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ON Semiconductor's Motor Control IGBTs and Free-Wheeling Diodes

Abstract

Using IGBTs in motor control environments requires several attributes which can be divided in two categories. The short circuit rating and SOAs are an indication of the robustness of a device. The conduction and switching energy losses are measures of the efficiency of a device. This application note will examine ON Semiconductor's IGBTs and free-wheeling diodes and show how the losses and ruggedness issues affect the selection of an IGBT for a motor drive application. Motor control applications have several important particularities which will also be examined.

Introduction

The Insulated Gate Bipolar Transistor (IGBT) is a minority-carrier device with high input impedance and large bipolar current-carrying capability. Many designers view the IGBT as a device with MOS input characteristics and bipolar output characteristics, making it a voltage-controlled bipolar device. While the MOS input and BJT output are integrated monolithically on a single silicon die, it is often necessary to add an anti-parallel or free-wheeling diode to obtain a fully functional switch, although in some special cases the free-wheeling diode is not necessary. The diodes can be incorporated monolithically or co-packaged or as a discrete diode external to the IGBT package.

The introduction of insulated gate bipolar-transistors (IGBTs) in the mid-1980s was an important milestone in the history of power semiconductor devices. They are extremely popular devices in power electronics for medium to high power levels (a few kW to a few MW) and are applied extensively in dc/ac drives and power supply systems. The IGBT is suitable for many applications in power electronics, especially in Pulse Width Modulated (PWM) servo and three-phase drives requiring high dynamic range control and low noise. It also can be used in Uninterruptible Power Supplies (UPS), Switched-Mode Power Supplies (SMPS), and other power circuits requiring high switch repetition rates. IGBTs improve dynamic performance and efficiency and reduce the level of audible noise. It is equally suitable in resonant-mode converter circuits. Optimized IGBTs are available for both low conduction loss and low switching loss.

One of the more common applications of an IGBT is for use as a switching component in voltage source inverter (VSI) circuits. Generally, inverters are used in power supply and motor-control applications. The main advantages of using

APPLICATION NOTE

IGBTs in these converters are simplicity and modularity of the converter, simple gate drive, elimination of snubber circuits due to the square Safe Operating Area (SOA), low switching loss, improved protection characteristics (over-current and short circuit fault) and simpler electrical and mechanical construction of the power converters [1]. These advantages make the IGBTs very popular and promising switching devices.

Electric Drives

In contrast to grid connected ac motor drives, which are essentially constant frequency, power electronic devices (e.g. inverters), offer voltage supplies that are variable in both frequency and magnitude and are used to operate ac motors at frequencies other than the supply frequency.

Motor-control applications include mainly variable voltage, phase and frequency inverters. The purpose of a power converter is to produce a controllable voltage and frequency, and provide an ac output waveform from a DC link circuit. This DC link is often supplied by a controllable or uncontrollable AC-DC converter. Variable voltage and frequency waveforms are required to operate variable speed drives, UPS, active filters, compensators etc. which are only a few types of applications.

Pulse-width modulated, variable-speed motor drives are an application well suited for IGBTs. In this application, as shown in Figure 1 and Figure 2, IGBTs are used as the power switch to PWM the voltage supplied to a motor to control its speed, position or electromagnetic torque. Normally, the IGBT will 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, are an excellent choice 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.

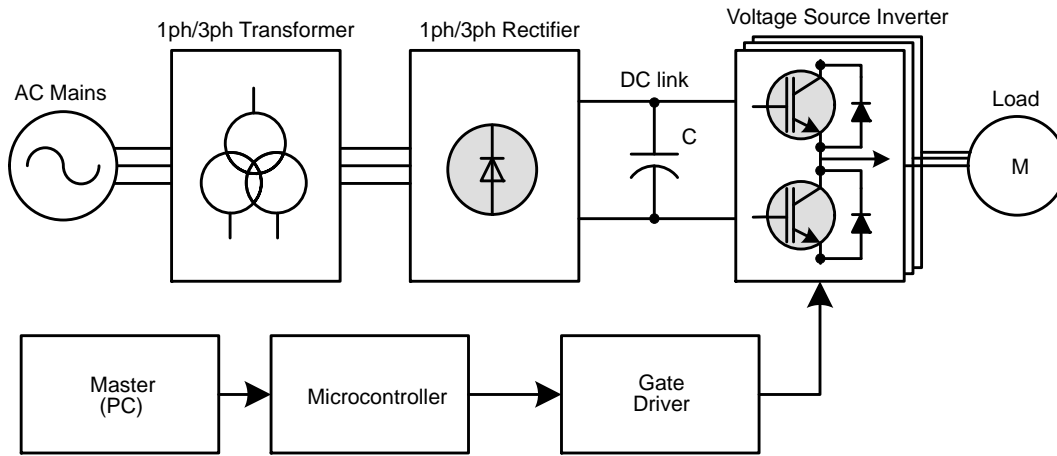


Figure 1. Typical AC Motor Drive Application

One of the most common converter topologies that is very widely used is shown in in Figure 1 and Figure 2. Figure 1 shows a general block structure of an electric drive and Figure 2 gives a more concrete view of the power topology. It consists of a three-phase bridge inverter with a diode rectifier in the front end. The rectifier (which can be single or three-phase) converts the ac input to an unregulated DC voltage. The harmonics in the DC link are filtered by an LC or C filter to generate a smooth DC voltage for the inverter. The inverter consists of three half-bridges or phase legs to generate three-phase ac for electric machines or other loads. Alternate sources for the DC power include a battery, fuel cell, or photovoltaic dc source. In all such cases, the DC voltage is usually unregulated. The battery-fed inverter

drive is commonly used for electric/hybrid vehicle drives. Note that because of the diode rectifier in the front end, the converter system cannot regenerate power. The filter capacitor C sinks the harmonics from the rectifier as well as inverter sides.

According to the type of ac output waveform, these topologies can be considered to be voltage-source inverters (VSIs), where the independently controlled ac output is a voltage waveform. These structures are the most widely used because they naturally behave as voltage sources which are required by many applications, such as electric drives and are the most popular application of inverters. The typical VSI topology is shown in Figure 1 and Figure 2.

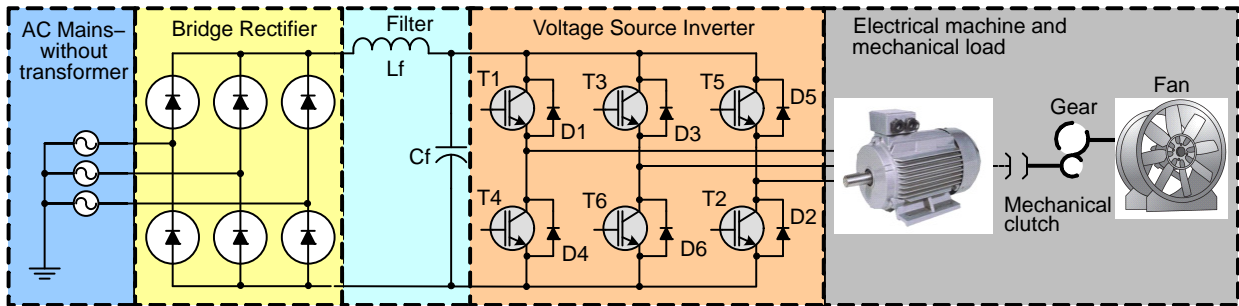


Figure 2. Common Topology of Motor Drive

Input Power Topology

The grid voltage is rectified by the line rectifier which typically consists of a diode bridge. Presently, attention paid to power quality and improved power factor has shifted the interest to more supply friendly AC-to-DC converters, e.g. a PFC topology. This allows simultaneous active filtering of the line current as well as regenerative motor braking schemes transferring power back to the mains.

It can be shown that single-phase diode rectifiers require a rather high transformer VA rating for a given DC output power. Therefore, these rectifiers are suitable only for low to medium power applications. For power outputs higher

than 15 kW, three-phase or poly-phase diode rectifiers should be employed. The diode bridge rectifier shown in the Figure 2 is extremely important for generation of unregulated DC voltage. The diode rectifiers are simple, but the disadvantages are large distortion in line current and a poor displacement factor, which lead to a poor power factor. To combat these problems, various power factor correction (PFC) techniques based on active wave shaping of the line current will be proposed. The power factor controller is another application where IGBTs play an important role.

Filters are commonly employed in rectifier circuits for smoothing out the DC output voltage of the load. The typical filter capacitor is of appreciable size (2–20 mF) and therefore a major cost item. They are classified as inductor-input DC filters and capacitor-input DC filters. Inductor-input DC filters are preferred in high-power applications because more efficient transformer operation is obtained due to the reduction in the form factor of the rectifier current. Capacitor-input DC filters can provide volumetrically efficient operation, but they demand excessive turn-on and repetitive surge currents. Therefore, capacitor-input DC filters are suitable only for lower-power systems.

PWM Voltage Source Inverter (VSI)

In general, two basic types of inverters exist: Voltage-source inverters (VSI), employing a dc link capacitor and providing a switched voltage waveform, and current-source inverters (CSI), employing a dc link inductance and providing a switched current waveform at the motor terminals. CS-inverters are robust in operation and reliable due to the insensitivity to short circuits and noisy environments. VS-inverters are more common compared to CS-inverters since the use of Pulse Width Modulation (PWM) allows efficient and smooth operation, free from torque pulsations and cogging [1]. Furthermore, the frequency range of a VSI is higher and they are usually more inexpensive when compared to CSI drives of the same rating.

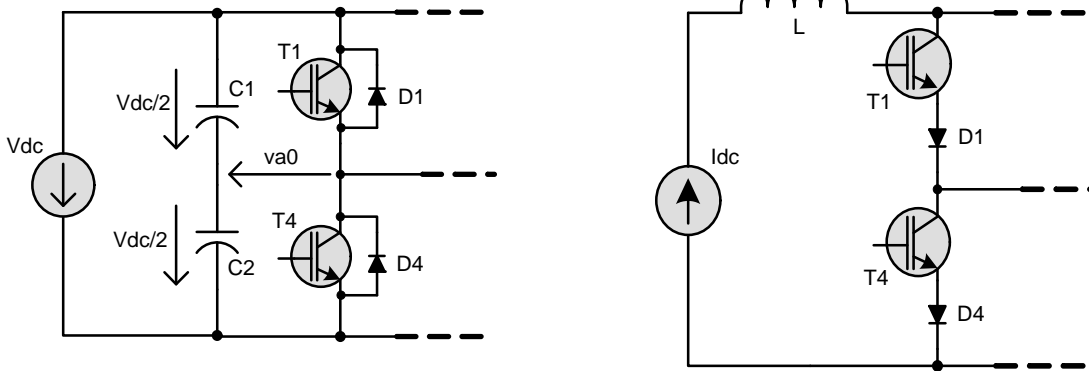


Figure 3. Voltage (Left) and Current (Right) Type of Half-bridge Converters

A typical voltage-source PWM converter performs the ac to ac conversion in two stages: ac to DC and DC to variable frequency ac. The basic converter design is shown in Figure 3. VSI, and as the name indicates, receives DC voltage at one side and converts it to an ac voltage on the other side. The ac voltage and frequency may be variable or constant depending on the application. In fact, the general name “converter” is given because the same circuit can operate as either an inverter or as a rectifier. A voltage-fed inverter should have a stiff voltage source at the input. This can also be obtained from a fuel cell, or solar photovoltaic array. The inverter output can be single-phase or polyphase and can have a square wave, sine wave, PWM wave, stepped wave, or a quasi-square wave at the output.

In voltage-fed converters, the power semiconductor devices always remain forward-biased due to the DC supply voltage, and therefore, self-controlled forward or asymmetric blocking devices, such as IGBTs are suitable. A free-wheeling (or anti-parallel) diode is always connected across the device to allow for reverse inductive current flow. One important characteristic of a voltage-fed converter is that the ac fabricated voltage waveform is not affected by the load parameters. The typical PWM output line and phase voltages are shown in Figure 4 and in Figure 5 along with the phase current.

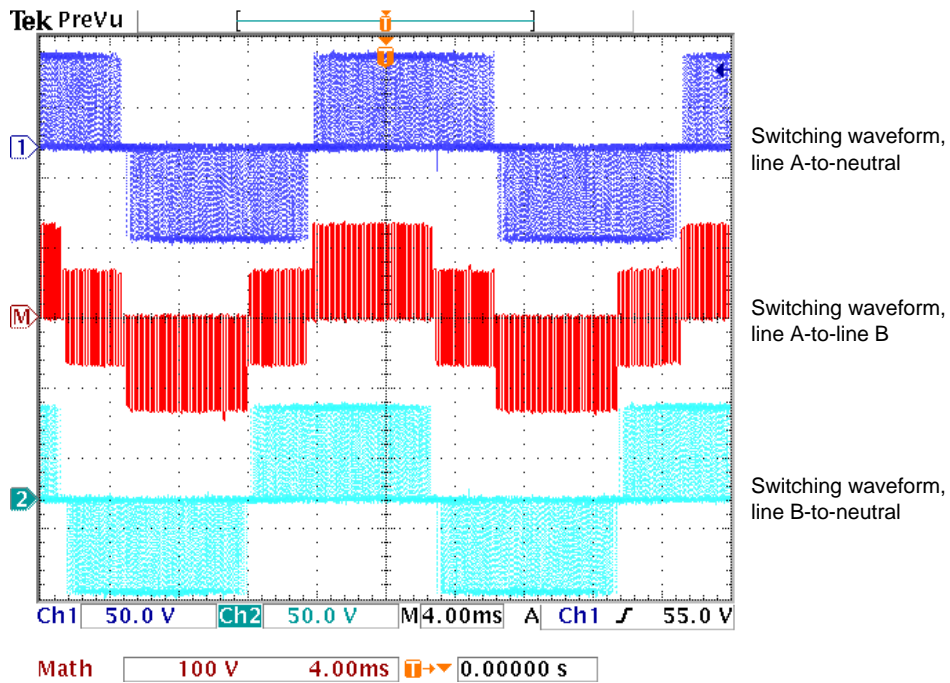


Figure 4. Phase-to-Neutral and Phase-to-Phase Switching Waveforms

IGBTs in Motor Drive Application

One of the critical issues in designing reliable power converters is the reliability of the power switches. The devices used in these applications must be robust and capable of withstanding faults long enough for a protection scheme to be activated. Inverters are a typical hard-switching application. In this switch-mode operation, the switches are subjected to high switching stresses and high switching power losses that increase linearly with the switching frequency of the PWM.

IGBT's have become the transistor of choice for motor control applications. The characteristics that make them favorable include their ability to pass greater current than an equivalent die size MOSFET transistor with more favorable drive schemes than bipolar transistors. In addition, IGBT's in many instances have lower conduction losses due to the V_{CEsat} when compared to the R_{DSon} of MOSFET's (this is due in part to the IGBT's loss based on collector current while the MOSFET's loss is based on the drain current squared).

An unfavorable attribute exhibited by IGBT's is the "tail time" that results from stored charge in the internal PNP transistor. The tail time is sacrificed at the expense of forward voltage drop. Devices are optimized for efficient operation in applications with regards to conduction and switching losses. The tail time issue also dictates switching speed. Motor controllers tend to operate at switching frequencies from 4 kHz to 20 kHz with 20 kHz being the preferred frequency due to the audible range of human hearing. IGBT's with tail times of less than 300 ns are being developed and these devices work well at 15 kHz. Work is under way to decrease the tail time and V_{CE} drop so that

IGBT's can be operated at even higher frequencies and compete better with existing MOSFET's in motor control and power supply applications.

Since no isolation transformer is required for most motor drive applications, raising the switching frequency above the audible range has little advantage since the filter inductance is inherent in the motor and a higher frequency will not allow for a more efficient motor design.

Anti-parallel Diode

Parallel to the power switches, free-wheeling diodes are placed across the collector-emitter terminals to conduct reverse current. These diodes are required, since switching off an inductive load current can generate high voltage peaks if a suitable path is not provided, which could destroy the power switch. The basic configuration of one inverter output phase consists of upper and lower power devices T1 and T4 (see Figure 5), and free-wheeling diodes D1 and D4. Due to the structural differences the IGBT does not have a parasitic diode like that found in a MOSFET. The optimal setup is to have the diode co-packaged with the IGBT.

A specific line of IGBTs has been created by ON Semiconductor 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. The diode forward drop multiplied by the average current it passes is the total conduction loss produced for the diode. In addition to the conduction losses, large reverse recovery currents can generate high switching losses. 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 co-packaging parts, the parasitic inductances that contribute to the ringing are greatly reduced. Also, co-packaged products can be used in designs to reduce power dissipation and increase design efficiency.

For one inverter leg, Figure 5 shows the basic configuration and the inverter output voltage depending on the switching state and the polarity of the current. The basic configuration of one inverter output phase consists of upper and lower power devices T1 and T4, and anti-parallel diodes D1 and D4.

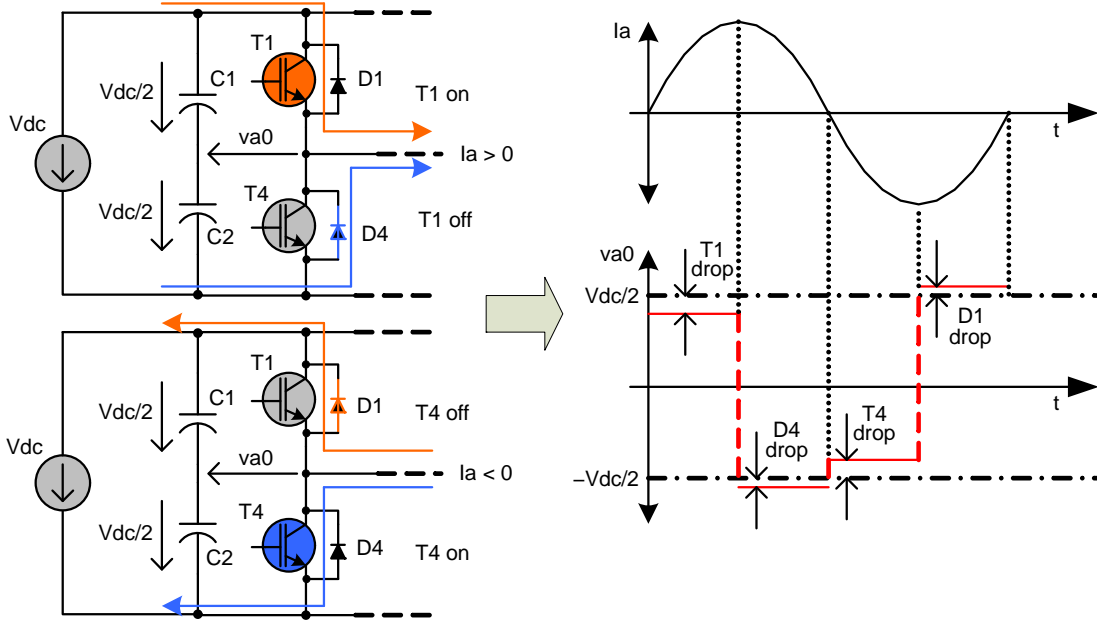


Figure 5. Fundamental Topology of a Voltage Half-bridge Inverter and Center-tapped Inverter Output Voltage. Left: Switching States and Current Direction. Right: Output Voltage and Line Current

Pulse Width Modulation (PWM)

Usually, the on and off states of the power switches in one inverter leg are always opposite. Therefore, the inverter circuit can be simplified into three (in the case of a three-phase inverter – see Figure 2) 2-position switches. Either the positive or the negative dc bus voltage is applied to one of the motor phases for a short time. Pulse width modulation (PWM) is a method whereby the switched voltage pulse widths are varied to produce different output frequencies and voltages. A PWM produces an average output voltage value, equal to the reference voltage (scaled by a constant factor) within each PWM period.

There are various PWM schemes. Well-known among these are sinusoidal PWM, hysteric PWM, space vector modulation (SVM) and “optimal” PWM techniques based on the optimization of certain performance criteria, e.g. selective harmonic elimination, increasing efficiency, and minimization of torque pulsation. While the sinusoidal pulse-width modulation and the hysteric PWM can be implemented using analog techniques, the remaining PWM techniques require the use of a microprocessor.

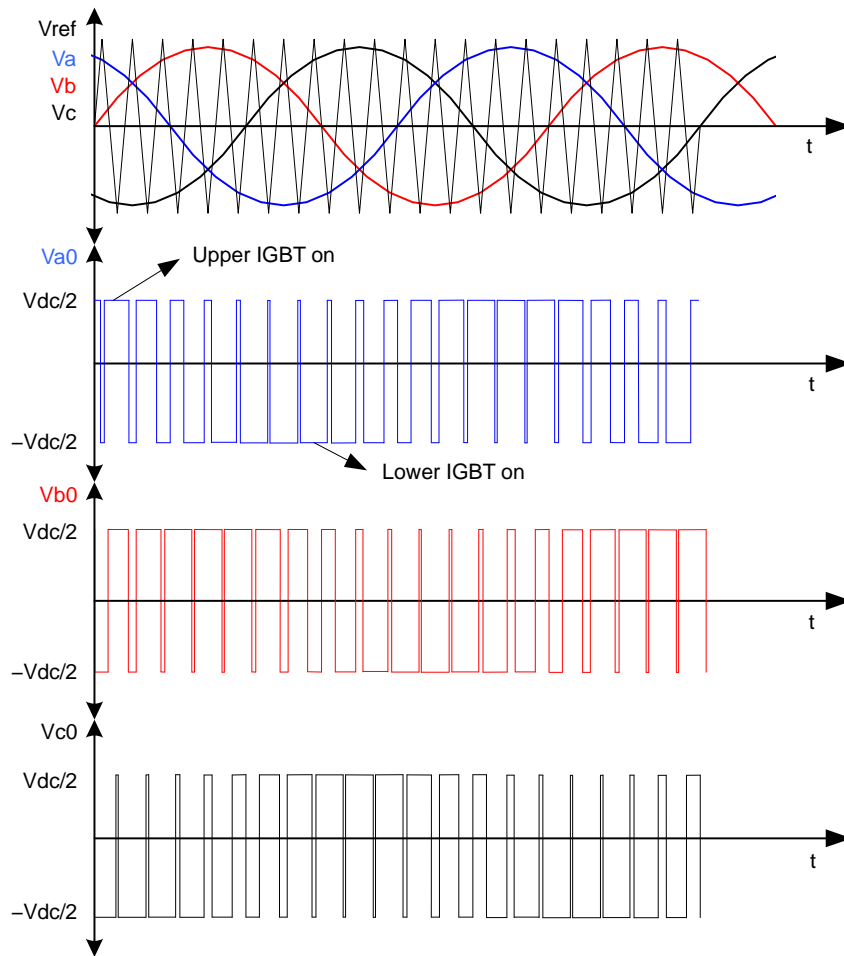


Figure 6. The Rule of Sinusoidal PWM Generation (SPWM)

As shown in Figure 6, a saw-tooth carrier wave is compared to the reference voltage for each phase to generate the fixed PWM pulses for all three phases. This modulation technique, also known as PWM with natural sampling, is called sinusoidal PWM because the pulse width is a sinusoidal function of the angular position in the reference signal. Since the PWM frequency, equal to the frequency of the carrier wave, is usually much higher than the frequency of the reference voltage, the reference voltage is nearly constant during one PWM period. Depending on the switching states, the positive or negative half DC bus voltage is applied to each phase. At the modulation stage, the reference voltage is multiplied by the inverse half dc bus voltage compensating the final inverter amplification of the switching logic into high power pulses that are applied directly to the motor windings.

Electrical Machines and Mechanical Loads

The electrical machine that converts electrical energy into mechanical energy (and vice versa) is the workhorse in

a drive system. Drive systems are widely used in applications such as pumps, fans, paper and textile mills, elevators, electric vehicles, subway transportation, home appliances, wind generation systems, servos and robotics, computer peripherals, steel and cement mills, ship propulsion, etc. A machine is a complex structure electrically, mechanically and thermally. However the evolution of machines has been slow compared to that of power semiconductor devices and power electronic converters [1].

Among all types of AC machines, the induction machine, particularly the cage type, is most commonly used in industry. These machines are very economical, rugged, reliable, and are available in ranges from fractional horse power to multi-megawatt capacity. Low-power machines are available as single-phase machines but poly-phase (three-phase) machines are used most often in variable-speed drives [1]. Figure 7 shows a typical induction machine, while Figure 8 illustrates the typical, mechanical linkage from the machine to the load.

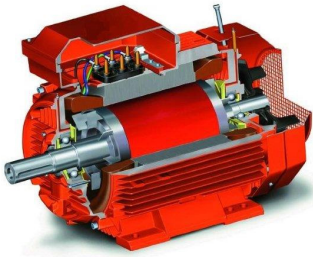


Figure 7. The Typical Induction Machine Construction

The motor is connected to a mechanical load, which may be simple or complex. Figure 8 shows an example of a mechanical load. The machine rotor with inertia J develops torque T while running at mechanical speed ω and instantaneous position θ . The motor shaft is usually connected through mechanical clutch and motor speed is adapted by a mechanical gear coupling. The secondary gear is connected to a load (in our case it is fan). Each mechanical load is characterized by a torque/speed characteristic which has, in this case, parabolic characteristics with speed ($T \approx \omega^2$).

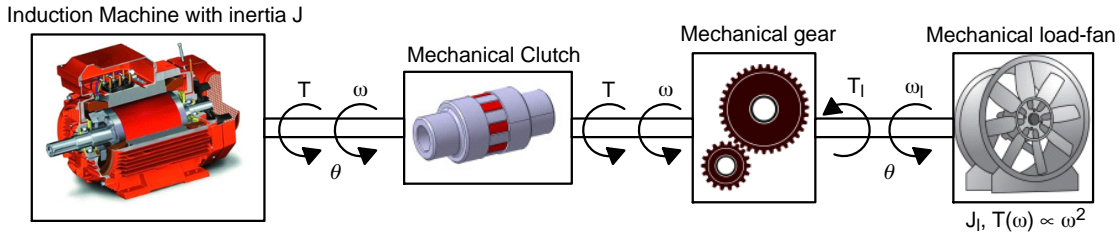


Figure 8. Simple Mechanical Load for a Motor

IGBTs for Motor Control Application

The fundamental trade-off between turn-off switching loss ($E_{sw(off)}$), on state voltage drop (V_{CEsat}) and robustness in IGBT chip design is well known. Standard industrial IGBTs are typically optimized for motor drive and similar applications in which the carrier frequency is typically 10 kHz or less. For these applications conduction losses tend to dominate so the IGBT chip is primarily optimized for low V_{CEsat} . Other applications such as electric drives for white goods often require higher operating frequencies to reduce audible noise for the overall system. In these higher frequency applications dynamic losses become more dominant and often limit the maximum switching frequency of the IGBT.

Hard Switching and Switching Losses

Most motor control applications for IGBTs require “hard” switching of ohmic-inductive loads with continuous load current, i.e. the time constant of the load L/R is much larger than the cycle $1/f_{sw}$ of the switching frequency [4]. The typical application of the IGBTs in motor control applications is a voltage source inverter (VSI) which is a hard-switched application.

The device waveforms (see turn-on and turn-off of an IGBT in Figure 9) of a hard-switched inverter have a number of detrimental effects, which can be summarized as follows [1]: **(a) Switching Loss** – the overlapping of voltage and current waveforms during each turn-on and turn-off switching cause a large pulse of power loss as shown in the math trace (M) in Figure 9. Since the amount of energy lost for each cycle is constant, as the switching frequency increases, the switching power losses increase.

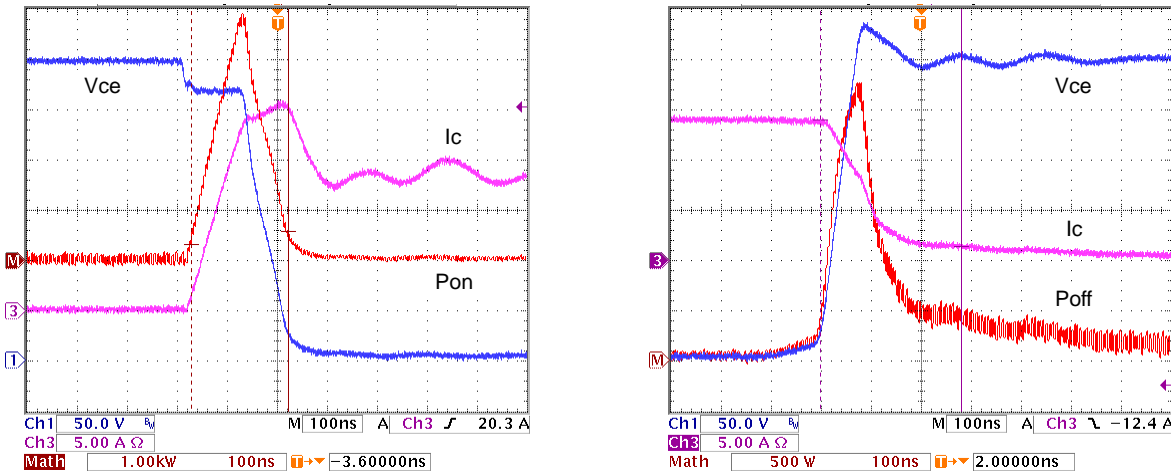


Figure 9. IGBT Turn-on and Turn-off Dynamics. Blue: Vce, Pink: Ic, Red: Ploss

The power loss due to the switching losses is

$$P_{SW} = (E_{on} + E_{off}) \cdot f_{SW} \quad (\text{eq. 1})$$

An additional problem is that the cooling system is burdened due to higher losses. In fact, the PWM switching frequency of an inverter is limited because of switching loss.

(b) Device Stress – In hard switching, the switching locus moves through the active region of the volt–ampere area which stresses the device. The reliability of the device may be impaired due to prolonged hard switching operation. This is one of the reasons for robust requirements of a power device in such applications. The SOA curve, on the data sheet, shows the limits for device operation beyond which the part may be damaged. **(c) EMI Problems** – High dv/dt, di/dt, and parasitic ringing effects at the switching transitions of a fast device can create EMI problems, which may affect the control circuit and nearby apparatus. Parasitic leakage or coupling inductance, although quite small, can be a source of EMI due to large induced ($L \cdot di/dt$) voltages. Similarly, high dv/dt transients can induce common mode coupling currents ($C \cdot dv/dt$) in the control circuit through the parasitic capacitance. **(d) Effect on Machine Insulation** – High dv/dt impressed across the stator winding insulation can create large displacement current ($C \cdot dv/dt$), which can deteriorate machine insulation. **(e) Machine Bearing Current** – Recently, it was determined that PWM inverter drives with switching IGBT devices are known to cause a machine bearing current problem. This is due to the fast switching of IGBTs. The switching of the IGBT creates a high dv/dt source that will cause $C \cdot dv/dt$ current flow to the ground through machine shaft and stray capacitance of the insulated bearing. This current will tend to shorten the bearing life. **(f) Machine Terminal Overvoltage** – PWM inverters are often required to link to a machine with a long cable. The high dv/dt at the inverter output boosts the machine terminal voltage by the reflection of the high-frequency travelling wave. High-frequency ringing occurs at the machine terminals due to stray circuit parasitics. The resulting excessive overvoltage threatens the motor insulation. As you can see in optimization triangle in Figure 12, some aspects of hard-switching are inputs to the optimization process.

Switching losses are the power losses dissipated during the turn-on and turn-off switching transitions. In high frequency PWM switching, losses can be substantial and must be considered in the thermal design. The most accurate method of determining switching losses is to plot the I_c and V_{ce} (see Figure 9 and Figure 10) waveforms during the switching transition. Multiply the waveforms point by point to get an instantaneous power waveform.

Most oscilloscopes have math functions available to perform the multiplication. This can be integrated to give the energy during the switching transition and then multiplied by the switching frequency to obtain the power loss for that transition.

Conduction Losses

Conduction losses are the losses that occur while the IGBT or FWD is on and conducting current. The total power dissipation during conduction is computed by multiplying the on-state voltage by the on-state current. In PWM applications the conduction loss must be multiplied by the duty factor to obtain the average power dissipated. A first order approximation of conduction losses can be obtained by multiplying the IGBT’s rated V_{CEsat} by the expected average device current. In most applications the actual losses will be less because V_{CEsat} is lower than the data sheet value at currents less than rated I_c . Conduction losses of an IGBT and FWD are an important part of total losses in motor control applications and the main indicators of these losses are the V_{CEsat} and V_f parameters. Due to the relatively low switching frequency we hold the V_{CEsat} as low as possible. Very often the forward voltage drop and switching speed are traded off to enhance the short circuit capability.

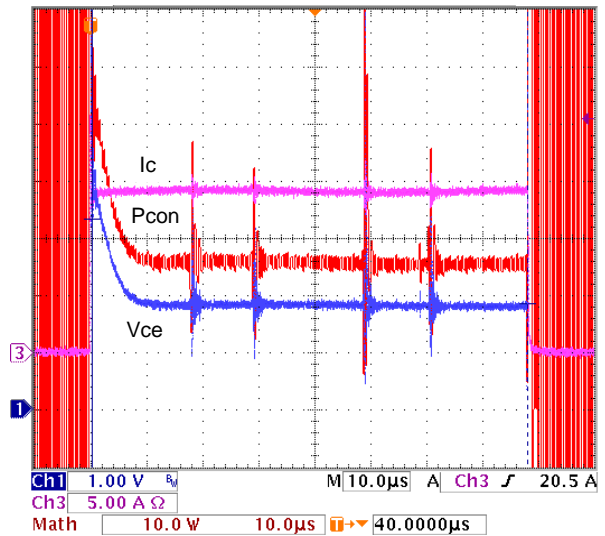


Figure 10. IGBT Conduction Dynamics
Blue: Vce, Pink: Ic, Red: Ploss

Free-wheeling diode conduction losses can be approximated by multiplying the data sheet V_f by the expected average diode current.

Process parameters of the IGBT such as threshold voltage, carrier lifetime, and the device thickness can be varied to obtain various combinations of SOA, on-state voltage, and switching time. However, there is very little overlap in the optimum combination for more than one performance parameter [2]. This is the reason that V_{CEsat} is one of the three inputs for process optimization.

FWD Importance in Hard Switching

For a long time, the importance of fast diodes had been underestimated. The performance of the IGBT switch had been impaired by the free-wheeling diodes [4]. However, ON Semiconductor free-wheeling diodes play an important role and similar optimized processes have been implemented (see Figure 12). Firstly, from an efficiency

point of view the main part of the total power loss is the conduction loss. The forward voltage drop is a very good indicator of this part of the loss so the V_f is one of the key optimization process inputs.

As soon as the IGBT is turned on, the diode will be commutated, and reverse recovery current will flow for a short period of time. During turn-on, the IGBT takes over the reverse current of the free-wheeling diode. Unfortunately, while the IGBT conducts the peak reverse

current, the IGBT-voltage is still at the DC-link voltage level (see Figure 9). This is the moment of maximum turn-on losses in the IGBT. This means that the reverse recovery time directly influences IGBT turn-on. In addition a snappy shape of the reverse recovery will make the system noisy so this phenomenon has to be held smooth and soft. That means reverse recovery is another input to the optimized process as you can see in Figure 12.

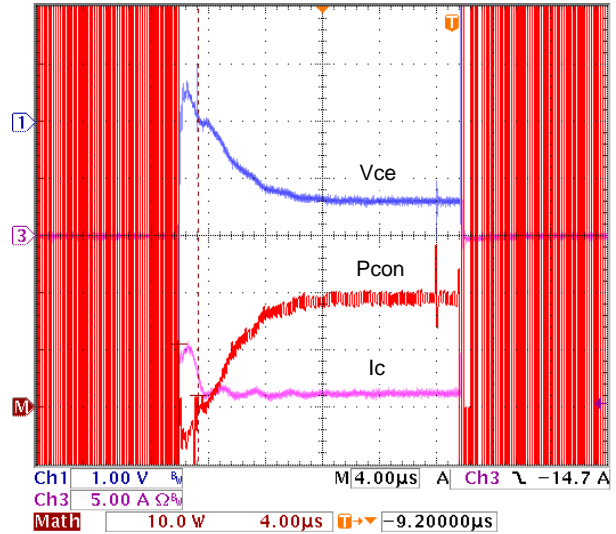
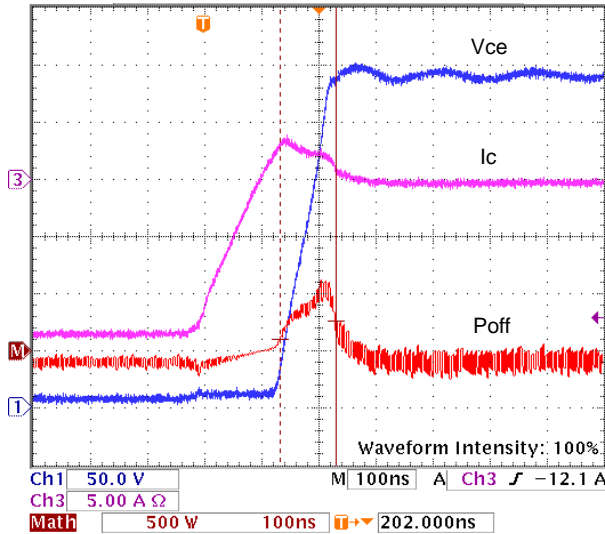


Figure 11. FWD Turn-off and Conduction Dynamics. Blue: Vce, Pink: Ic, Red: Ploss

An equally important requirement for free-wheeling diodes is dynamic ruggedness. Figure 11 shows that nearly the whole DC-link voltage is taken up by the diode, while it is still conducting a substantial tail current. If the IGBT is switched very quickly, reverse current and tail current will rise, at the same time causing a decrease of the breakdown voltage of the IGBT, which switches over to the diode with a respectively higher dv/dt . The density of the current-carrying charge carriers will then be above the original doping density, which causes the diode to avalanche while it is turning off. This in turn reduces its breakdown voltage until the junction is depleted of carriers at which time the breakdown voltage returns to its normal level. The dynamic ruggedness is defined as the diodes ability to manage high commutating di/dt and a high DC-link voltage at the same time [4].

IGBT Robustness and Reliability

As mentioned the IGBT has to manage an almost rectangular characteristic between Vce and Ic in the case of hard switching. The SOA (Safe Operating Area) diagrams are defined as the current-voltage-power boundary within which a power switching device can be operated without destructive failure. For an IGBT, the area is defined by the maximum collector-emitter voltage Vce and collector current Ic within which the IGBT operation must be confined to protect it from damage. The robustness and

reliability can be quantified by several SOA curves. There are SOA curves for switching, on-state and single pulse operation. The short-circuit capability is described by short-circuit safe operating area (SCSOA), switching capability by Forward-Biased Safe Operating Area (FBSOA), Reverse-Biased Safe Operating Area (RBSOA) and Unclamped Inductive Switching (UIS). The FBSOA is an important characteristic for applications with inductive loads and the RBSOA is important during the turn-off transient. The UIS is an important in high speed switching circuits. The simple definitions of mentioned are:

- SCSOA – describes the capability of a transistor to be controllable by its gate voltage at significant levels of collector-emitter voltage and collector current within a defined time interval.
- FBSOA – is defined as the maximum collector-emitter voltage allowable at a specified value of saturated collector current.
- RBSOA – describes the capability of a transistor to withstand significant levels of collector-emitter voltage and collector current in the turn off mode.
- UIS – the result from UIS testing is amount of energy a device can safely handle in avalanche mode resulting from an unclamped inductive load.

ON Semiconductor optimizes its IGBTs for every aspect of robustness and reliability. The short-circuit capability is one of the features that is important for bridge applications because there are several circumstances under which the IGBT can see a short-circuit path from the DC voltage across the motor phase IGBTs. An IGBT must withstand this failure for time interval appropriate for its application. In addition, electric drives often work in very harsh conditions, which increase the stresses on the IGBTs. ON Semiconductor has designed its IGBTs for motor control applications and for other bridge applications with values of time periods up to 10 μ s.

IGBT Trade Offs

ON Semiconductor has developed a new generation of 600 V IGBTs co-packed with free-wheeling diodes (FWD). These co-packaged products have been introduced in standard discrete packages such as the TO-247 package. The IGBTs are based on a technology platform specifically developed to serve the ever increasing requirements for motor control applications. The cell structure, fabrication

process, and starting material are optimized to obtain the best possible trade-offs for this type of application. The triangles, shown in Figure 12, symbolize the trade-off processes involved in the design of IGBTs and their free-wheeling diodes. The three vertices of this triangle represent conduction losses switching losses and robustness.

While the switching losses are lowered as carrier injection efficiency is increased and the life time is reduced, the conduction losses go exactly the opposite way. The short circuit time withstanding capability is improved by incorporating design changes which reduce the short circuit current. Just as for switching losses, improvement in short circuit rating is accompanied by increase in conduction losses [6].

There are, however, design parameters which help reduce conduction losses without adversely influencing the other two. This was achieved for ON’s IGBTs. Consequently ON Semiconductor’s IGBTs offer low conduction losses and short circuit robustness while maintaining ultra fast switching speeds.

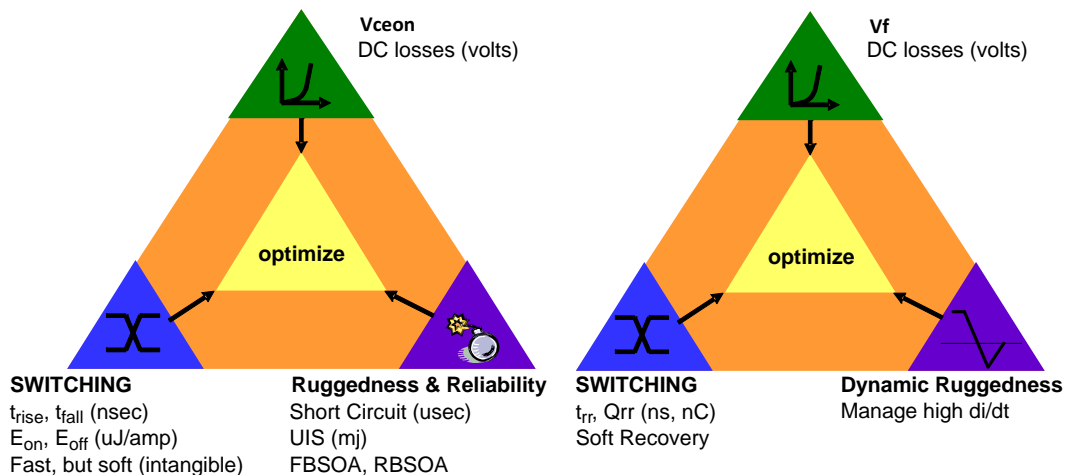


Figure 12. The IGBT and FWD Trade-off Triangle

The free-wheeling diodes are an integral part of motor drive application. ON Semiconductor has recently made tremendous strides toward perfecting the speed and softness in the recovery of these diodes. The rectifiers are optimized for fast switching speed and softer recovery throughout the current and di/dt range. These characteristics have helped reduce turn-on losses in IGBTs and generation of EMI and other transients.

Motor Drive Test Set-up for Comparison of IGBT Technologies

The specific utilization of IGBTs and freewheeling diodes within a motor control system is designed to provide the inversion function from a DC Bus to a sinusoidal waveform. The AC waveform provided to the load is in the 1.0 Hz to 120 Hz frequency range, and is achieved by switching the IGBTs at PWM frequencies in the range of 4.0 kHz to

20 kHz. Typical output voltage waveforms are shown in Figure 4 and Figure 15.

Recent developments in IGBT technologies have focused on the tradeoffs of the device’s forward voltage drop (V_{CEsat}) versus switching speed limitations due to device “tail time” in motor drive applications. Tail times are related to the stored charge in the IGBT’s internal BJT and can be reduced at the expense of increasing the V_{CEsat} of the device. In general an increase in carriers will reduce the V_{CEsat} but slow down the switching speed. Conversely, a decrease in carriers will increase the V_{CEsat} but speed up the switching speed. Several technologies have been developed that attempt to optimize both switching times and forward voltage drop while providing rugged short circuit capability. The following work investigates the performance of several IGBT technologies in an adjustable speed motor drive

application. An off-line, 3 kW motor control test bed was used to test the performance of 600 V, 15 A IGBT's.

3 kW Variable Speed Drive Test Set-up

A new line of IGBT devices has recently been introduced by ON Semiconductor. Devices rated at 600 V, 15 A, are included and targeted for industrial drives of one phase 120 Vrms and/or 230 Vrms. These particular IGBT's are ruggedized for motor control applications and are specified to withstand 10 μ s of short circuit current. Six of these devices were inserted into a bridge configuration in a 3-phase, 3 kW, variable speed, motor controller that operated at 10 kHz. The test system was then used to

evaluate the different generations of IGBT's. Figure 13 illustrates the block structure of test system which uses a volt-Hz open-loop or closed-loop control technique, field-oriented control or direct torque control technique. The overall test bed can be divided into the motor drive system and load drive system. Both are mechanically coupled with a clutch. The energy is then transformed from electrical to mechanical energy by an induction machine. This mechanical energy is then transferred back to electrical energy by another load induction machine (generator) and then dissipated as thermal energy by an attached loading device.

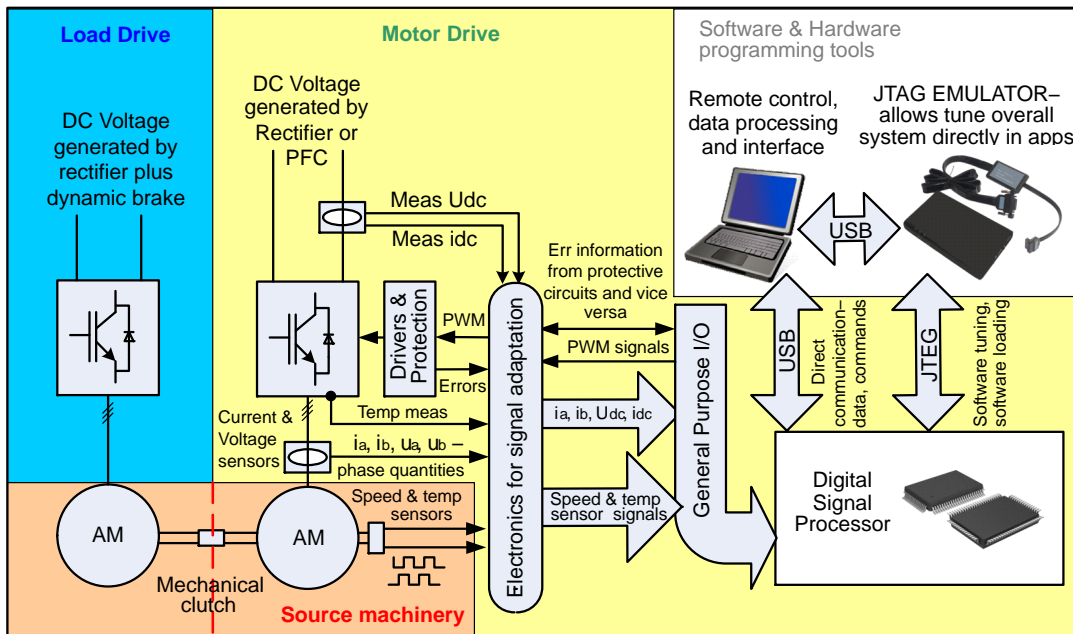


Figure 13. Block Structure of Laboratory Test Set-up

Motor drive technology has been established as a complex and multidisciplinary technology. Specialization in this area requires knowledge of power semiconductor devices, converter circuits, electrical machines and mechanics, control electronics, microprocessors and DSPs, ASIC chips, control theories, power systems, and computer-aided design and simulation techniques. Knowledge of electromagnetic interference, the passive components of such a system, and the accompanying specialized design, fabrication, and testing techniques are equally important [1].

Due to the complexity and number of sensing parameters, it is important to pay special attention to the signal processing circuits. The signals that are required to be monitored possess different forms – voltage or current and analog, digital and quadrature signal. For the proper functioning of an electric drive, multiple signals must be sensed, processed and converted for the drive to operate properly and be adequately protected [3]. The system flow

block diagram is shown in Figure 13 which is also the basic structure of the test bench used in the lab for the testing of ON Semiconductor's IGBTs. Most modern motor control systems use a microcontroller or DSP to process the motor signals and control the IGBT switches.

IGBT Testing in a Motor Control Application

In order to understand the efficiency of ON Semiconductor's new IGBTs, they were installed in a three phase motor drive system and waveforms and temperatures were measured and analyzed under controlled operating conditions. Dynamic measurements include the IGBT's collector current and collector-emitter voltage values captured on an oscilloscope (see Figure 14 for more details of measurement techniques). These values were measured near the peak of the ac line current half sine wave shown in Figure 15. These data were captured by scope and then processed on a personal computer.

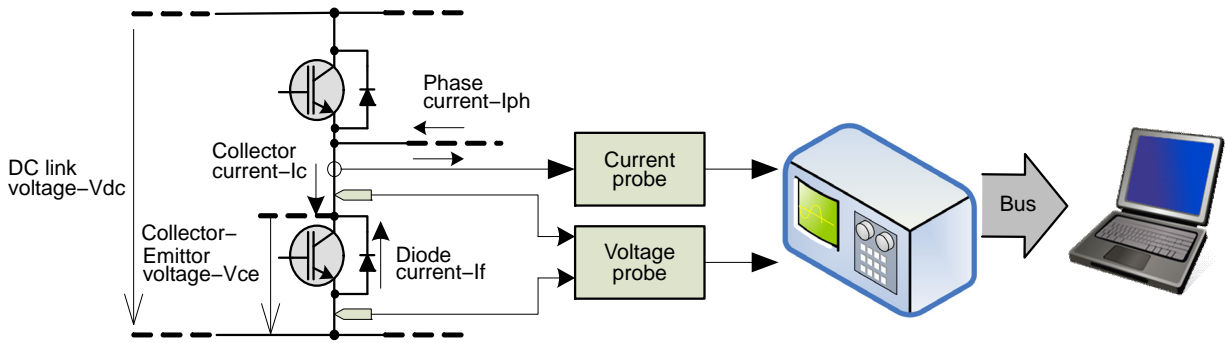


Figure 14. The Measurement Block Structure

The IGBTs are compared by loss energies computed over one switching period which means the energies represent the peak value for a single cycle switching waveform. The measurement conditions are held constant at these values: $V_{dc} = 300\text{ V}$, $I_c = 14\text{ A}$ (these conditions correspond to approx. 3 kW output), $R_g = 22\ \Omega$, $V_{GE} = 15\text{ V}$, $f_{sw} = 10\text{ kHz}$, $T_j \approx 100^\circ\text{C}$. The measurements were taken on the same test setup under the same test conditions for each IGBT technology.

Overall IGBT drop is difficult to measure due to the varying AC waves of the controller. However, by using the differential method proposed in Figure 14, V_{CEsat} measurements were measured. The case temperature of the IGBT was sensed by the use of an IR camera to measure device operating temperatures for comparison.

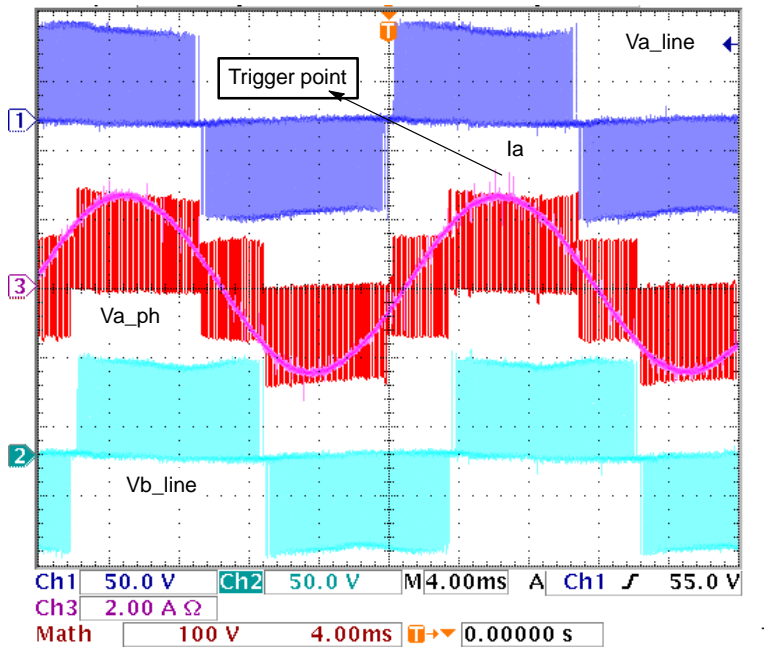


Figure 15. Output Line (Blue and Turquoise) and Phase Voltages (Real Value should be $V_{ph}/3$) together with Phase Current (Pink Waveform)

IGBT and FWD Losses Evaluation

When using existing solid-state switching technologies, the designer must deviate from the ideal switch and choose a device that best suits the application with a minimal loss of efficiency.

One way to compare power devices such as IGBTs is power or energy loss comparison. The power losses in a power-switching device constitute of conduction losses, off-state blocking losses, turn-on switching losses, and turn-off switching losses. In practice the blocking losses are neglected.

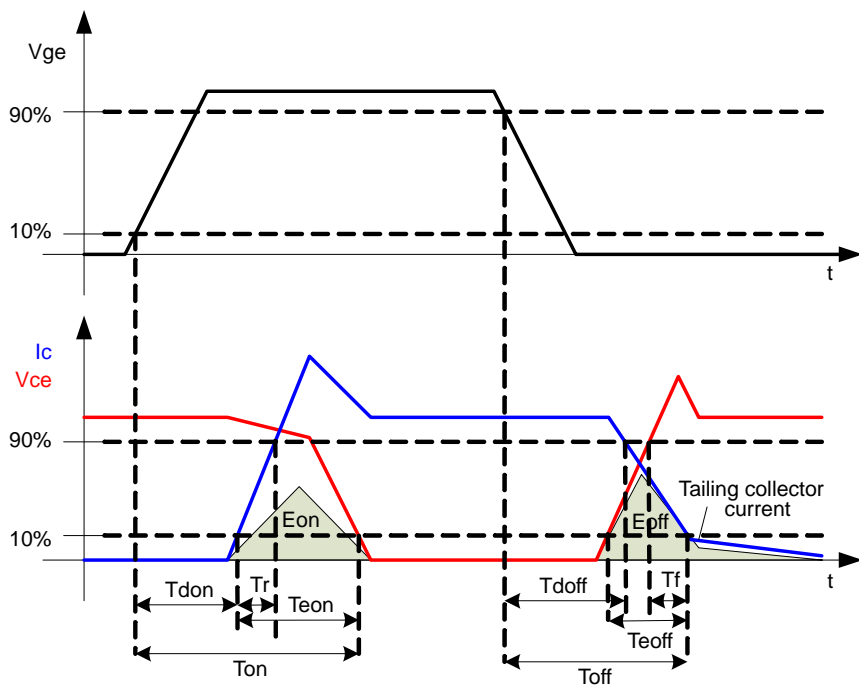


Figure 16. IGBT Current and Voltage Turn-on and Turn-off Waveform Parameters

The turn-on energy loss E_{on} is defined as the area under power loss waveform ($P(t) = I_c(t) \cdot V_{ce}(t)$) within the limit of 10% I_c rise to 90% V_{ce} fall. The amount of turn-on energy loss mainly depends on the reverse recovery behavior of the diode [5]. The fundamental turn-on and turn-off parameters during turn-on and turn-off dynamics of an IGBT are depicted in Figure 16. The turn-off energy loss E_{off} is defined as the area under power loss waveform ($P(t) = I_c(t) \cdot V_{ce}(t)$) within the limit of 10% V_{ce} rise to 90% I_c fall [5].

IGBT and FWD Conduction Losses Evaluation

The conduction power loss is calculated in a straightforward manner as the product of the device current and the forward saturation voltage. The blocking

loss is the product of the blocking voltage and the leakage current [1]. The conduction loss of an IGBT in VSI application doesn't depend on only the V_{CEsat} parameter but this is very good indicator of resultant conduction losses. Figure 17 shows the waveforms during the IGBT conduction time. In this picture we can see collector-emitter voltages, collector currents and the time interval where we computed the resultant V_{CEsat} voltage. Figure 17 compares resultant saturation voltages for standard planar and ON Semiconductors' trench (non-punch through) technology measured in a dynamic motor control application (this is not static measurement). The difference in saturation voltages between the two technologies is significant and can be clearly seen in this scope shot.

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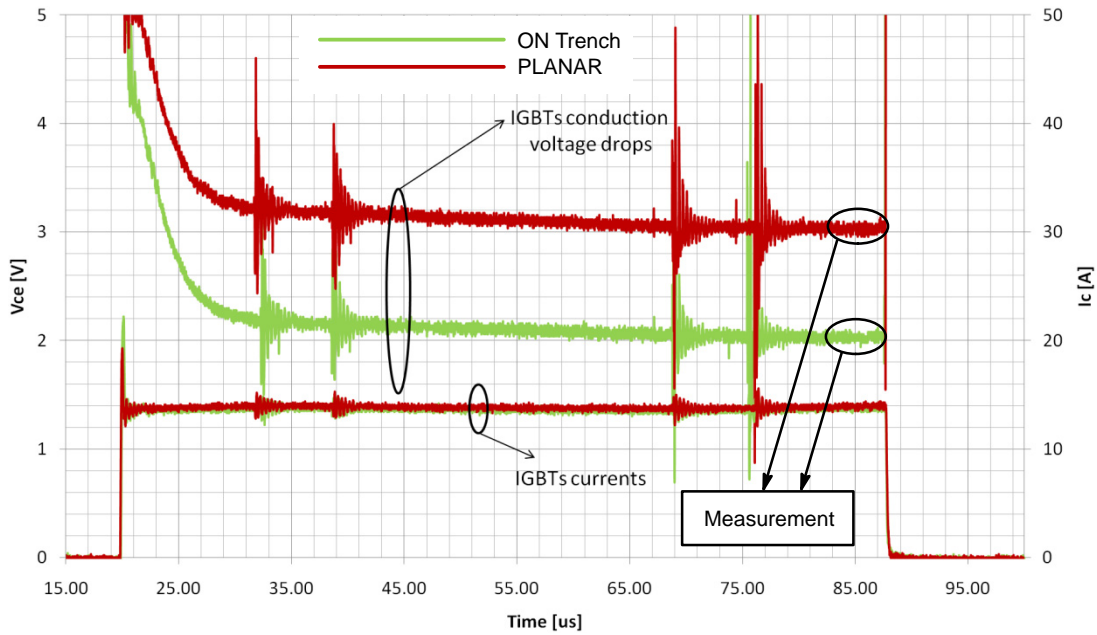


Figure 17. Conduction Dynamics Comparison of ON Semiconductor First and Second Generation Trench with Planar Technologies

This is an application measurement of V_{CEsat} at $100^{\circ}C$ as a function of current and time for all technologies. As seen from this graph, the V_{CEsat} of the new IGBT designs is significantly reduced. The reduction in the typical value of V_{CEsat} combined with the tightening of process related parameter distribution has made it possible to spec ON Semiconductor's IGBTs more aggressively. Note that this improvement was achieved without sacrificing the fast switching speed of these motor control IGBTs.

Modern fast switching devices require fast diodes as free-wheeling diodes. With every turn-on of the switch, the free-wheeling diode is commutated from its conduction to its blocking state. These devices must be very fast but still show soft-recovery behavior and low forward voltage. Free-wheeling diodes in IGBT-converter have to cope with different requirements depending on whether they are used in a motor, a generator or a machine that can operate in either mode.

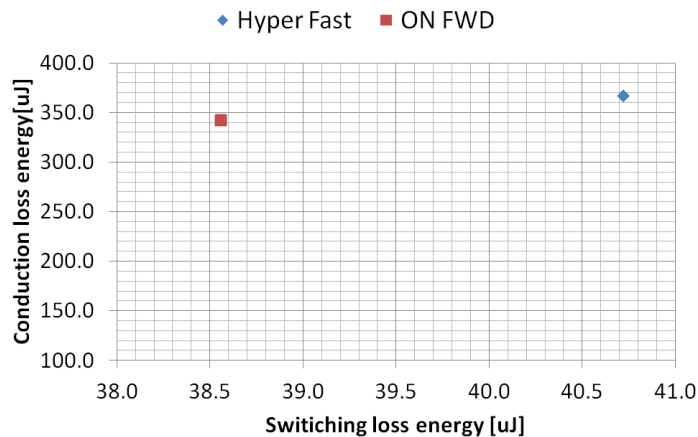


Figure 18. Trade-offs between Conduction and Switching Losses

Similarly to V_{CEsat} , the conduction losses of a free-wheeling diode (FWD) in VSI application don't depend on the V_f parameter alone but this is very good indicator of resultant conduction loss. For inverter-operation the power factor is positive ($\cos(\theta) > 0$) and the power losses in the semiconductors reach their limits, if $m \cdot \cos(\theta) = 1$, where m is modulation index. In this case maximum on-state losses and therefore, total losses in the IGBTs have been reached, whereas losses in the free-wheeling diodes are at their minimum. In the case of rectifier operation ($\cos(\theta) < 0$), power losses in semiconductors reach their limits if $m \cdot \cos(\theta) = -1$. In this case, minimum on-state losses and, therefore, total losses in the IGBTs have been reached, whereas losses in the free-wheeling diodes are at their maximum. For this reason, ON Semiconductor optimizes V_f performance together with switching performance. The performance of a free-wheel diode in a switching application (Figure 18) shows the comparison between ON Semiconductor's optimized diode with a hyper fast diode. The switching performance is important in a motor control application thus the switching losses are optimized with consideration for the voltage drop.

IGBT and FWD Switching Losses Evaluation

When passing over from the conduction to the blocking state, the internal diode storage charge has to be discharged. This results in a current flowing in the reverse direction in the diode. The waveform of this current is characterized as the reverse-recovery behavior. The typical turn-off dynamics and comparison can be seen in Figure 19, where peak current, time duration and electrical charge play important roles for optimized results. Figure 20 shows us reverse recovery of an silicon diode together with fundamental parameters during turn-off transient. The commutation slope di/dt is determined by voltage and inductance. At t_0 current crosses the zero level and at t_w the diode starts to block. At t_{rrm} the reverse current reaches its maximum value. After t_{rrm} the current falls to leakage current. The current characteristics depend on the diode. If the current drops steeply, this is called snappy recovery behaviour. If the current drops softly, this is called soft recovery behaviour. The reverse recovery time t_{rr} is defined as the time between t_0 and the time, where the current reach 20% of I_{rrm} . The subdivision of t_{rr} into t_f and t_s defines a quantitative value for the recovery behavior [4].

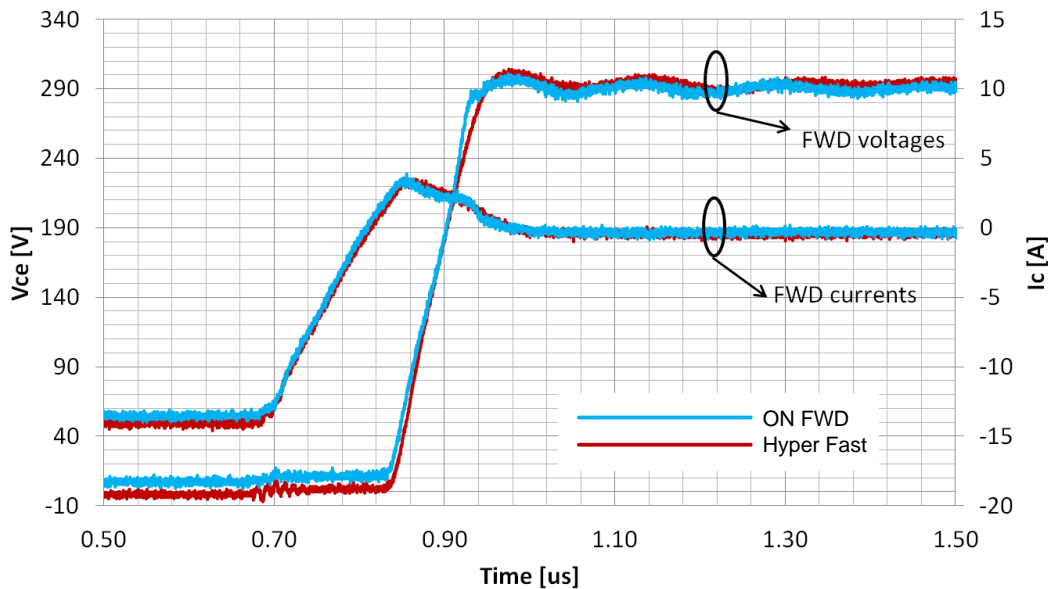


Figure 19. Reverse Recovery of FWDs

The reverse recovery behavior of a diode is the significant portion of its switching losses since its turn on losses are minimal. ON Semiconductor works to minimize the switching losses and in Figure 21 we can see the result of the optimization process.

By measuring a single switching period in a motor control application we are able to get very important information about the distribution of the power losses. The impact of the turn-on, reverse recovery and conduction losses is quite apparent. The switching losses are very often the smaller part of the total power losses of a diode as can be seen in Figure 21. On the other hand turn-off phenomenon strongly influences IGBT turn-on losses.

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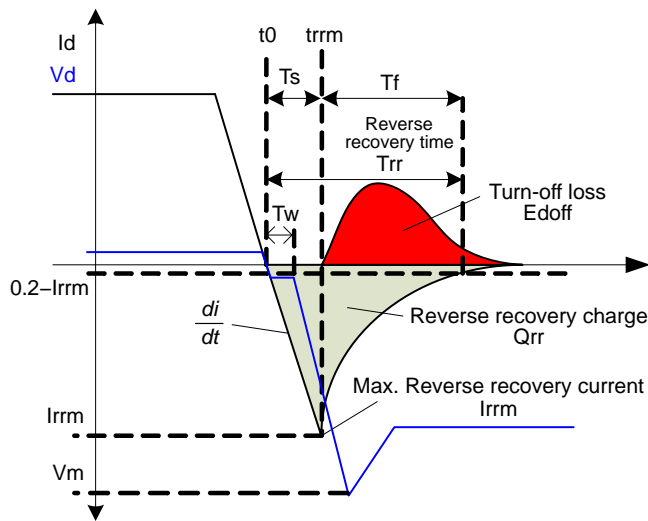


Figure 20. Current and Voltage Characteristic of the Reverse Recovery Transient of a Soft-recovery Diode and Definition of the Recovery Behavior

Generally the reverse recovery effect is more important for its impact on the IGBT switching losses. We can define the soft recovery factor as quantitative value for the recovery behavior. This soft factor s can be computed by several methods, such as $s = t_f/t_s$, but the general goal is a soft

waveform without a snappy recovery characteristic which means that s is held as high as possible. The optimization process must balance the switching speed with the soft recovery and also keep the forward drop as low as possible.

FWD Switching vs Conduction Energy Losses

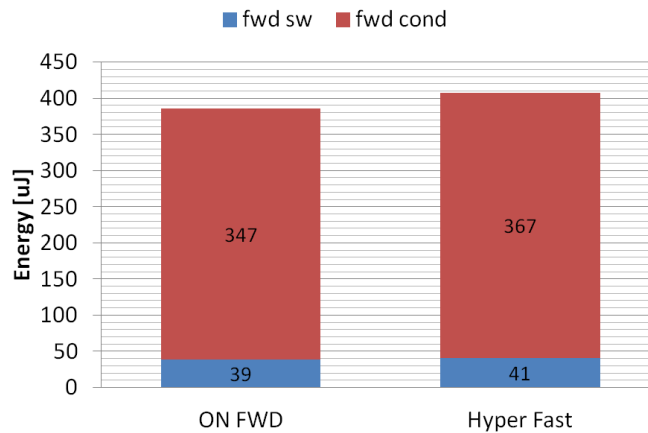


Figure 21. Switching versus Conduction Losses of FWDs

Turn-on switching losses of IGBTs are largely dependent on reverse recovery behavior of the FWD in inductive load applications. The turn-on process is complete only after the FWD has recovered and begins to block the full DC link voltage. Slower diodes, besides adding their reverse recovery current transient to the load, prolong the turn-on process. Switching times can be decreased by using a higher gate input voltage and/or lower gate resistance, thereby increasing the rate of rise of current in the IGBT and corresponding rate of fall of current in the FWD. The

reduction in turn-on time is limited by the nature of the reverse recovery. Snappier recovery requires that the turn-on di/dt be reduced in order to avoid the occurrence of unsafe recovery voltage transients and generation of excessive EMI. Softer FWDs, on the other hand, allow faster IGBT turn-on. Faster and softer recovery of the FWD is therefore very important in such applications. ON Semiconductor has accomplished this by designing a series of co-packed diodes.

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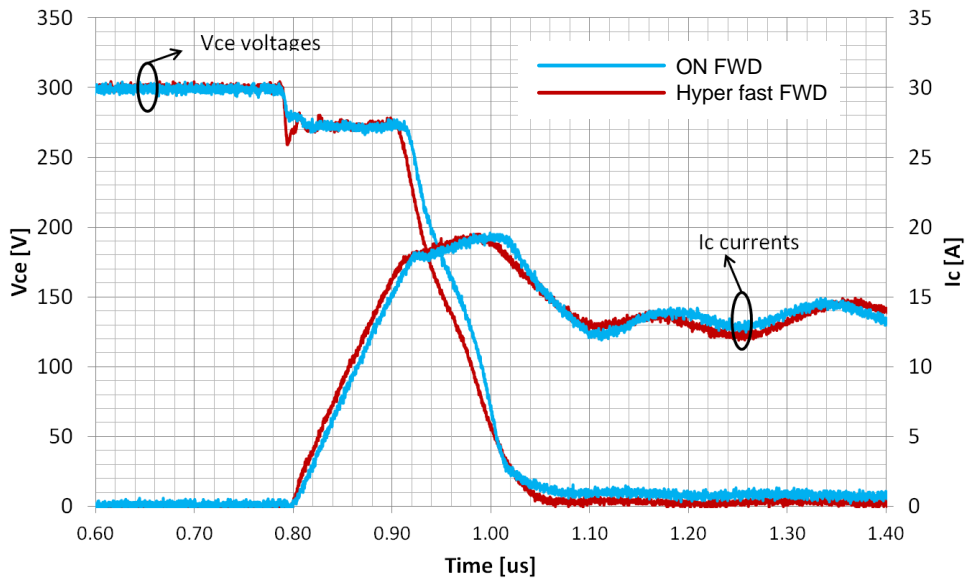


Figure 22. IGBT Turn-on

The goal of optimization is a very fast turn-on together with low reverse current peak. Figure 22 shows a comparison of diodes' effects on IGBT turn-on between ON Semiconductors' standard free-wheeling diode and a hyper-fast free-wheeling diode. These waveforms demonstrate that the hyper-fast diode responds faster and thus has a lower power loss. But we must not forget that in

a motor control application the diode can operate as rectifier (in generator mode or during motor braking) and under this condition the conduction loss of diode is dominant. So, the dv/dt rate between the reverse recovery transient and its effect on the IGBT turn-on loss versus conduction loss is crucial for an efficient diode. This trade-off is apparent from Figure 18.

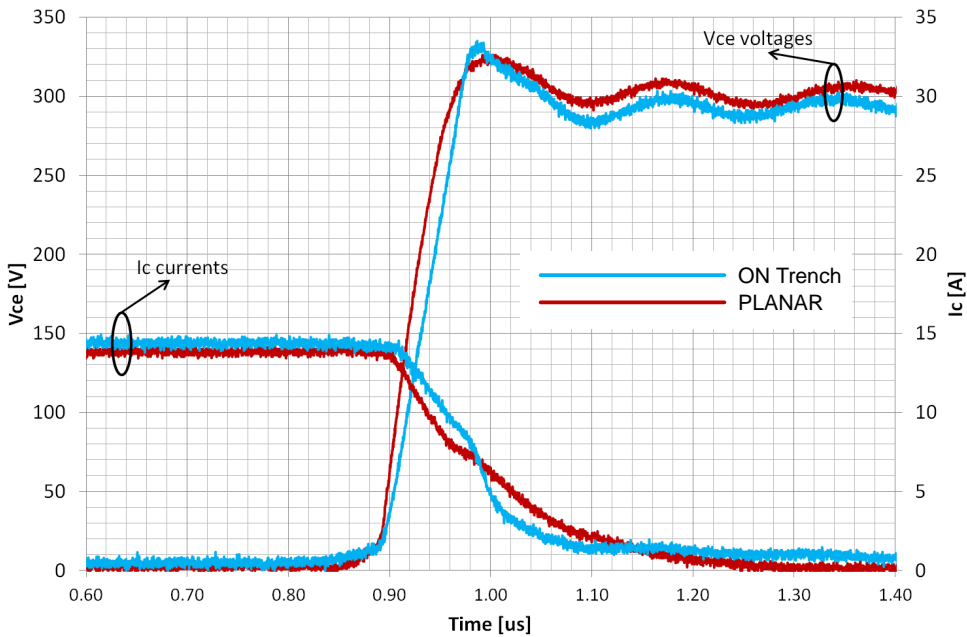


Figure 23. IGBT Turn-off

The tail current is one of the undesirable features that causes its turn-off to be slower than that of a MOSFET. While turn-on is fairly rapid, early IGBTs had current fall times in the order of microseconds. In addition, due to the long tail current the dead-time in the PWM control logic must be long enough to allow the current to go to zero. The power loss during turn-on is governed by this time interval, which is determined by the reverse recovery behavior of the power rectifier. The turn-off speed of an IGBT is limited by the lifetime of the stored charge or minority carriers in the N-drift region which is the base of the PNP transistor. The base is not accessible physically thus an external means cannot be applied to sweep out the stored charge from the N-drift region to improve the switching time. The only way the stored charge can be removed is by recombination within the IGBT. Traditional lifetime killing techniques or an N+ buffer layer to collect the minority charges at turn-off are

commonly used to speed-up recombination time. Figure 23 shows comparison between ON Semiconductor’s trench technology and one of the planar technology. The waveforms show that the current designs allow us to use a very short dead-time which is beneficial and suitable for higher switching speed motor control applications.

Evaluation of Total Losses

In the optimization process of the new and better IGBT or FWD it is convenient to make energy loss measurements for the IGBT and FWD separately. In addition it is desirable to divide these measurements for each area of loss within each switching time interval such as turn-on, conduction and turn-off for both the IGBT and FWD. This measurement gives us information about energy losses distribution and thus heat production inside of the package over one switching period and under a specific set of conditions.

IGBT Switching vs Conduction Energy Losses

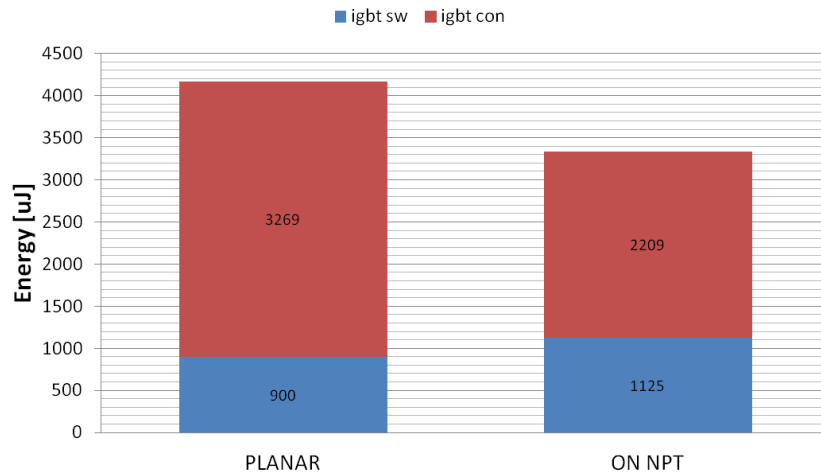


Figure 24. IGBT’s Total Losses Distribution

Figure 24 shows us the total IGBT power loss division for switching and conduction losses for ON Semiconductor trench IGBTs with respective FWDs together with a convectional planar high-speed IGBTs with hyper fast diodes. The same power loss distribution but for diode is depicted in Figure 21. The measurement was done for a 10 kHz switching frequency and the conduction losses dominate; however for increasing frequencies (up to 20 kHz

in motor control applications) its effect will be less and less until switching losses will dominate. If the IGBT and FWD losses are measured separately it is easy to understand the breakdown of the losses which is very useful in selecting the best device for the application. Figure 25 shows the division of the conduction and switching losses for both the IGBT and the FWD together.

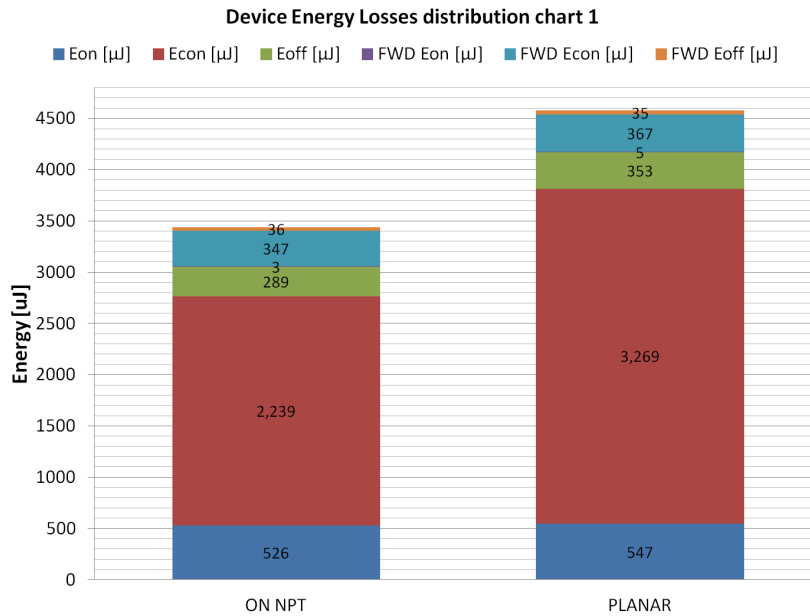


Figure 25. IGBT plus FWD Power Losses Distribution

Generally, in power electronics, IGBTs as well as diodes operate mainly as switches. They take on various static and dynamic states within one cycle and, in addition, within one motor drive supply period. In any of these states, one power dissipation or energy dissipation component is generated, which heats the semiconductor and its environment [4]. This means that the total loss over one motor drive supply period

is the sum of the losses generated over all switching periods. The electrical measurement of this total loss is very difficult, but for the comparison of the total losses we can measure the case temperature in a given system. Then in steady state conditions the thermal resistance is the only constant of proportionality and is the same for all measurements.

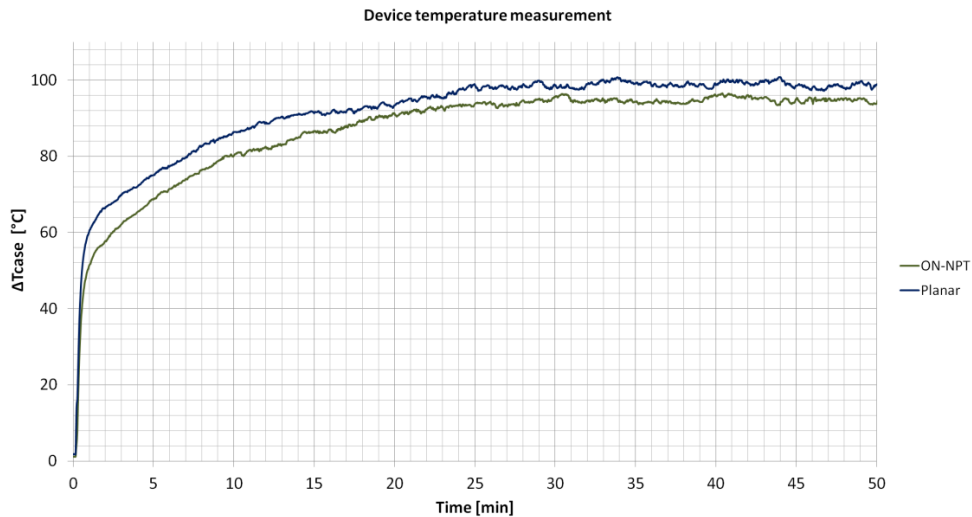



Figure 26. Steady State Temperature Measurement as Total Loss Comparison

The measurement in Figure 26 shows us the comparison of ON Semiconductor planar and trench technologies in

a motor control application. This makes it easy to deduce which part generates a lower level of power loss.

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