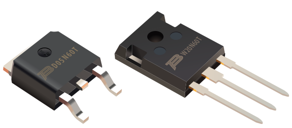
Measuring IGBT Conduction Loss to Maximize Efficiency

WHITE PAPER



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INTRODUCTION

Performance and efficiency of an Insulated Gate Bipolar Transistor can be quantified by its switching loss while transitioning between the ON- and OFF-state and its conduction loss. Higher performance IGBTs are typically constructed with both an IGBT and a diode in the same semiconductor package. The IGBT and the diode each contribute to the combined losses and their interactions need to be considered.

IGBT and diode conduction losses are the result of current flowing through the collector, or the ON-state voltage (saturation and anode voltage) during the conducting cycle. This white paper will present one of the most effective ways to decrease switching losses through the manipulation of an IGBT's voltage and current waveforms during the turn-ON and turn-OFF phases. It will also illustrate how this approach helps to significantly reduce, or even eliminate, losses that occur during the overlap time.

IGBT BASICS

The construction of an IGBT warrants additional exploration to lay a foundation for analysis. Decades ago, when IGBTs were first introduced, they were developed as a switching device that combined the voltage-controlled MOSFET at its gate with the current-controlled bipolar junction transistor at its collector and emitter. This design effectively combined the benefits of two proven switching devices to create a voltage-controlled bipolar device. Figure 1 shows the IGBT equivalent circuit, in which the gate is a MOSFET and the output stage is a PNP bipolar minority carrier device. Additionally, an IGBT is shown in Figure 2 in a test circuit that is labeled with parameters of interest.

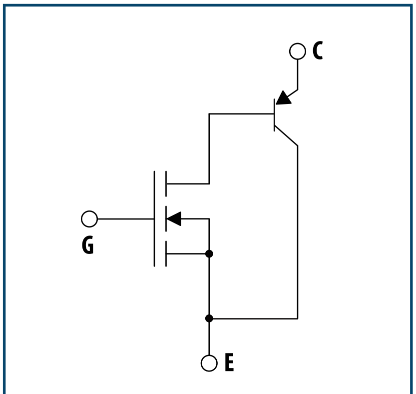

Figure 1. | *IGBT equivalent circuit.*

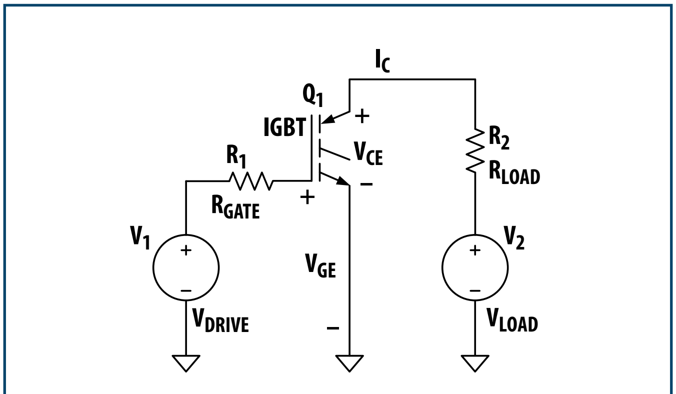

Figure 2. | *IGBT test circuit.*

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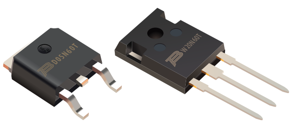

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CONTROLLING VOLTAGE DROPS

An IGBT has a fixed voltage drop not proportional to the current it is conducting. This is different than a MOSFET that has a voltage drop that can be measured as its channel resistance multiplied by the current. Because a MOSFET is a majority carrier device, it uses a conduction channel implemented with its own type of carriers – typically an N-channel power device conducting with electrons. The MOSFET controls the flow of current by changing the resistance of the channel, while a bipolar transistor controls the current by changing the injected carriers.

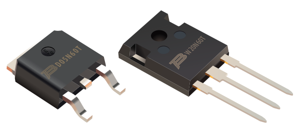
These effects are optimized internally during the design of the semiconductor junctions and doping concentrations of the separate regions. In particular, the MOSFET channel resistance is reduced to increase the PNP base current, which subsequently reduces the amount of P charges needed to achieve the same voltage drop across the IGBT. This also will reduce the stored charge and tail current. Separately, reducing the thickness of the PNP base helps produce these positive results.

OVERCOMING SHORTCOMINGS AND TAILS

An IGBT is the device of choice for medium-to-high current and high voltage applications. In hard-switched applications and inverter drives, an IGBT can pass more current than a standalone MOSFET in a similarly-sized package. Side benefits of this are reduced input capacitance and reduced cost. Generally, an IGBT offers enhanced conduction loss compared to a MOSFET due to the contribution of the IGBT collector current in contrast to the MOSFET's squared drain current.

However, IGBTs are known to have larger switching losses than MOSFETs. This means IGBTs are better suited for applications with lower switching frequency due to the minority carrier bipolar output. Specifically, the transition between states is not instantaneous. Stored charge in the internal BJT creates a 'tail' current for a short 'tail time' until all the minority carriers have been removed. When optimizing the device for efficiency, the tail time dictates the maximum allowable switching frequency so that the switching losses remain reasonable. There is a tradeoff between tail time and the forward voltage drop of the diode. It is desirable to reduce tail time and forward voltage drop to allow IGBTs to operate efficiently - closer to the high end of the common 4 kHz to 20 kHz range.

In many white goods applications, the desired frequency is 20 kHz largely due to the audible noise generated by the device not being detectable to the human ear. In motor drives and hard-switching applications that do not require an isolation transformer, there is no advantage in exceeding the audible range since the higher frequency would not increase the efficiency of the motor design. This solidifies the IGBT as the optimal choice in motor drives and hard-switching applications.



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OVERLAP CAUSES SWITCHING LOSS

Robustness in chip design, turn-OFF switching loss, and ON-state voltage loss are the leading trade-offs in IGBT design. It is important to measure and understand the interactions of voltage, current and loss waveforms during normal IGBT operation in order to manipulate the parameters, and thus maximize the efficiency of the IGBT in various applications.

In applications that use IGBTs as hard switches, there is a defined period of power loss at each transition from OFF to ON or from ON to OFF. This is due to the occurrence of voltage across the switch collector-emitter connections while current is flowing through the IGBT. Figure 3 illustrates the voltage, current and loss experienced around and at each of these transitions.

The voltage and current waveforms are multiplied at each point to obtain the instantaneous power loss waveform. Of note is the large pulse of power loss during switching. Since the power lost for each switching transition is constant and the switching transition is constant, the switching power loss increases with switching frequency. Therefore, lower frequencies reduce the total switching loss. Bourns® IGBTs are constructed using Trench-Gate Field-Stop (TGFS) technology. The Trench-Gate (TG) structure results in higher channel density in the MOSFET portion of the device. Plus, TGFS technology helps in reducing the ON-state voltage drop when compared to a planar IGBT structure. This helps in reducing the conduction losses. The presence of the Field-Stop (FS) layer also helps in reducing the total switching energy. FS also helps in increasing the gain and reducing the minority carrier lifetime, which results in the quenching-off of the tail current when the IGBT is turned OFF. This also aids in increasing the speed of the device when compared to a device of similar dimensions but without the FS layer.

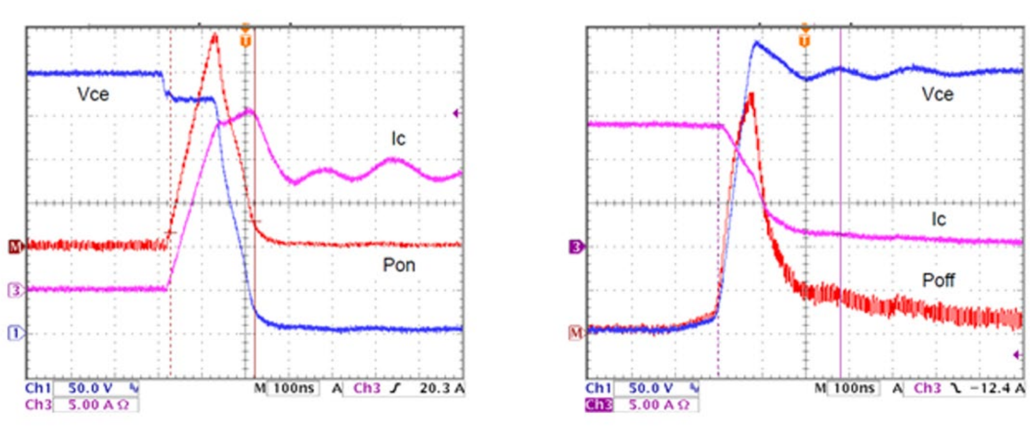

Figure 3. | *Shown are IGBT turn-ON and turn-OFF voltage and current waveforms where blue is voltage collector-emitter, pink is collector current, and red is power loss.*

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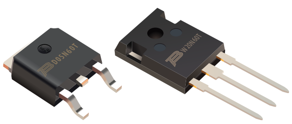

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DETERMINING CONDUCTION LOSS

Whenever an IGBT or its co-packaged fast recovery diode is ON and conducting current, there will be conduction loss. This loss is characterized as power dissipation and is obtained by multiplying the ON-state voltage by the ON-state current. In Pulse Width Modulation (PWM) technology-based applications, the duty factor must be included as a multiplier in order to arrive at the average dissipated power.

The first place to look for the approximation of the conduction losses is the IGBT and free-wheeling diode data sheets. The IGBT has a rated voltage ($V_{CE(sat)}$) based on temperature, and multiplying this value by the expected average device current for the application gives the approximate dissipated power for the IGBT. Similarly, the free-wheeling diode data sheet will have a forward voltage drop (V_f) that can be multiplied by the expected average diode current to get its contribution to the overall dissipated power. Duty cycles must be factored in to get the best approximation for PWM applications. These estimates tend to be conservative since the $V_{CE(sat)}$ in practice will be lower than the data sheet value when the current is less than the rated current (I_C).

At switching frequencies below 10 kHz, the majority of the total power loss is from conduction loss. Low conduction loss results from the conduction mechanism that is characteristic of a negative-positive-negative (NPN) bipolar power transistor, which is nearly constant V_{CE} with collector current. This is contrary to a low resistance channel as in the MOSFET, where the voltage drop is calculated by multiplying current by resistance. Conventionally disregarded due to its negligible contribution to total power loss, the IGBT blocking loss can be calculated by multiplying the blocking voltage and leakage current when the IGBT is turned OFF.

Since conduction loss dominates the total loss in motor control applications, the saturation voltage and forward voltage drop become critical variables in the design. $V_{CE(sat)}$ should be reduced as much as possible because of the low switching speed characteristic of motor applications. A popular application tradeoff between the forward voltage drop and switching speed often is employed to enhance short circuit capability.

LOW AND SLOW

The question then centers around how to reduce V_{CE}. The answer is with a harder gate drive, higher voltage (V_{CC}), lower operating current and reduced gate drive impedance.

As discussed, the IGBT has switching speed limitations due to device tail time. Tail times can be reduced if the $V_{CE(sat)}$ of the device is higher. However, that tradeoff may not be worthwhile. In general, there is an inverse relationship between carriers and both the $V_{CE(sat)}$ and switching frequency. The presence of more carriers will result in a slower switching frequency with lower $V_{CE(sat)}$. Conversely, fewer carriers result in higher $V_{CE(sat)}$ and switching frequency. Several technologies have been developed that attempt to optimize both switching times and forward voltage drop while providing rugged short circuit capability.

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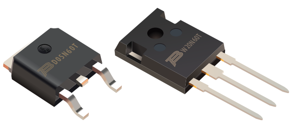

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VISUALIZING LOSSES

Figure 4 illustrates the fundamental parameters of switching loss and conduction loss over a full switching cycle. Note that the transition is considered effective at the 10 % and 90 % levels of V_{GE}, I_C and V_{CE}. When the gate to emitter voltage (V_{GE}) reaches the 10 % level, the transition to turning ON begins. Time delays are measured as the waveforms cross those 10 % and 90 % levels.

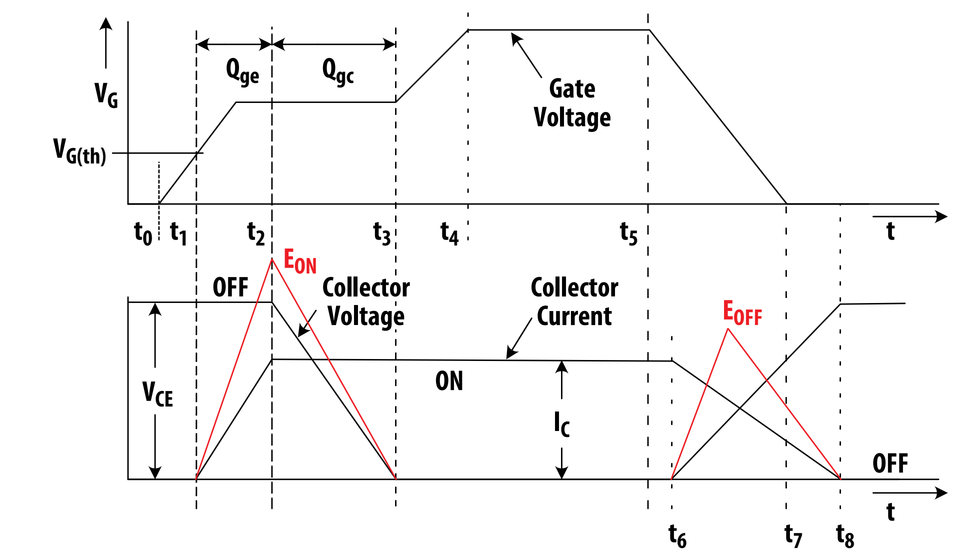

Figure 4. Illustrated are switching loss and conduction loss over a full switching cycle.

The time it takes for the IGBT to switch to ON is given by t_3-t_0. The delay from the time V_{GE} reaches 10 % until the time it takes for I_C to reach 10 % is given by t_1-t_0. The rise time is the time that it takes for I_C to rise from 10 % to 90 %, given by t_2-t_1.

The E_{on} is the turn-ON energy loss, which is the area under the power loss waveform from 10 % I_C rise, t_1, to 90 % V_{CE} fall, t_3-t_1. The power loss waveform is calculated by multiplying I_C and V_{CE} at each point in time and is approximated by the shaded area under E_{on} and E_{off}. The E_{off} is the turn-OFF energy given by the area under the curve from 10 % V_{CE} rise, t_6, to 90 % I_C fall, t_7.

The delay in beginning the voltage transition to high in order to switch the IGBT OFF is given by t_6-t_5. Looking at the transition from 90 % V_{GE} to 10 % I_C, the time is given by t_7-t_5. The delay from the time I_C falls from 90 % to 10 % is the fall time, given by t_7-t_6. Finally, the tail time is shown by the tailing collector current that exists from the time I_C falls to the 10 % mark until all the charges have been eliminated and the current reaches zero. This can be measured as the difference from t_8 to t_7.

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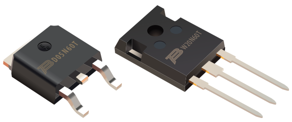

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CONCLUSION

In summary, the power losses to consider in a power-switching device consist of: conduction loss, turn-ON switching loss, turn-OFF switching loss, and blocking loss. The calculations and waveforms presented in this paper were developed to help designers understand the effects of various IGBT parameters and their impact on power loss and overall efficiency. For hands-on or application specific analysis, a testbed can be used to evaluate the performance and measure waveforms typically encountered with IGBTs. As the technology built into IGBTs continues to mature in efficiency and robustness, the range of applications for IGBTs is expected to grow. Tradeoffs will remain consistent, and the dominant loss of power will continue to be switching loss or conduction loss. Measuring and manipulating IGBT parameters allows designers to maximize the device's utility and application advantages.

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