

AN1541

Introduction to Insulated Gate Bipolar Transistors

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INTRODUCTION

As power conversion relies more on switched applications, semiconductor manufacturers need to create products that approach the ideal switch. The ideal switch would have: 1) zero resistance or forward voltage drop in the on-state, 2) infinite resistance in the off-state, 3) switch with infinite speed, and 4) would not require any input power to make it switch.

When using existing solid-state switch technologies, the designer must deviate from the ideal switch and choose a device that best suits the application with a minimal loss of efficiency. The choice involves considerations such as voltage, current, switching speed, drive circuitry, load, and temperature effects. There are a variety of solid state switch technologies available to perform switching functions; however, all have strong and weak points.

HIGH VOLTAGE POWER MOSFETs

The primary characteristics that are most desirable in a solid-state switch are fast switching speed, simple drive requirements and low conduction loss. For low voltage applications, power MOSFETs offer extremely low on-resistance, $R_{DS(on)}$, and approach the desired ideal switch. In high voltage applications, MOSFETs exhibit increased $R_{DS(on)}$ resulting in lower efficiency due to increased conduction losses. In a power MOSFET, the on-resistance is proportional to the breakdown voltage raised to approximately the 2.7 power (1).

MOSFET technology has advanced to a point where cell densities are limited by manufacturing equipment capabilities and geometries have been optimized to a point where the $R_{DS(on)}$ is near the predicted theoretical limit. Since the cell density, geometry and the resistivity of the device structure play a major role, no significant reduction in the $R_{DS(on)}$ is foreseen. New technologies are needed to circumvent the problem of increased on-resistance without sacrificing switching speed.

$$R_{DS(on)} \propto V_{DSS}^{2.7} \quad (1)$$

ENTER THE IGBT

By combining the low conduction loss of a BJT with the switching speed of a power MOSFET an optimal solid state switch would exist. The Insulated-Gate Bipolar Transistor (IGBT) technology offers a combination of these attributes.

The IGBT is, in fact, a spin-off from power MOSFET technology and the structure of an IGBT closely resembles that of a power MOSFET. The IGBT has high input impedance and fast turn-on speed like a MOSFET. IGBTs exhibit an on-voltage and current density comparable to a bipolar transistor while switching much faster. IGBTs are replacing MOSFETs in high voltage applications where conduction losses must be kept low. With zero current switching or resonant switching techniques, the IGBT can be operated in the hundreds of kilohertz range [1].

Although turn-on speeds are very fast, turn-off of the IGBT is slower than a MOSFET. The IGBT exhibits a current fall time or "tailing." The tailing restricts the devices to operating at moderate frequencies (less than 50 kHz) in traditional "square waveform" PWM, switching applications.

At operating frequencies between 1 and 50 kHz, IGBTs offer an attractive solution over the traditional bipolar transistors, MOSFETs and thyristors. Compared to thyristors, the IGBT is faster, has better dv/dt immunity and, above all, has better gate turn-off capability. While some thyristors such as GTOs are capable of being turned off at the gate, substantial reverse gate current is required, whereas turning off an IGBT only requires that the gate capacitance be discharged. A thyristor has a slightly lower forward-on voltage and higher surge capability than an IGBT.

MOSFETs are often used because of their simple gate drive requirements. Since the structure of both devices are so similar, the change to IGBTs can be made without having to redesign the gate drive circuit. IGBTs, like MOSFETs, are transconductance devices and can remain fully on by keeping the gate voltage above a certain threshold.

As shown in Figure 1a, using an IGBT in place of a power MOSFET dramatically reduces the forward voltage drop at current levels above 12 amps. By reducing the forward drop, the conduction loss of the device is decreased. The gradual rising slope of the MOSFET in Figure 1a can be attributed to the relationship of V_{DS} to $R_{DS(on)}$. The IGBT curve has an offset due to an internal forward biased p-n junction and a fast rising slope typical of a minority carrier device.

It is possible to replace the MOSFET with an IGBT and improve the efficiency and/or reduce the cost. As shown in Figure 1b, an IGBT has considerably less silicon area than a similarly rated MOSFET. Device cost is related to silicon area; therefore, the reduced silicon area makes the IGBT the lower cost solution. Figure 1c shows the resulting package area reduction realized by using the IGBT. The IGBT is more space efficient than an equivalently rated MOSFET which makes it perfect for space conscious designs.

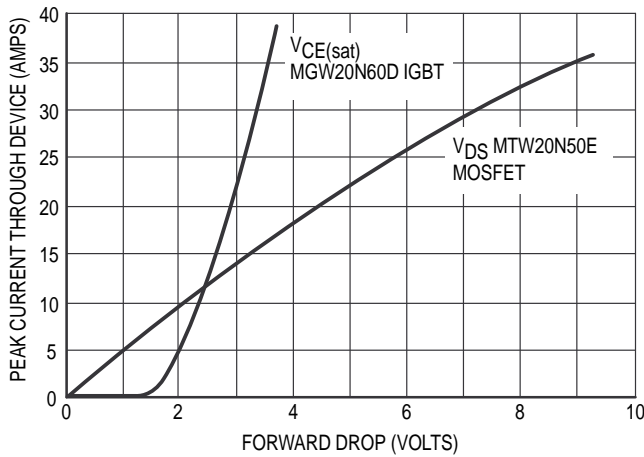


Figure 1a. Reduced Forward Voltage Drop of IGBT Realized When Compared to a MOSFET with Similar Ratings

When compared to BJTs, IGBTs have similar ratings in terms of voltage and current. However, the presence of an isolated gate in an IGBT makes it simpler to drive than a BJT. BJTs require that base current be continuously supplied in a quantity sufficient enough to maintain saturation. Base currents of one-tenth of the collector current are typical to keep a BJT in saturation. BJT drive circuits must be sensitive to variable load conditions. The base current of a BJT must be kept proportional to the collector current to prevent desaturation under high-current loads and excessive base drive under low-load conditions. This additional base current increases the power dissipation of the drive circuit. BJTs are minority carrier devices and charge storage effects including recombination slow the performance when compared to majority carrier devices such as MOSFETs. IGBTs also experience recombination that accounts for the current "tailing" yet IGBTs have been observed to switch faster than BJTs.

Thus far, the IGBT has demonstrated certain advantages over power MOSFETs with the exception of switching speed. Since the initial introduction of IGBTs in the early 1980s, semiconductor manufacturers have learned how to make the devices faster. As illustrated in Figure 2, some trade-offs in conduction loss versus switching speed exist. Lower frequency applications can tolerate slower switching devices.

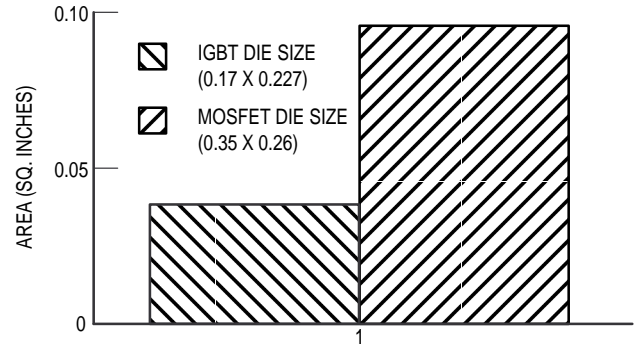


Figure 1b. Reduced Die Size of IGBT Realized When Compared to a MOSFET with Similar Ratings

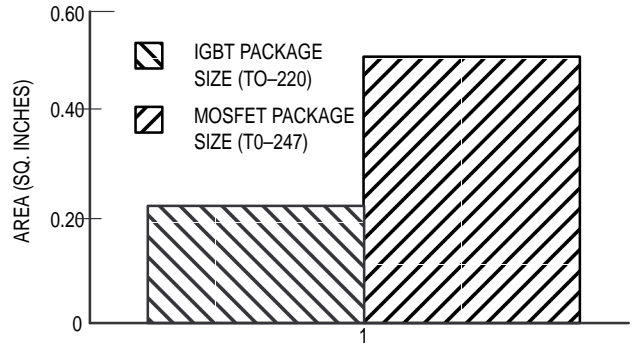


Figure 1c. Reduced Package Size of IGBT Realized When Compared to a MOSFET with Similar Ratings

Because the loss period is a small percentage of the total on time, slower switching is traded for lower conduction loss. In a higher frequency application, just the opposite would be true and the device would be made faster and have greater conduction losses. Notice that the curves in Figure 2 show reductions in both the forward drop ($V_{CE(sat)}$) and the fall time, t_f of newer generation devices. These capabilities make the IGBT the device of choice for applications such as motor drives, power supplies and inverters that require devices rated for 600 to 1200 volts.

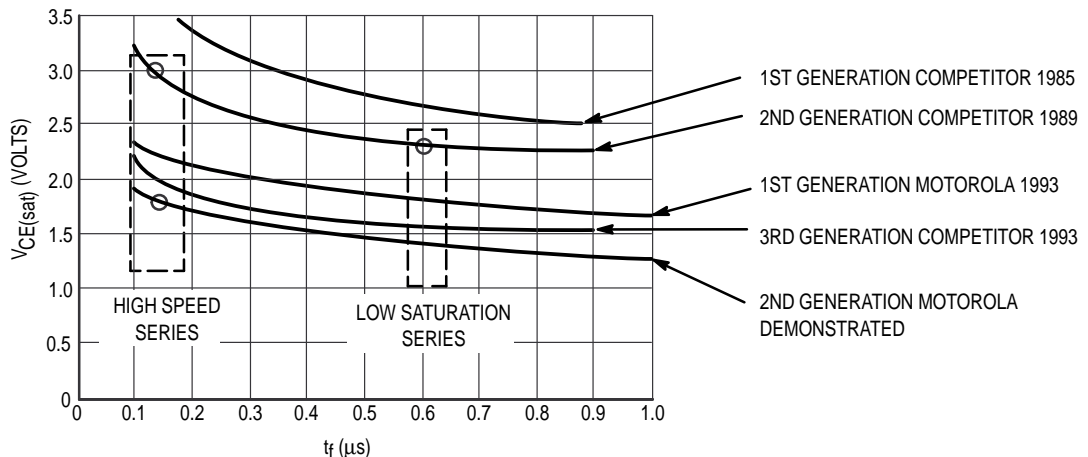


Figure 2. Advanced Features Offered by the Latest Motorola IGBT Technologies for Forward Voltage Drop ($V_{CE(sat)}$) and Fall Time (t_f)

CHARACTERISTICS OF IGBTs: DEVICE STRUCTURE

The structure of an IGBT is similar to that of a double diffused (DMOS) power MOSFET. One difference between a MOSFET and an IGBT is the substrate of the starting material. By varying the starting material and altering certain process steps, an IGBT may be produced from a power MOSFET mask; however, at Motorola mask sets are designed specifically for IGBTs. In a MOSFET the substrate is N+ as shown in Figure 3b. The substrate for an IGBT is P+ as shown in Figure 3a.

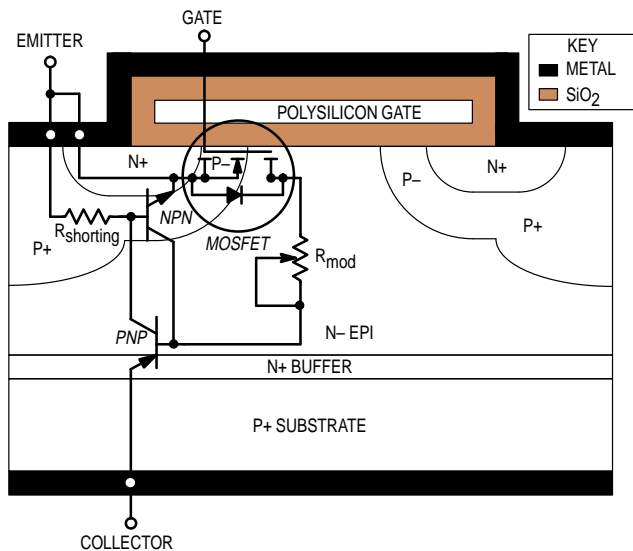


Figure 3a. Cross Section and Equivalent Schematic of an Insulated Gate Bipolar Transistor (IGBT) Cell

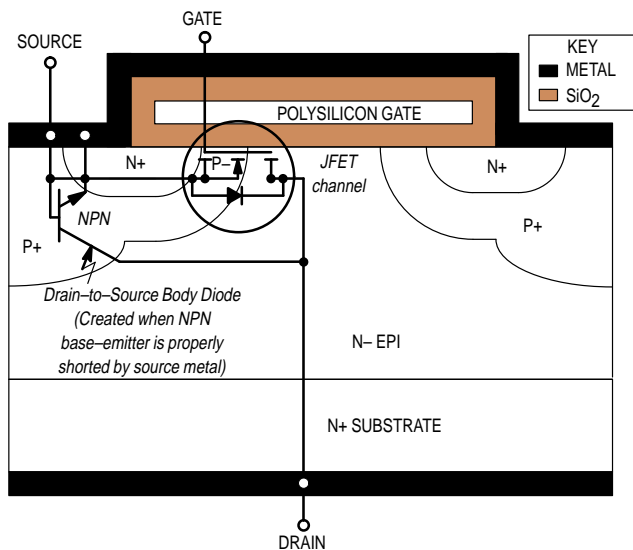


Figure 3b. Cross Section and Equivalent Schematic of a Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) Cell

The n- epi resistivity determines the breakdown voltage of a MOSFET as mentioned earlier using relationship (1).

$$R_{DS(on)} \propto V_{DSS}^{2.7} \quad (1)$$

To increase the breakdown voltage of the MOSFET, the n- epi region thickness (vertical direction in figure) is increased. As depicted in the classical resistance relationship (2), reducing the $R_{DS(on)}$ of a high voltage device requires greater silicon area A to make up for the increased n- epi region.

$$R \propto \frac{1}{A} \quad (2)$$

Device designers were challenged to overcome the effects of the high resistive n- epi region. The solution to this came in the form of conductivity modulation. The n- epi region to this was placed on the P+ substrate forming a p-n junction where conductivity modulation takes place. Because of conductivity modulation, the IGBT has a much greater current density than a power MOSFET and the forward voltage drop is reduced. Now the P+ substrate, n- epi layer and P+ "emitter" form a BJT transistor and the n- epi acts as a wide base region.

The subject of current tailing has been mentioned several times. Thus far, the device structure as shown in Figure 3 provides insight as to what causes the tailing. Minority carriers build up to form the basis for conductivity modulation. When the device turns off, these carriers do not have a current path to exit the device. Recombination is the only way to eliminate the stored charge resulting from the build-up of excess carriers. Additional recombination centers are formed by placing an N+ buffer layer between the n- epi and P+ substrate.

While the N+ buffer layer may speed up the recombination, it also increases the forward drop of the device. Hence the tradeoff between switching speed and conduction loss becomes a factor in optimizing device performance. Additional benefits of the N+ buffer layer include preventing thermal runaway and punch-through of the depletion region. This allows a thinner n- epi to be used which somewhat decreases forward voltage drop.

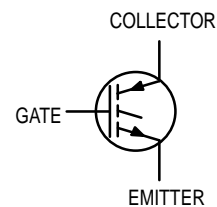


Figure 4a. IGBT Schematic Symbol

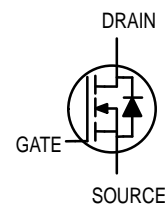


Figure 4b. MOSFET Schematic Symbol

The IGBT has a four layer (P–N–P–N) structure. This structure resembles that of a thyristor device known as a Silicon Controlled Rectifier (SCR). Unlike the SCR where the device latches and gate control is lost, an IGBT is designed so that it does not latch on. Full control of the device can be maintained through the gate drive.

To maximize the performance of the IGBT, process steps are optimized to control the geometry, doping and lifetime. The possibility of latching is also reduced by strategic processing of the device. Geometry and doping levels are optimized to minimize the on-voltage, switching speed and achieve other key parametric variations. Because the IGBT is a four-layer structure, it does not have the inverse parallel diode inherent to power MOSFETs. This is a disadvantage to motor control designers who use the anti-parallel diode to recover energy from the motor.

Like a power MOSFET, the gate of the IGBT is electrically isolated from the rest of the chip by a thin layer of silicon dioxide, SiO_2 . The IGBT has a high input impedance due to the isolated gate and it exhibits the accompanying advantages of modest gate drive requirements and excellent gate drive efficiency.

Equivalent Circuit of IGBT

Figure 4b shows the terminals of the IGBT as determined by JEDEC. Notice that the IGBT has a gate like a MOSFET yet it has an emitter and a collector like a BJT.

The operation of the IGBT is best understood by again referring to the cross section of the device and its equivalent circuit as shown in Figure 3a. Current flowing from collector to emitter must pass through a p–n junction formed by the P^+ substrate and n–epi layer. This drop is similar to that seen in a forward biased p–n junction diode and results in an offset voltage in the output characteristic. Current flow contributions are shown in Figure 3a using varying line thickness with the thicker lines indicating a high current path. For a fast device, the N^+ buffer layer is highly doped for recombination and speedy turn off. The additional doping keeps the gain of the PNP low and allows two-thirds of the current to flow through the base of the PNP (electron current) while one-third passes through the collector (hole current).

R_{shorting} is the parasitic resistance of the P^+ emitter region. Current flowing through R_{shorting} can result in a voltage across the base–emitter junction of the NPN. If the base–emitter voltage is above a certain threshold level, the NPN will begin to conduct causing the NPN and PNP to enhance each other's current flow and both devices can become saturated. This results in the device latching in a fashion similar to an SCR. Device processing directs currents within the device and keeps the voltage across R_{shorting} low to avoid latching. The IGBT can be gated off unlike the SCR which has to wait for the current to cease allowing recombination to take place in order to turn off. IGBTs offer an advantage over the SCR by controlling the current with the device, not the device with the current. The internal MOSFET of the IGBT when gated off will stop current flow and at that point, the stored charges can only be dissipated through recombination.

The IGBT's on-voltage is represented by sum of the offset voltage of the collector to base junction of the PNP transistor, the voltage drop across the modulated resistance R_{mod} and the channel resistance of the internal MOSFET. Unlike the MOSFET where increased temperature results in increased $R_{\text{DS(on)}}$ and increased forward voltage drop, the forward drop of an IGBT stays relatively unchanged at increased temperatures.

Switching Speed

Until recently, the feature that limited the IGBT from serving a wide variety of applications was its relatively slow turn-off speed when compared to a power MOSFET. While turn-on is fairly rapid, initial IGBTs had current fall times of around three microseconds.

The turn-off time of an IGBT is slow because many minority carriers are stored in the n–epi region. When the gate is initially brought below the threshold voltage, the n–epi contains a very large concentration of electrons and there will be significant injection into the P^+ substrate and a corresponding hole injection into the n–epi. As the electron concentration in the n–region decreases, the electron injection decreases, leaving the rest of the electrons to recombine. Therefore, the turn-off of an IGBT has two phases: an injection phase where the collector current falls very quickly, and a recombination phase in which the collector current decrease more slowly. Figure 5 shows the switching waveform and the tail time contributing factors of a “fast” IGBT designed for PWM motor control service.

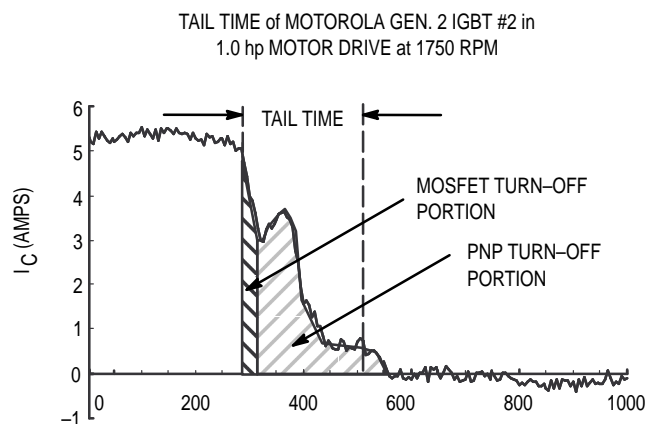


Figure 5. IGBT Current Turn-off Waveform

In power MOSFETs, the switching speed can be greatly affected by the impedance in the gate drive circuit. Efforts to minimize gate drive impedance for IGBTs are also recommended. Also, choose an optimal device based on switching speed or use a slower device with lower forward drop and employ external circuitry to enhance turn off. A turn-off mechanism is suggested in a paper by Baliga et al [2].

A FINAL COMPARISON OF IGBTs, BJTs AND POWER MOSFETs

The conduction losses of BJTs and IGBTs is related to the forward voltage drop of the device while MOSFETs determine conduction loss based on $R_{DS(on)}$. To get a relative comparison of turn-off time and conduction associated losses, data is presented in Table 1 where the on-resistances of a power MOSFET, an IGBT and a BJT at junction temperatures of 25°C and 150°C are shown.

Note that the devices in Table 1 have approximately the same ratings. However, to achieve these ratings the chip size of the devices vary significantly. The bipolar transistor requires 1.2 times more silicon area than the IGBT and the MOSFET requires 2.2 times the area of the IGBT to achieve the same ratings. This difference in die area directly impacts the cost of the product. At higher currents and at elevated temperatures, the IGBT offers low forward drop and a switching time similar to the BJT without the drive difficulties. Table 1 confirms the findings offered earlier in Figure 1a and elaborates further to include a BJT comparison and temperature effects. The reduced power conduction losses offered by the IGBT lower power dissipation and heat sink size.

Thermal Resistance

An IGBT and power MOSFET produced from the same size die have similar junction-to-case thermal resistance because of their similar structures. The thermal resistance of a power MOSFET can be determined by testing for variations in temperature sensitive parameters (TSPs). These parameters are the source-to-drain diode on-voltage, the gate-to-source threshold voltage, and the drain-to-source on-resistance. All previous measurements of thermal resistance of power MOSFETs at Motorola were performed using the source-to-drain diode as the TSP. Since an IGBT does not have an inverse parallel diode, another TSP had to be used to determine the thermal resistance. The gate-to-emitter threshold voltage was used as the TSP to measure the junction temperature of an IGBT to determine its thermal resistance. However before testing IGBTs, a correlation between the two test methods was established by comparing the test results of MOSFETs using both TSPs. By testing for variations in threshold voltage, it was determined that the thermal resistance of MOSFETs and IGBTs are essentially the same for devices with equivalent die size.

Short Circuit Rated Devices

Using IGBTs in motor control environments requires the device to withstand short circuit current for a given period. Although this period varies with the application, a typical value of ten microseconds is used for designing these specialized IGBT's. Notice that this is only a typical value and it is suggested that the reader confirm the value given on the data sheet. IGBTs can be made to withstand short circuit conditions by altering the device structure to include an additional resistance (R_e , in Figure 6) in the main current path. The benefits associated with the additional series resistance are twofold.

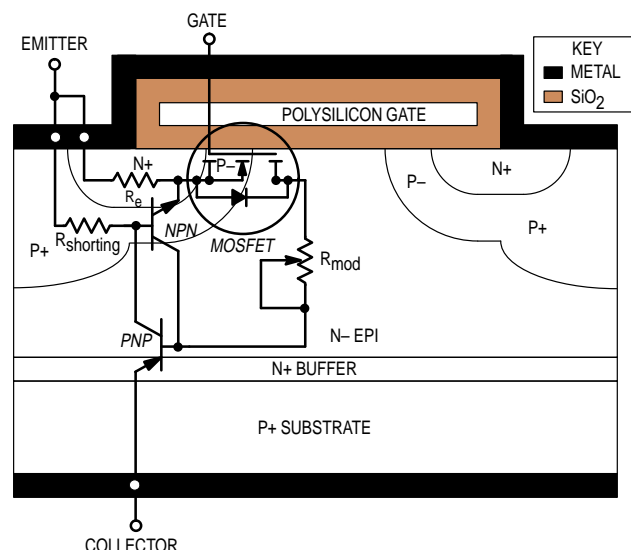


Figure 6. Cross Section and Equivalent Schematic of a Short Circuit Rated Insulated Gate Bipolar Transistor Cell

First, the voltage created across R_e , by the large current passing through R_e , increases the percentage of the gate voltage across R_e , by the classic voltage divider equation. Assuming the drive voltage applied to the gate-to-emitter remains the same, the voltage actually applied across the gate-to-source portion of the device is now lower, and the device is operating in an area of the transconductance curve that reduces the gain and it will pass less current.

Table 1. Advantages Offered by the IGBT When Comparing the MOSFET, IGBT and Bipolar Transistor On-Resistances (Over Junction Temperature) and Fall Times (Resistance Values at 10 Amps of Current)

Characteristic	TMOS	IGBT	Bipolar
Current Rating	20 A	20 A	20 A
Voltage Rating	500 V	600 V	500 V*
$R_{(on)}$ @ $T_J = 25^\circ\text{C}$	0.2 Ω	0.24 Ω	0.18 Ω
$R_{(on)}$ @ $T_J = 150^\circ\text{C}$	0.6 Ω	0.23 Ω	0.24 Ω^{**}
Fall Time (Typical)	40 ns	200 ns	200 ns

* Indicates V_{CEO} Rating

** BJT $T_J = 100^\circ\text{C}$

Second, the voltage developed across R_E results in a similar division of voltage across R_{shorting} and V_{BE} of the NPN transistor. The NPN will be less likely to attain a V_{BE} high enough to turn the device on and cause a latch-up situation.

The two situations described work together to protect the device from catastrophic failure. The protection period is specified with the device ratings, allowing circuit designers the time needed to detect a fault and shut off the device.

The introduction of the series resistance R_E also results in additional power loss in the device by slightly elevating the forward drop of the device. However, the magnitude of short circuit current is large enough to require a very low R_E value. The additional conduction loss of the device due to the presence of R_E is not excessive when comparing a short circuit rated IGBT to a non-short circuit rated device.

Anti-Parallel Diode

When using IGBT's for motor control, designers have to place a diode in anti-parallel across the device in order to handle the regenerative or inductive currents of the motor. As discussed earlier, due to structural differences the IGBT does not have a parasitic diode like that found in a MOSFET. Designers found that the diode within the MOSFET was, in fact, a parasitic, i.e., not optimized in the design process, and its performance was poor for use as a current recovery device due to slow switching speed. To overcome the lack of performance, an optimized anti-parallel diode was used across the MOSFET source-to-drain. Placing a packaged diode external to the MOSFET itself created performance problems due to the switching delays resulting from the parasitics introduced by the packages. The optimal setup is to have the diode copackaged with the device. A specific line of IGBTs has been created by Motorola to address this issue. These devices work very well in applications where energy is recovered to the source and are favored by motor control designers.

Like the switching device itself, the anti-parallel diode should exhibit low leakage current, low forward voltage drop and fast switching speed. As shown in Figure 7, the diode forward drop multiplied by the average current it passes is the total conduction loss produced. In addition, large reverse recovery currents can escalate switching losses. A detailed explanation of reverse recovery can be found in the Appendix. A secondary effect caused by large reverse recovery currents is generated EMI at both the switching frequency and the frequency of the resulting ringing waveform. This EMI requires additional filtering to be designed into the circuit. By copackaging parts, the parasitic inductances that contribute to the ringing are greatly reduced. Also, copackaged products can be used in designs to reduce power dissipation and increase design efficiency.

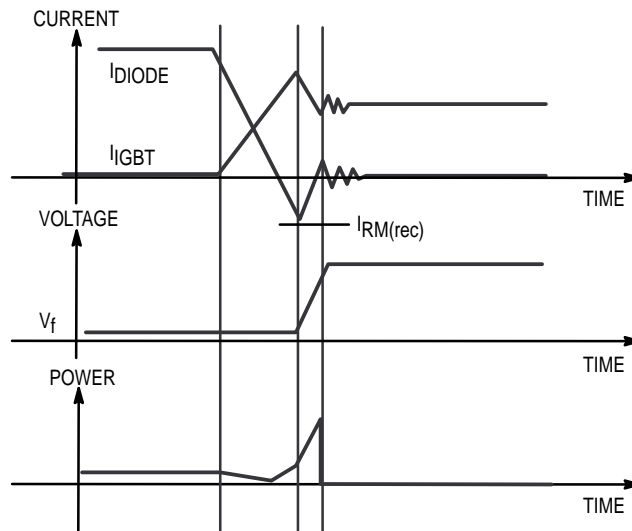


Figure 7. Waveforms Associated with Anti-Parallel Diode Turn-off

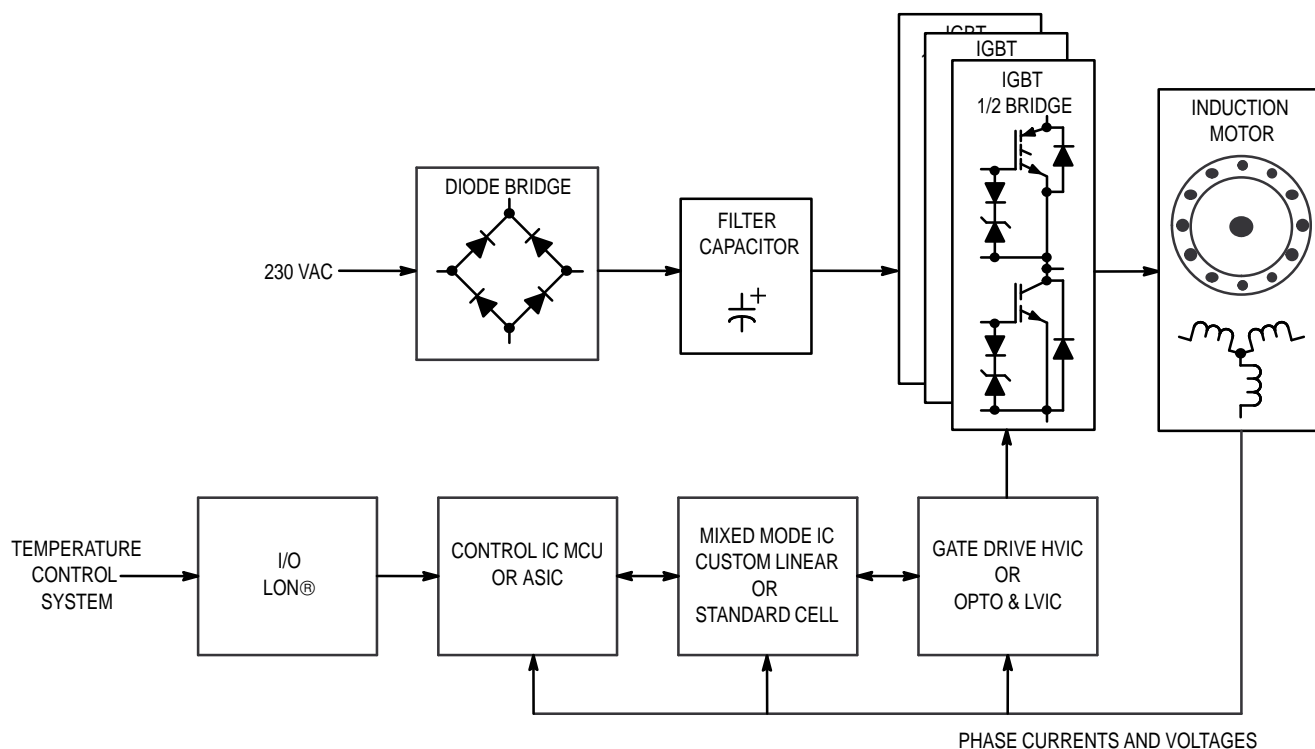
APPLICATION OF IGBTs: PULSE WIDTH MODULATED INDUCTION MOTOR DRIVE APPLICATION

Line-operated, pulse-width modulated, variable-speed motor drives are an application well suited for IGBTs. In this application, as shown in Figure 8, IGBTs are used as the power switch to PWM the voltage supplied to a motor to control its speed.

Depending on the application, the IGBT may be required to operate from a full-wave rectified line. This can require devices to have six hundred volt ratings for 230 VAC line voltage inputs, and twelve hundred volt ratings for 575 VAC line inputs. IGBTs that block high voltage offer fast switching and low conduction losses, and allow for the design of efficient, high frequency drives of this type. Devices used in motor drive applications must be robust and capable of withstanding faults long enough for a protection scheme to be activated. Short circuit rated devices offer safe, reliable motor drive operation.

CONCLUSION

The IGBT is a one of several options for designers to choose from for power control in switching applications. The features of the IGBT such as high voltage capability, low on-resistance, ease of drive and relatively fast switching speeds makes it a technology of choice for moderate speed, high voltage applications. New generations of devices will reduce the on-resistance, increase speed and include levels of integration that simplify protection schemes and device drive requirements. The reliability and performance advantages of IGBTs are value added traits that offer circuit designers energy efficient options at reduced costs.



**Figure 8. Typical Pulse-Width, Modulated, Variable-Speed Induction Motor Drives
Are Where IGBT's Offer Performance Advantages**

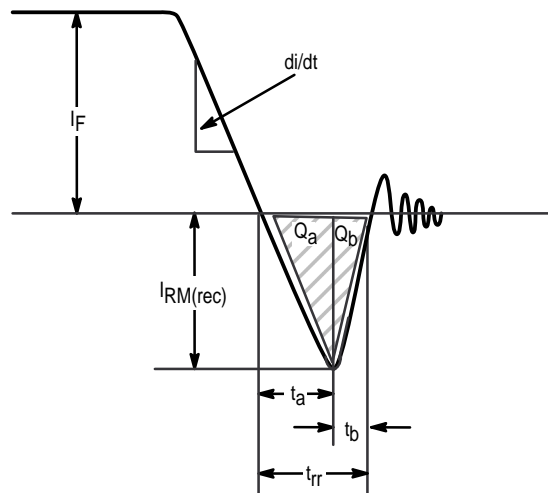
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Diode Reverse Recovery Analysis [4]




t_{rr} = total reverse recovery time
 t_a = fall time due to stored minority charge
 t_b = application and device dependent
 $I_{RM(rec)}$ = peak reverse recovery current

Figure A-1. Reverse Recovery Waveform

A typical reverse recovery waveform is shown in Figure A-1. The reverse recovery time t_{rr} has been traditionally defined as the time from diode current zero-crossing to where the current returns to within 10% of the peak recovery current $I_{RM(rec)}$. This does not give enough information to fully characterize the waveform shape. A better way to characterize the rectifier reverse recovery is to partition the reverse recovery time into two different regions, t_a and t_b , as shown in Figure A-1. The t_a time is a function of the forward current and the applied di/dt . A charge can be assigned to this region denoted Q_a , the area under the curve. The t_b portion of the reverse recovery current is not very well understood. Measured t_b times vary greatly with the switch characteristic, circuit parasitics, load inductance and the applied reverse voltage. A relative softness can be defined as the ratio of t_b to t_a . General purpose rectifiers are very soft (softness factor of about 1.0), fast recovery diodes are fairly soft (softness factor of about 0.5) and ultrafast rectifiers are very abrupt (softness factor of about 0.2).

[4] Source: "Motor Controls," *TMOS Power MOSFET Transistor Data*, Q4/92, DL135, Rev 4, (Phoenix: Motorola, Inc., 1992), pp. 2-9-22 to 2-9-23.

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