types of SOA problems in motor drives:

1) Average forward current capability is significantly less than that of the transistor.

2) Maximum power dissipation is also significantly less.
3) Gain multiplication of stored charge results in reverse recovery times significantly slower than what would normally be expected.

In other words, the capabilities of the parasitic diode are somewhat limited. SOA problems in motor drives have been further exacerbated by the failure of the semiconductor industry to fully communicate what the capabilities are.

In an effort to improve communication on this subject, a brief description of how the typical monolithic freewheeling diode is made follows.

The typical freewheeling diode is a result of the way that the output base-emitter resistor is made in a monolithic darlington transistor. A portion of the emitter metal is shorted to the base, as shown in Figure 10. The resistor is formed by the sheet resistance of the base between the metalized areas.

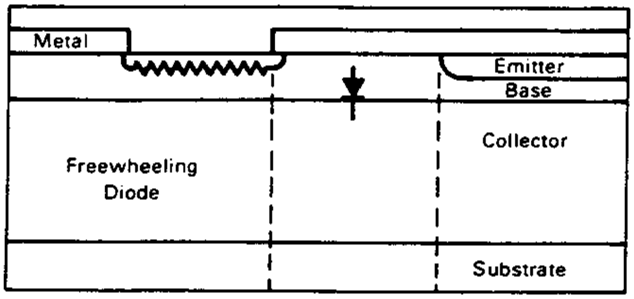

FIGURE 10 — Parasitic Freewheeling Diode

Underneath the short, there is a single P-N junction between the emitter metal and the collector. This area underneath the short forms the diode. It is a relatively small portion of the total collector-base junction. Consequently it does not have the same power, or current handling capability as the transistor.

The parasitic nature of this diode also has some implications regarding its speed. During the time that forward current passes through the diode, charge is stored in its anode and cathode. Since the anode is the base of the transistor, and the cathode is the collector, charge is stored in the base-collector junction of the transistor. When the voltage on the diode is abruptly reversed, there is an opportunity for this charge to be gain multiplied by the transistor. This phenomenon has been known to cause serious problems in bridge type PWM applications. It is not an issue in six step ac drives.

In most bridge-type motor drives, the parasitic diode needs to be supplemented with an external rectifier. The parallel rectifier provides the required forward current capability. It also provides more fully specified characteristics.

An important additional consideration, in bridge type PWM systems, is keeping current out of the parasitic diode. If current is allowed to flow through this diode, speed problems can be counted upon. Gain multiplication of stored charge in the parasitic will swamp out the switching speed of the external rectifier, even if it is a fast recovery type.

Since circuit techniques for keeping current out of the parasitic diode are generally messy, semiconductor manufacturers are beginning to offer a number of high voltage darlingtons with no internal collector-emitter diode. These transistors can be extremely useful in PWM systems.

New families of transistors, designed specifically for motor drives, address the diode issue in a much better way than merely leaving it out. These transistors include the diode as a separate hybrid chip. Forward current capability is equivalent to that of the transistor. The communication problem is solved by including important diode parameters on the data sheet. As a minimum these include:

—Power Dissipation
—Forward Voltage Specification
—Forward Voltage versus Current Curve
—Forward Turn-On Time
—Reverse Recovery Time
—Surge Current

Again, the MJ10100 serves as a good example of the changes that take place when a transistor is designed specifically for motor control. The data sheet communicates the capabilities of the diode. More important, the diode will take all the abuse that the transistor will handle, and then some.

Overload Safe Operating Area

The usual forward bias safe operating area (FBSOA) specifications adequately describe transistor capability for normal operation in motor drives. When a short between two phases of the drive occurs however, the usual transistor specifications are not always applicable. A specification called overload safe operating area (OLSOA) has been developed to describe the transistor's ability to survive this situation.

OLSOA comes in two varieties, Type I and Type II. Type I applies when maximum collector current is limited and known. A good example is a circuit where an inductor is inserted between the transistor and the bus which limits the rate of rise of collector current to a known value. If the transistor is then turned off within a specified amount of time, maximum collector current is also known. Figure 11 depicts a Type I OLSOA curve.

In Figure 11, maximum allowable collector-emitter voltage versus collector current is plotted for several pulse widths. Pulse width is defined as the time lag between the fault condition and the removal of base drive. Storage time of the transistor has been factored into the curve. Therefore, with bus voltage and maximum collector current known, Figure 11 defines the maximum time which can be allowed for fault detection and shutdown of base drive.

Type I OLSOA is measured in a common base circuit (Figure 12). This circuit allows relatively precise definition of collector-emitter voltage and collector current. This is the same circuit which is used to measure forward bias safe operating area. Type II OLSOA (Figure 13) applies when maximum collector current is not limited by circuit design. Collector current is limited

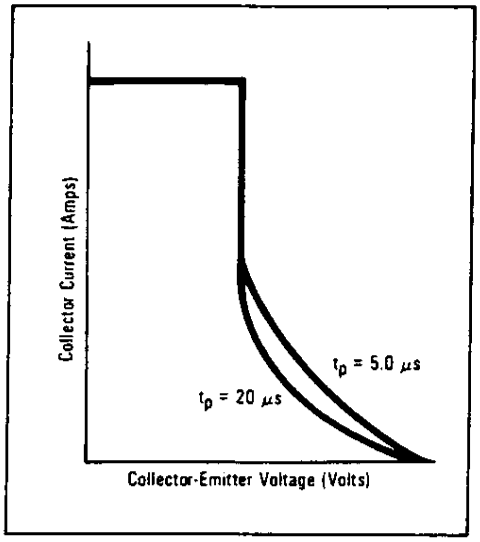

FIGURE 11 — Type I OLSOA

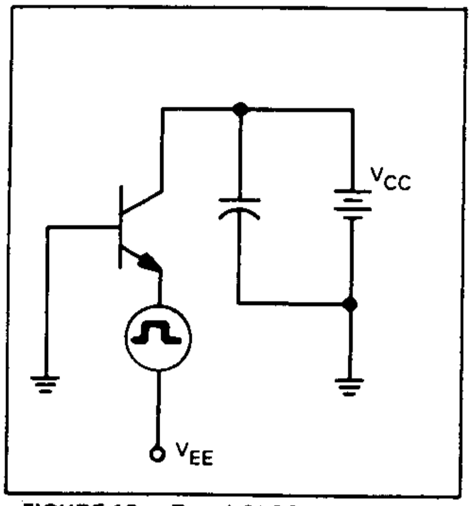

FIGURE 12 — Type I OLSOA Test Circuit

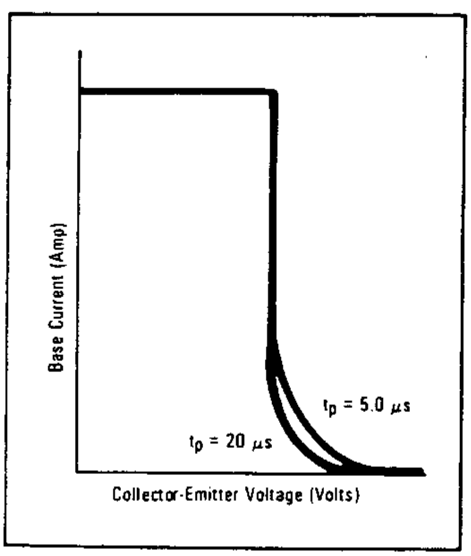

FIGURE 13 — Type II OLSOA

only by the gain of the transistor. Therefore, collector current does not appear on the Type II OLSOA curve. An SOA curve without collector current may look strange at first. However, the idea is to define a safe region of operation from the information that the designer has readily available.

This information is usually base drive, bus voltage, and time. In terms of the OLSOA curve, bus voltage is assumed to be worst case collector-emitter voltage, and time is defined to be the same pulse width that was described for Type I OLSOA. Using these variables, maximum collector-emitter voltage versus base drive is plotted for several values of pulse width. A safe region of operation is thus determined by the circuit parameters.

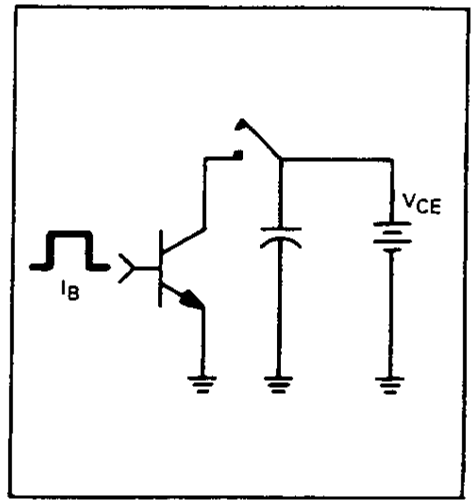

FIGURE 14 — Type II OLSOA Test Circuit

Type II OLSOA is measured in the circuit shown in Figure 14. The essence of this measurement is as follows: Base current is applied while the collector is open, allowing a highly overdriven saturated condition. Next, a stiff voltage source is applied to the collector. The rising voltage at the collector of the transistor triggers a delay function. At the end of this delay base drive is removed. The delay time is the time variable on the Type II OLSOA curve. Storage time of the transistor is thereby factored into the curve.

There are several not so obvious factors to be taken into account regarding OLSOA. First and foremost, OLSOA is strictly a NON-REPETITIVE rating. It is intended to describe the survivability of the transistor during an accidental overload. It is not intended to describe a stress level which the transistor can handle indefinitely. The number of non-repetitive cycles for which OLSOA is defined varies from manufacturer to manufacturer. At Motorola we have chosen this limit as 100 cycles.

Another factor is turn-off bias. Since motor drives generally operate output transistors in the common-emitter configuration, turn-off bias is relevant to the OLSOA condition.

The effect of turn-off bias on OLSOA has been investigated for MJ 10000 series products which do not have base-emitter speedup diodes. For these products, turn-off bias has a second order effect upon OLSOA. Within reasonable limits, it matters very little whether the turn-off bias is relatively soft or relatively stiff. This observation is valid through the range $I_{B2} = 0$ (soft) to $V_{BE(off)} = 5.0$ V (stiff).

As of this writing, the effect of off-bias on OLSOA has not been determined for products which have the speedup diode. It is reasonable to expect that the characteristics of these products may be different.

Finally, OLSOA is subject to the same derating with temperature as normal FBSOA. The second breakdown derating curve is applied to the allowable current at any given voltage, using the same procedure that is followed with pulsed FBSOA.

Screening

When an application requires a large amount of a particular characteristic, it is sometimes tempting to screen for those components that have the largest amount of the desired characteristic. Motor drives and power transistor SOA fit into this category.

Where power transistor SOA is concerned, this temptation is to be avoided. Any time an SOA specification cuts into the distribution of the product (Figure 15), there will always be those transistors which pass - but have just barely made the spec. Invariably some of these units will have been overstressed, degraded and weakened. They can be a reliability hazard.

The preferable situation is to choose the SOA spec limit as depicted in Figure 16. This limit lies below the normal healthy distribution, yet weeds out product which is defective. It does not cut into the distribution of healthy transistors.

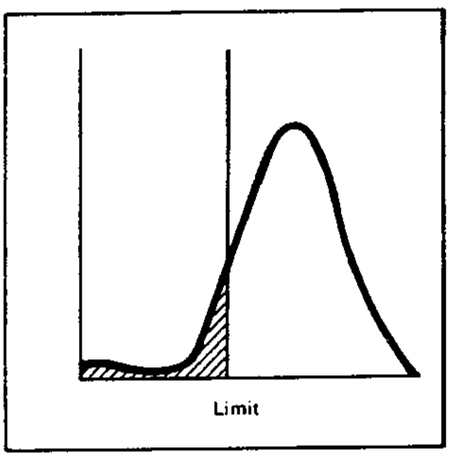

FIGURE 15 — Undesirable Screening Limit

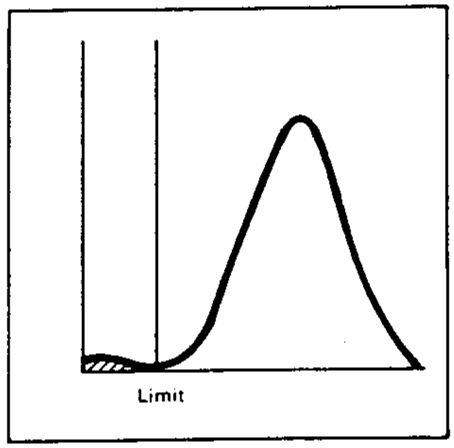

FIGURE 16 — Desirable Screening Limit

CONCLUSION

The kind of safe operating area information that is needed to design a reliable motor drive is becoming increasingly available from semiconductor manufacturers. The need for this information has been recognized, and has resulted in new methods of specification. The product itself has also been changed to meet the demanding needs of the motor control industry.

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