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IGBT Technologies and Applications Overview: How and When to Use an IGBT

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ABSTRACT

Proliferation of high-performance power conversion equipment in applications such as solar inverters, UPS, motor drives, inductive heating, welding, automotive and traction has rekindled the interest in understanding and optimizing IGBT characteristics in order to optimize the system performances. Efficiency and thermal performance are the key metrics along with reliability and ruggedness. The power electronics environment is continuously changing, mainly due to new application-requirements and the availability of new technologies in the market. The so-called wide band gap technologies (SiC- and GaN-based) are becoming popular and most of the power electronics designers are investigating how to implement such new technologies in their new designs. Still the silicon technologies are the rock-solid solution for the today design. The emphasis of this paper is to provide a framework on IGBTs: how to use them in high-power and high-voltage designs. A contextual overview of power silicon technologies and general topologies/applications is provided. Common system requirements for high power applications are discussed. It is shown that each end-application has a different set of requirements in terms of IGBT characteristics. In the last part, some practical issues related to IGBT design are covered with special focus on gate driving.

Keywords: IGBT, high voltage, gate-drive

INTRODUCTION

In the last twenty years, many changes occurred in power electronics: from the power switches to the applications design and controls. Twenty years ago, the bipolar junction transistor or BJT was the predominant silicon transistor technology used, which has been replaced by the power metal oxide semiconductor field effect transistor (MOSFET) (mainly because it was easy to use) in most of applications and by the insulated gate bipolar transistor (IGBT) in applications where high current and high voltage were required. Unlike MOSFETs or bipolar transistors, by changing a relatively small set of device and process parameters, IGBT switching speed, softness and controllability, conduction losses, short circuit and pulse current-withstand capability can be tuned over a wide range to meet specific application requirements.

The recent technology evolution and price erosion have led to stretching the realm of usage of such devices (see Figure 1).

One decade ago, the IGBT technology was used only in applications were the MOSFET was either too expensive or not an option for its weakness (such as intrinsic body diode or limitation in performances at low-frequency operations). Today, the proliferation of industrial applications (high voltage) and the expected booming of the electric vehicle market is driving even more investment in the IGBT technologies and packages.

Figure 1. Power Switch Environment [1]

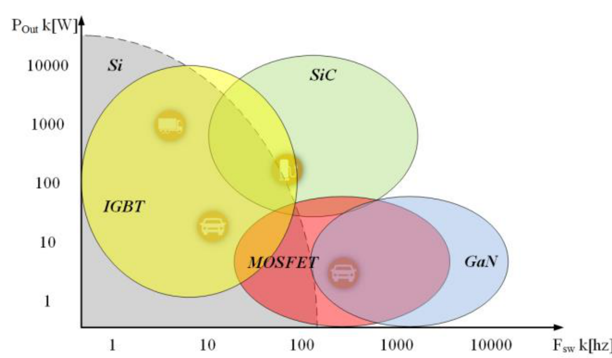

Figure 2. Range of Operation of Silicon and Wide Band Gap Devices

It is amazing when you realize the technology jumps in IGBT developments over the last 10 years: starting from the trench structures up to the field-stop and the combination of these. These improvements further accentuate the inherent characteristics of an IGBT: high-voltage and high-current density, good performances in switching, robustness. Initially, IGBTs, which emerged from power MOSFETs technology, were formed by epitaxy and using what is known as the punch-through (PT) technique [3].

INSULATED GATE BIPOLAR TRANSISTORS

The IGBT is a power semiconductor transistor based on four alternating layers (P-N-P-N), which are controlled by a metal-oxide-semiconductor (MOS) gate structure without regenerative action.

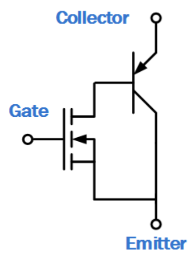

Figure 3. IGBT – Darlington Structure

It is possible to associate an IGBT with a darlington configuration between a high-voltage PNP bipolar transistor and a power-MOSFET (see Figure 3). The idea behind this power device is to overcome the difficulty in increasing the power MOSFET current handling capability. The first IGBT concept has been presented in 1968 by Yamagami in his Japanese patent S47–21739 [2]. Since then, many structures have been proposed. The first concept was based on the planar technology. Figure 4 shows the IGBT structure with its parasitics. The most popular IGBT structures were punch-through (PT) and non-punch-through (NPT), shown in Figure 5 [3] [4] [5].

PT IGBTs are based on heavily-doped p^+ substrates used for Epi growth. These substrates cause large turn-off energy (E_{off}) due to the long current tail during turn-off. Further enhancements of the switching performances in PT IGBT are obtained by minority carrier lifetime control through platinum diffusion or radiation. This causes a negative temperature coefficient for saturation voltage.

NPT IGBTs are based on n- substrate with a lightly-doped P layer implanted. Thick substrates are used to sustain high breakdown voltage implied high development costs for IGBTs. The NPT technology was later introduced using float zone (FZ) Si substrates for the IGBT structure and then thinning the substrate backside to form a p^+ collector region. This technique has enabled a reduction of switching losses and conduction losses to a relatively low levels and improved IGBT device and system level performance.

The most innovative structure for sure was the introduction of the field-stop (FS) technology which was about a decade ago.

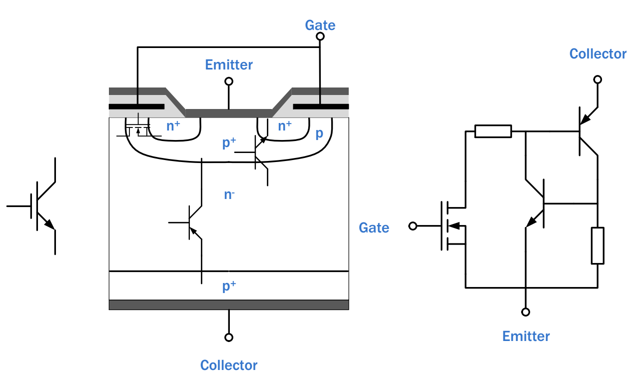

Figure 4. IGBT with Parasitic Structure

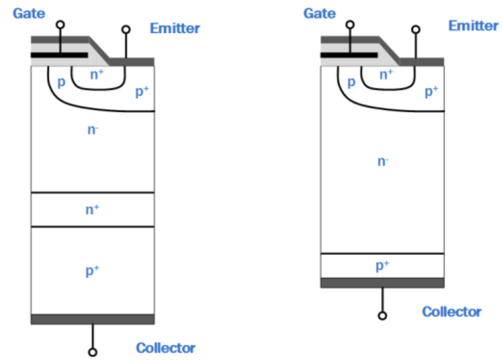

Figure 5. Left) Punch-through (PT) IGBT; Right) Non-punch-through (NPT) IGBT

The FS structure is shown in Figure 6. The FS technology combines the features of NPT and PT IGBTs structures: implanted backside p^+ of NPT and N buffer of a PT, although the depletion region is not punching through in FS IGBT, while it is supposed to punch through the N buffer in PT IGBT. The main big changes in the field stop FS IGBT are: thin drift region achieved via thin-film technology; p^+ replace lightly doped by robust and transparent p anode layer. These improvements offer an excellent tradeoff between conduction and switching losses, and superior performance in comparison with the state-of-the-art NPT and PT IGBTs [6]. FS technology allows the same high-voltage operation with significantly thinner Si die. This reduction in thickness has led a simultaneous reduction of E_{off} and VCE_sat.

From the first release of FS IGBTs, in the last decade there were several process and device improvements, as well as detailed physics characterization and circuit level modeling.

Then the introduction of the trench gate has increased the performance. In conventional planar IGBTs, current crowding is causing JFET effect leading an increase of V_{CE_sat}. This effect is alleviated by introducing trench structures. The free carrier concentration in the N-drift region near the emitter is also enhanced, leading to a lower V_{CE_sat}. Using trench gate structure makes it easier to suppress the effect of the parasitic NPN.

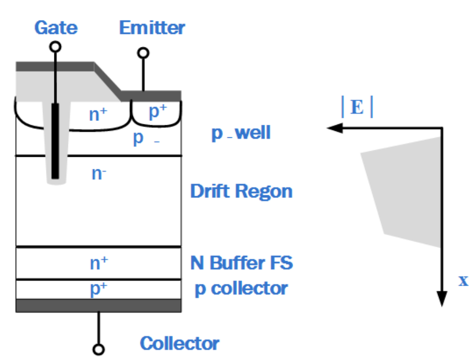

Figure 6. Field Trench Stop IGBT Structure

Having a thinner device also means a better thermal resistance and this leads to a smaller die size for the same current rating (increasing the power density of these power devices with respect to the standard technology) [7] [8].

Factors	Punch Through (PT)	Non-Punch Through (NPT)	Field Stop	
			Planar Gate	Trench Gate
V_{CE_sat}	Low Strong negative temperature coefficient	Medium Positive temperature coefficient	Low Positive temperature coefficient	Lower - Same V_{GE} allows to modulate a much greater drift region area leading a lower $R_{DS(ON)}$
E_{on}	Main loss contribution comes from E_{off}, so rarely considered		Lower E_{OFF} in newer devices so E_{on} losses now is more important	Lower – Higher Cell density
E_{off}	High/Medium (Depends on Current Tail)		Low	
	Short duration, high amplitude current tail. Large increase of current tail at high temperatures	Long duration, low amplitude current tail, almost independent of temperature	Short duration, low amplitude current tail, almost independent of temperature	
Short Circuit	Limited	Yes	Yes	Yes

Figure 7. IGBT Technologies Assessments

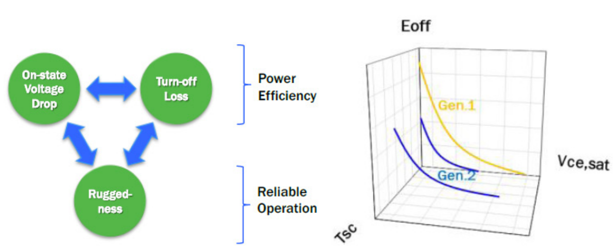

Figure 8. Left) The IGBT Triangle; Right) Trade Off Relationship

Today IGBT designers have reached a very high understanding of the device physics and how to tune it. Hence most of the IGBT manufacturers design the devices for applications specifics. They are optimizing the trade-off curve in order to achieve the highest efficiency for a given applications. Figure 8 and Figure 9 show the principle of the IGBT triangle optimization and some of the trade-off example that a technology can reach. Some examples of parameter optimization are given:

- Mesa-engineered for low conduction losses and good energy handling robustness
- Drift area tuned for target BV (Breakdown Voltage) and fast switching
- Balanced buffer and anode providing excellent robustness and low energy losses
- Top and bottom metal tailored for discrete packages or modules.
- Gate designed for low capacitance and high reliability

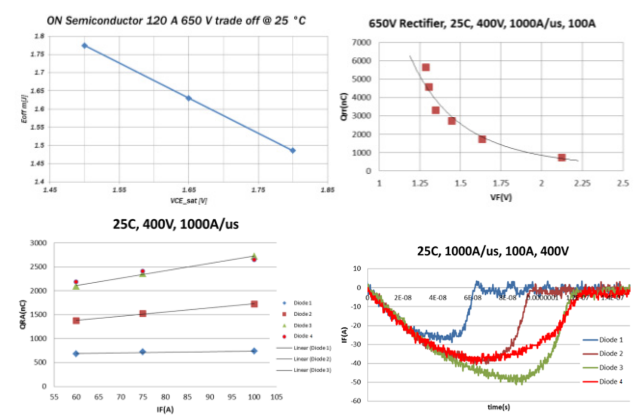

Figure 9. Examples of IGBT and Antiparallel Diode Possible Trade Off

APPLICATIONS OVERVIEW

In the following section some of the relevant applications are discussed, with special focus on the IGBT optimization.

Welding

Today, a good share of welding machines in the markets uses inverters. A welding inverter represents an alternative to conventional welding transformers and offers advantages in output power control. Considering a dc output current helps controlling the welding process with great accuracy. Further, dc output currents are less dangerous than ac currents and prevent arc extinction. Another advantage of the inverter machines is the lower weight as the SPMS offers higher power density and weight compared to the classic transformer-based solutions. Figure 10 shows the system block diagram of a welding machine. The power stage, which can be single or three-phase type transforms the ac input into a dc bus voltage and then feeds the inverter with isolation. The most common output voltage is 30 V and can reach up to 60 V dc during open load operations. It collapses to nearly 0 V (as in a short circuit condition) when initiating arcs.

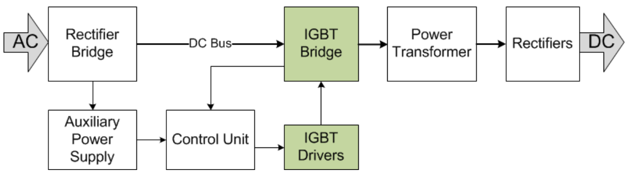

Figure 10. System Block Diagram of Welding Machines

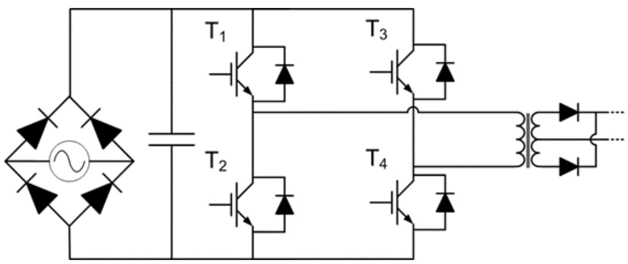

Figure 11. Full-bridge Topology

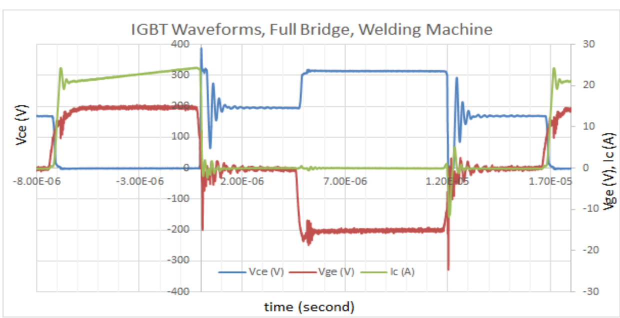

Figure 12. Waveform of a Full-bridge Welding Machine

(The blue trace represents the collector voltage across one of the IGBTs (100 V/div); The red is the gate voltage across the gate driving circuit; The green trace represents the collector current across one of the IGBTs)

The most common topologies in welding inverters are full-bridge, half-bridge, and two-switch forward. Figure 11, Figure 12, Figure 13, Figure 14, Figure 15 and Figure 16 show the above mentioned topologies and their usual operating waveforms [9][10].

The most common control scheme used in welding applications is the constant current. The duty ratio varies according to load level/output voltage

The most common IGBT switching frequency of full-bridge and half-bridge topologies ranges from 20 to 50 kHz. Commonly-used frequencies are in the vicinity of 30 kHz. Switching frequency in the two-switch forward topology aims at 60 kHz and above.

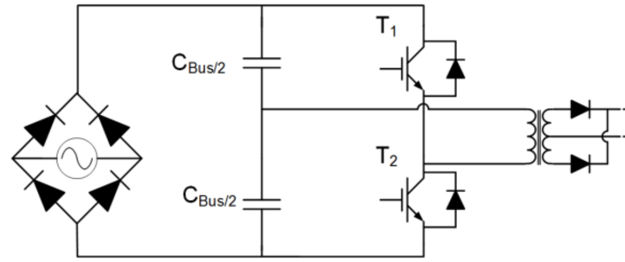

Figure 13. Half-bridge Topology

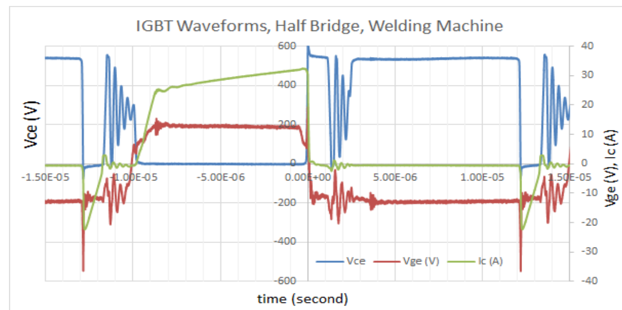

Figure 14. Waveform of a Half-bridge Welding Machine

(The collector voltage across one of the IGBTs appears in blue (100 V/div) while the red trace depicts the gate voltage across the gate driving circuit; The green curve represents the collector current across one of the IGBT)

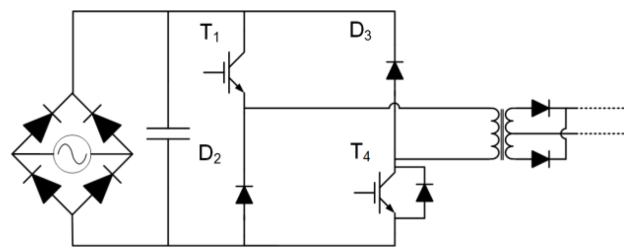

Figure 15. Double Switches Forward Topology

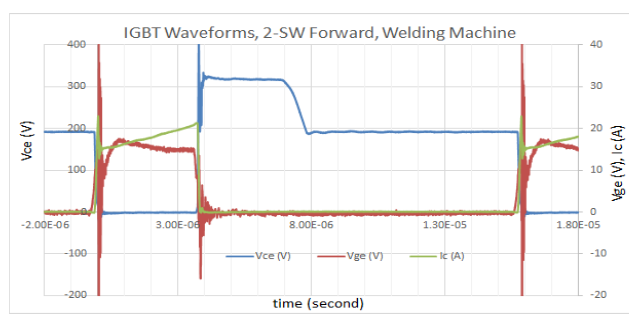

Figure 16. Waveform of a Two-switch Forward Welding Machine

(The blue curves is the collector voltage across one of the IGBTs (100 V/div); the red waveform is the gate voltage across the gate driving circuit; The green trace shows the collector current across one of the IGBTs)

Figure 17 shows detailed waveforms of the switching commutation in a full-bridge welding machine.

Figure 18 shows the IGBT losses distribution in a full-bridge welding machine. Below are listed a few takeaways from this chart:

- Conduction losses are not the predominant contribution to the total losses
- E_{on} is much smaller than the datasheet value: zero-current switching (ZCS) due to low inductance/long dead-time/discontinuous conduction time (DCM). Diode contribution to E_{on} is negligible
- E_{off} is the dominant portion of IGBT losses. Conduction loss caused by V_{CE_sat} is secondary because of low duty ratio
- Reverse recovery loss is the main part of the diode losses for the same reason of low E_{on}. The V_F is less important for the welding machine application

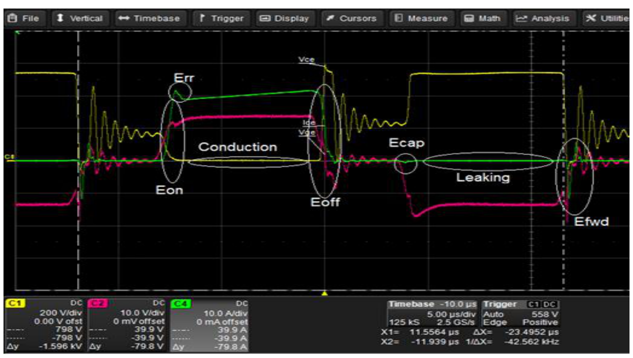

Figure 17. Switching Waveforms for a Full-bridge Welding Machine

(C1 collector voltage across one of the IGBTs (200 V/div);
C2 is the gate voltage across the gate driving circuit (10 V/div);
C4 collector current across one of the IGBTs (10 A/div).
Time scale 5 μs/div)

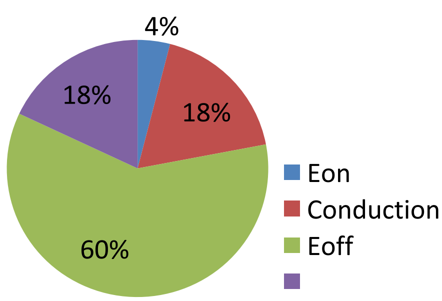

Figure 18. IGBT Losses Distribution in a Full-bridge Welding Machine 5 kW. Nominal ac 230 V Input. Output Current Full Load (250 A)

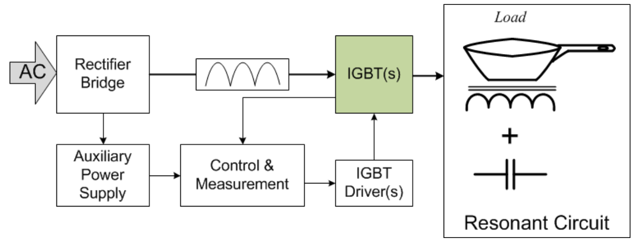

Figure 19. System Block Diagram of Welding Machines

IH System

The principle behind an induction cooking stove consists of exciting a coil of wire and force (or couple) the circulation of currents in a pot made of a material featuring a high magnetic permeability and placed close to the aforementioned coil. The way it works can be approximated to a transformer in which the coil plays the role of the primary side and the bottom of the stove represents the secondary side. Most of the generated heat finds its source in the circulation of eddy currents generated in the pot bottom layer [11].

According to the U.S. department of energy (DoE) the efficiency of energy transfer in these systems is about 90%, compared to 71% for a smooth-top non-inductive electrical unit, providing an approximate 20% saving in energy for the same amount of heat transfer [12].

Figure 19 shows a scheme of an induction cooker. Basically, the inverter induces a current into the copper coil and this generates an electromagnetic field which penetrates the bottom of the pot and generates a current. The heat generation follows the Joule effect formula, that is R (the pot resistivity) times the square of the induced current.

The main requirements for IH converter are as follows:

- High-frequency switching
- Power factor close to unity
- Wide load range

The most common output power control for induction heating applications is based on a variable frequency scheme. This is a basic method that is applied against the variation of load or line frequency. The major disadvantage of this method is the large frequency variation required for output power control over a wide range.

The most common topologies in induction heating are based on a resonant thank. The main advantage brought by resonant converters is the high switching frequency range at which they can operate without sacrificing efficiency. Several control techniques, like zero current switching (ZCS) or zero voltage switching (ZVS), can be used to reduce power losses in resonant converters.

The most popular topologies are resonant half-bridge (RHB) converters and the quasi-resonant inverter [13]. Figure 20 and Figure 21 show the topology structure and the normal operating waveforms of a resonant half-bridge. The advantage of this configuration lies in the high range of load operation together with the possibility to deliver the maximum of power. In most of the designs, the RHB is operated in the so-called inductive regions. Hence the IGBTs are turned on when their anti-parallel diodes are conducting, resulting in ZCS/ZVS for E_{on}.

The main characteristic of the RHB are listed below:

- Peak power is obtained when IGBTs' switching frequency approaches resonant frequency:
  - E_{on} is significantly lower due to ZCS/ZVS
  - Diode freewheeling loss at E_{on} is significantly lower
- E_{off} increases when the cooker operates at a lower power level due to the switching of higher resonant currents
- Pan material affects resonant characteristics and the diode freewheeling loss/stress

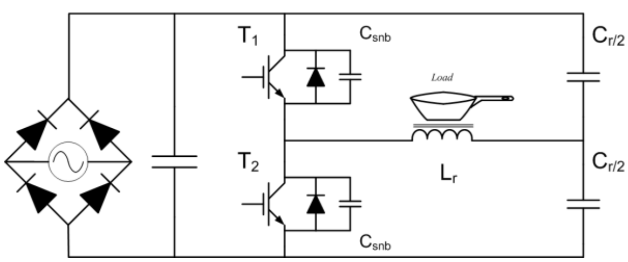

Figure 20. Resonant Half-bridge Topology for Induction Cooking Applications

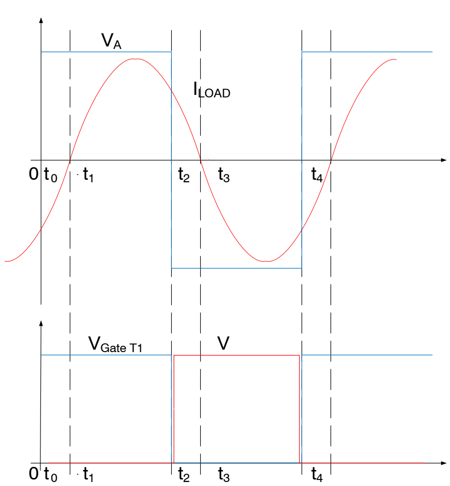

Figure 21. Resonant Half-bridge Inverter and its Waveforms

(The red trace shows the current into the resonant coil, L_r,
The blue trace represents the voltage between point A and B;
The lower graph shows the gate signal for T_1 and T_2)

Figure 22 and Figure 23 show the topology structure and the normal operating waveforms of a single-ended quasi-resonant inverter (QR). The main advantage of this converter is the lower cost. It is a perfect fit for low- to mid-power range (up to 2 kW peak power). The frequency operation is in the range of 20 to 35 kHz. During the on-phase, the energy is partially transferred to the load and partially stored in the resonant tank. During the off-phase, the energy stored in the resonant tank is transferred to the load. For certain L_r and C_r the regulation range (maximum-minimum power) is limited by the maximum IGBT voltage and current stresses. In an ideal situation, the IGBT is turned on when V_{CE} = 0 V resulting in ZVS for E_{on}.

The main characteristic of the QR converter are listed here below:

- Peak power is limited by VBR and resonant tank design:
  - E_{off} changes proportionally to the power level
  - E_{on} is eliminated and diode freewheeling loss is minimized

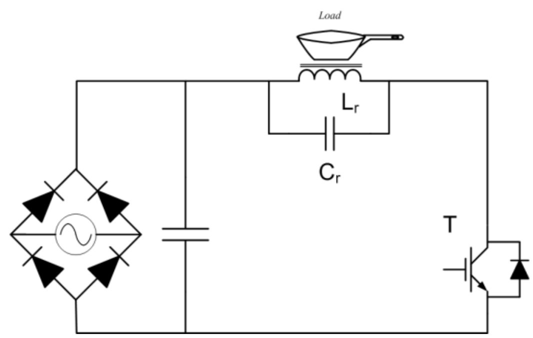

Figure 22. QR Topology for Induction Application

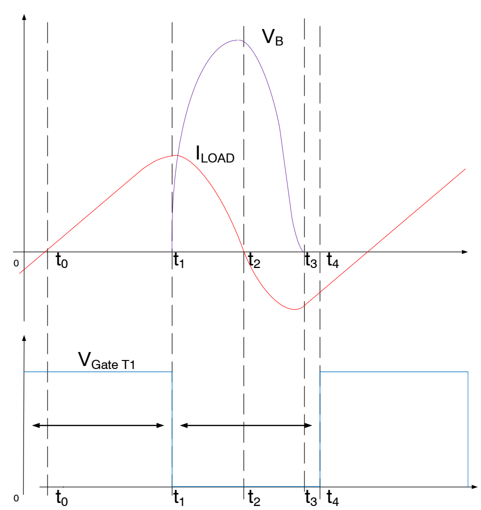

Figure 23. QR Single − End Inverter and its Associated Waveforms

(Upper graph: current into the resonant coil L_r appears in the red curve while the voltage across T_1 is the purple curve.
The lower graph shows the gate signal for T_1)

Figure 24 shows the QR operating modes. In QR mode, frequency increases at lighter load or pan lifting. At light load the ZVS is lost and E_{on} increases dramatically. Further at every turn-on the remain charges in the resonant capacitor is discharge at every turn on in the IGBT.

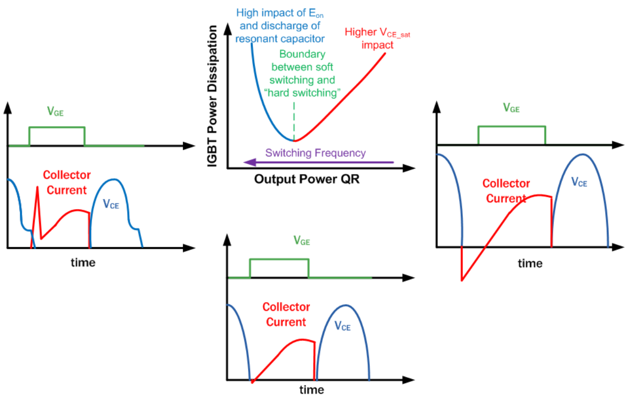

Figure 24. QR Operation Mode Left) Light Load; Center) Mid Load; Right) Heavy Load. Top) IGBT Losses for Different Load Conditions

$$I_c = C_r \times \frac{dV_{ce}}{dt} \qquad \text{(eq. 1)}$$

Pulse skipping is an alternative control method to avoid entering this zone.

Frequency decreases at heavier loads. The IGBT maintains near-ZVS operation but the diode is conducting a higher current. Low-resistive pans can cause the same effect for the diode.

Half Bridge for UPS Solar and Motor Drives

The half-bridge converter (HB) is one of the most popular topologies in power electronics especially in uninterruptible (UPS), solar inverters and motor drive applications. The HB output voltage depends on the switching state and current polarity as shown in Figure 25. Considering an inductive load, the current increases subsequently. If the load draws positive current (I_g>0), it will flow through T_1 and supplies energy to the load (V_g). On the contrary, if the load current I_g is negative, the current flows back through D_1 and returns energy to the dc source. Similarly, if T_4 is on (which happens when T_1 is off), a voltage $-1/2\ V_{bus}$ is applied to the load and the current decreases. If I_g is positive, the current flows through D_4 returning energy to the bus source (see Figure 27).

The HB can operate in the four quadrants, as shown in Figure 28.

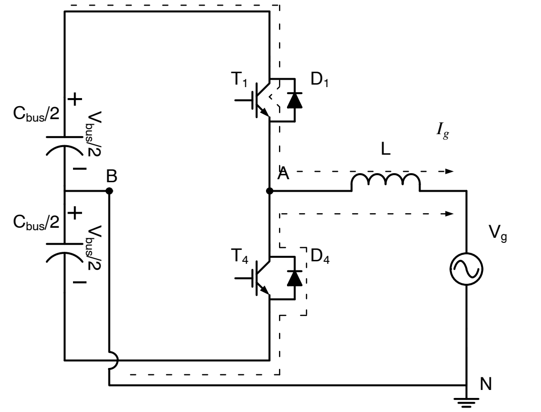

Figure 25. Half-bridge – Operating Waveforms for Positive Current Output

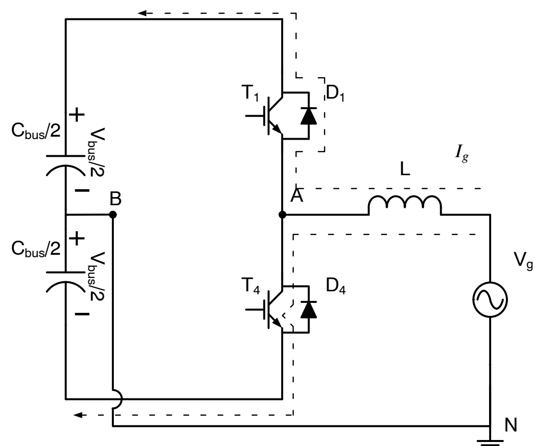

Figure 26. Half-bridge – Operating Waveforms for Negative Current Output

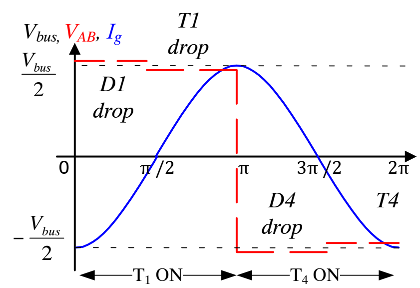

Figure 27. Half-bridge Operating Modes

During the four-quadrant operation, different aspects of IGBT characteristics are stressed:

- V_{CE_sat} in inverter mode
- V_F in rectifier mode
- E_{on}/E_{off} in reactive modes

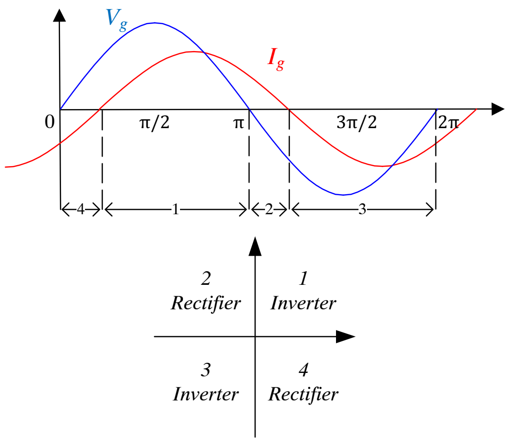

Figure 28. Half-bridge Four-quadrants Operations

Power at time interval 4 and 2 is negative. This negative power is called reactive power. Reactive power is common in motor drives for example and it increases the apparent power of a converter. A converter must be able to accommodate this part of power to properly drive a reactive load. The power line networks in most of the courtiers have not been upgraded to support the increase number of new solar generators (solar inverter). As a consequence during the peak of the sun, while all generators feed the line, at sub-nodes it is likely to have an overvoltage. Hence all the new solar inverters have to be able to absorb the over-voltage through the generation of reactive power.

Figure 29 and Figure 30 show typical switching waveforms for motor drive and solar UPS applications.

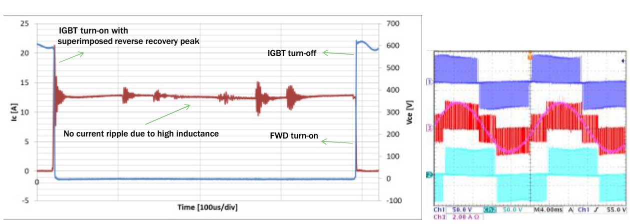

Figure 29. Switching Waveforms in Motor Drive Applications

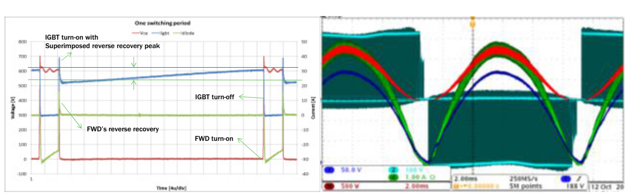

Figure 30. Switching Waveforms in Motor Drive Applications

The main characteristics for a motor drive application are given below:

- No current ripple is observed at high inductive load
- E_{on} is generally higher than E_{off} due to high reverse recovery current
- Low switching frequency ends with high conduction loss
- Always hard switching

Below are listed the main characteristic for inverters suitable for solar and UPS applications.

- Current ripple is higher (up to 30%) compared to drive applications
- IGBT turn-on and forward diode (FWD turn-off are occurring at a lower current than for the same IGBT at turn-off and FWD turn on-respectively (10-A difference in the waveform above)
- E_{off} is more important
- Overvoltage at turn-off is higher due to the high turn-off current.

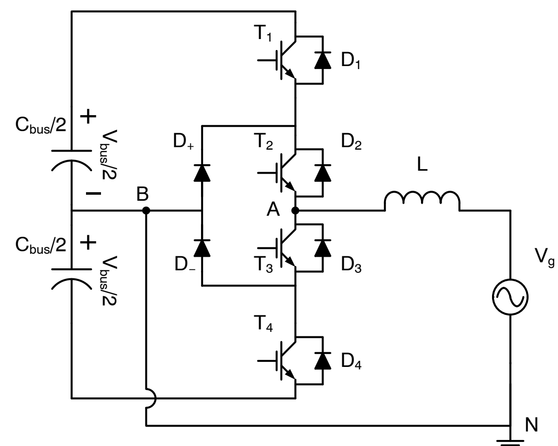

Figure 31. I–Type Converter

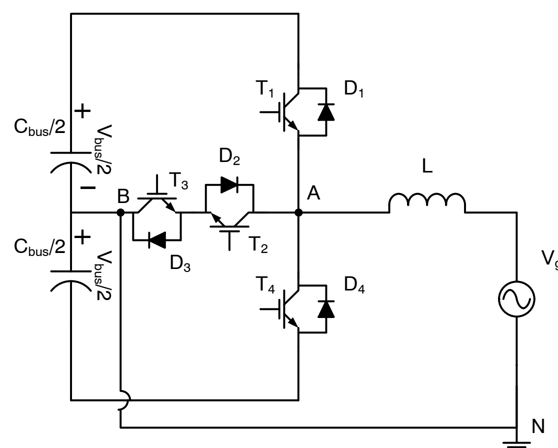

Figure 32. T–Type Converter

Emerging Topologies for High Power Conversion

The classical HB has some limitations:

- A standard half-bridge converter produces only two levels of output voltage
- High *dV*/*dt* stresses passive and active components
- High *dV*/*dt* produces high switching loss
- High *dV*/*dt* makes gate drive more difficult
- Voltage pattern produces higher ripple current
- High *dV*/*dt* produces higher EMI
- Voltage handling (it cannot work with a high-voltage bus)
- Series connection of devices leads to implementation complexities
- High switching losses
- Thermal balancing is difficult to achieve
- High filtering requirement

In order to overcome all the aforementioned limitations, new topologies with multi-voltage levels have been designed and used in power electronics. The most common structures are the so-called I–Type and T–Type converters. These topologies can operate at higher bus voltages. Due to the availability of more output states, the voltages across filter components is reduced and results in much lower filter losses/size. Even the switching losses go down significantly while conduction losses go up slightly (suitable for higher frequencies). These topologies employ a unipolar switching by connecting to neutral point during the so-called off cycles (see Figure 33).

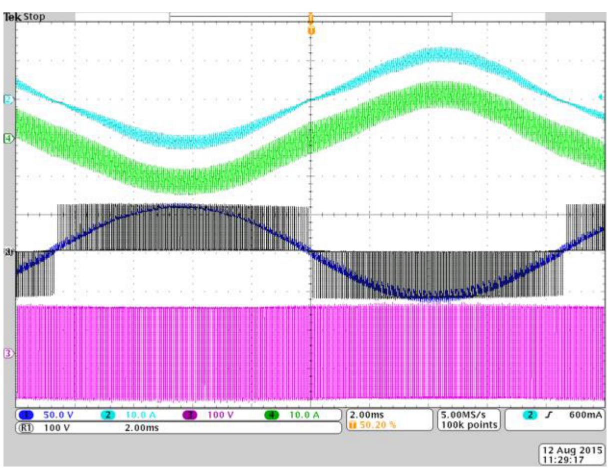

Figure 33. Comparison between a Classical Half-bridge and a Three-level Converter in Terms of Voltage and Current Output

(Light blue: output current of a three-level topology;
In green, output current of a HB converter;
In black: output voltage of a three-level converter and in purple, output voltage of an HB converter)

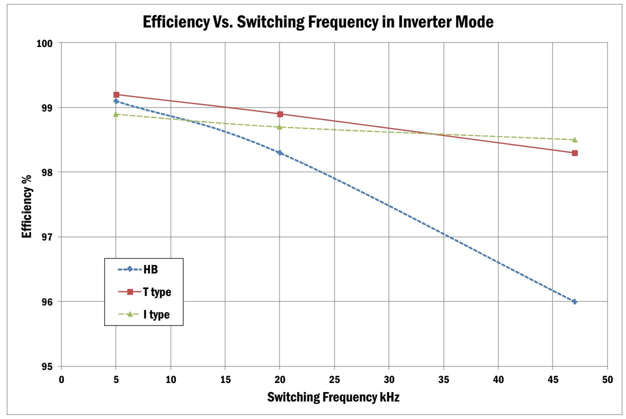

Figure 34. Efficiency versus Switching Frequency in Inverter Mode. Comparison between an HB, I–Type and T–Type [14]

It is worth mentioning that beside the numerous advantages, these multilevel topologies present some challenges, such as:

- Capacitor voltage balancing – addressed by active control
- Loss distribution imbalance under certain operating conditions
- Dependence on modulation index/duty ratio
- More complex control
- Advances in semiconductors and control technologies are enabling the usage of these converters in mid-low power ranges (< 10 kW)
- Better optimization techniques needed

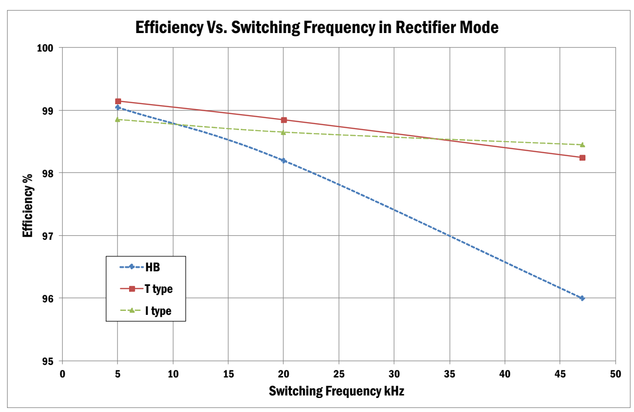

Figure 35. Efficiency versus Switching Frequency in Rectifier Mode. Comparison between an HB, I–Type and T–Type [14]

Each topology, I and T type, has its own advantages and disadvantages depend on operating conditions. T–type shines at lower frequencies. It has lower switching losses compared to HB. While I−type (NPC) has better performances at high frequency. There are other aspects to account for like the fact that semiconductor improvements can shift the transition point to the right (crossover of the efficiency between I and T Type). A similar comment applies for the higher dc link voltage that can shift the transition point to lower frequency. In general, it is true that 3-level inverters help improve efficiency and increase the operating frequency. In rectifier mode, T−type is better for mid-frequencies while in rectifier mode, I−type offers better high-frequency operation and better thermal balance. One of the main disadvantages lies in the more complex control circuitry and the need for more semiconductor components (not necessarily more silicon area).

CONCLUSION

Despite the fact that IGBTs have been in the market for a while, this technology is still perfectly suited for high-voltage and high-current applications. The usage of IGBTs is growing not only in the classical applications, but also in new ones. This is due to the fact that new technologies are able to switch up to 100 kHz. Hence, it is important to better understand the application requirements and choose the right IGBT trade off. Figure 36 shows how a given IGBT can produce a different pattern of losses in different topologies operating at the same frequency: (A) Vienna topology [15]; (B) HB; (C) Full-bridge. Even in the same topology, the pattern can vary with the operating point. Figure 37 shows the patterns of the losses in a T−Type topology for the outer (A & C) and the inner (B & D) IGBT in inverter (A & B) and rectifier (C & D) mode. Understanding system requirements and measurement systems is important for the reliable design with IGBTs. It is even more important when approaching very high efficiencies enabled by modern IGBTs and topologies. Additional analysis and measurement time invested during the design phase can lead to the selection of the right IGBT for the targeted application.

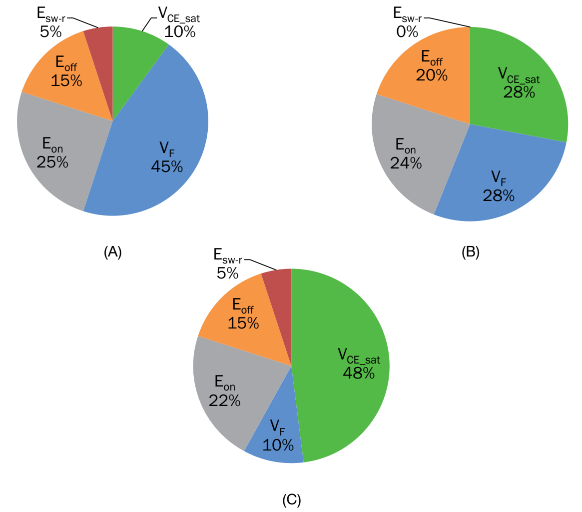

Figure 36. Losses Distribution of a Given IGBT Operating in the Vienna Topology, Half-bridge and Full-bridge

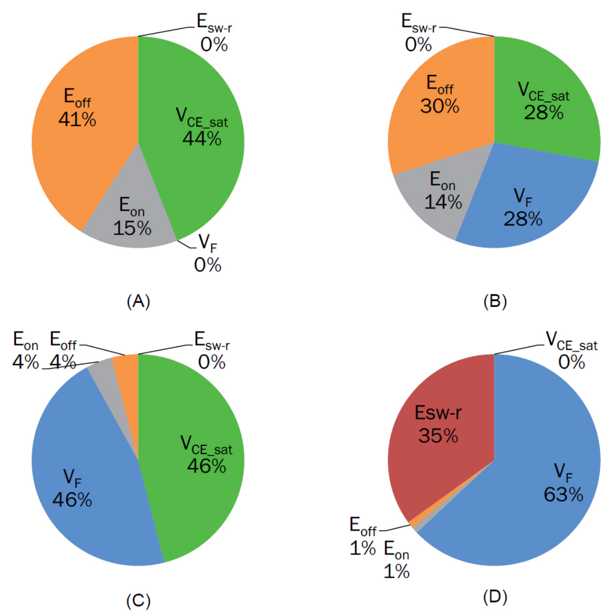

Figure 37. Losses Distribution of a Given IGBT Operating in a T−Type Inverter in the Outer (T_1 and T_4) and Inner (T_2 and T_3) Position in Inverter and Rectifier Mode

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