

Reverse Conducting IGBT for Induction Cooking and Resonant Applications

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1 Introduction

The principle of induction heating was discovered by Michael Faraday in 1831. By an experiment with two coils wired around an iron core he discovered that during the switching event of a battery connected to the first coil an opposite current flow could be measured with a galvanometer on the second coil. He concluded that an electric current can be produced by a changing magnetic field. Since there is no galvanic connection from the primary to the secondary coil he called the voltage in the second coil induced. His general law formed out of this experiment is called as a general law that is explained as the “EMF electro-motive force induced in a circuit is directly proportional to the time rate of change of magnetic flux through the circuit”. Heinrich Lenz formed in a later stage the “The polarity of the induced EMF is such that it tends to produce a current that will create a magnetic flux to oppose the change in magnetic flux through the loop”. [1] This principle was used for transforming different levels of voltage for efficient transmission of electricity and the operation of electrical machines. An effect observed during the energy transformation was heat generated in the cores. These cores are generally realized with laminated stacks of steel, but this effect could be used in induction heating with the complete opposite effect in order to use it for induction heating and the well known purpose for inductive cooking.



Figure 1.1: Typical application Single-Plate cooker end-customer product and open circuit inside view

The devices used for commercial household cooking to allow a high-frequency change of the magnetic field in the coils are generally IGBTs due to their high current rating capability and high frequency operation without a significantly high driving current capability. In Figure 1.1 a commercial example of a cooker is shown.

According to the U.S. Department of Energy the savings of primary energy to 25% can be up to 60% in process heating in today's induction heating appliances [1]. Improving the degree of efficiency of the inverters in commercial and residential applications requires advanced control systems and new generations of power semiconductors. To optimize the electrical behavior of these devices new generations of semiconductors are rapidly developed by Infineon these days. IGBTs from 600V to 1600V are widely used for induction heating appliances using mainly the single ended quasi-resonant and the half-bridge topology. The trench stop technology enables developers of induction heating systems in resonant topologies to design systems with the lowest losses in the application. The conduction-losses, the switching losses and the resulting heat transferred to a cooling system can be reduced. Due to a high-efficiency and a precise power control there are to mainstream topologies shown in Figure 1.2 and Figure 1.3 that are used in reliable systems with the best trade-off between the bill-of-material and the resulting electrical and thermal performance. The topology uses the principle of parallel or series resonance to generate eddy current losses

in the pod material. The used materials of the working vessel are strongly dependent on the working frequency so a wide range from 19kHz to 100kHz is required to have a wide control over the power transfer to the pot. Due to the limitation of the power semiconductors due to their switching losses and the resulting thermal stress of the components today's cookers for the highest power rating operation frequencies of 19kHz to 40kHz can be found in the household systems. The main interested is of course to reduce the audible noise generated by the coils and a wide operation for different pot materials.

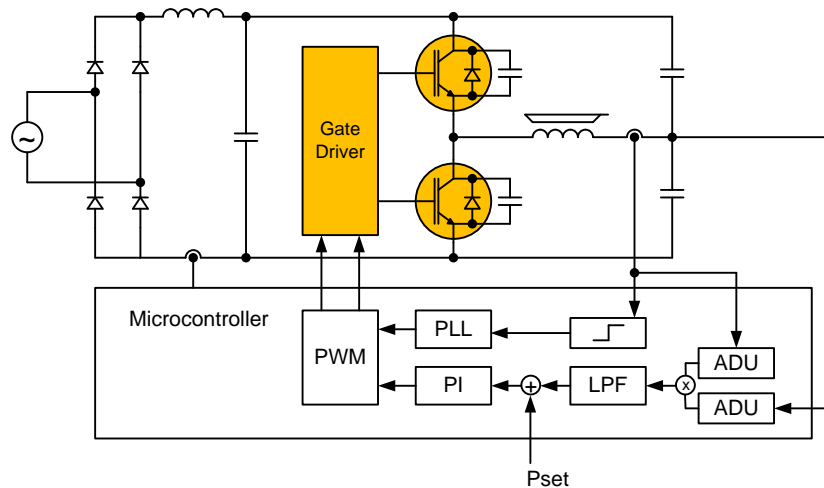


Figure 1.2: Half-Bridge induction cooking application schematic and operation

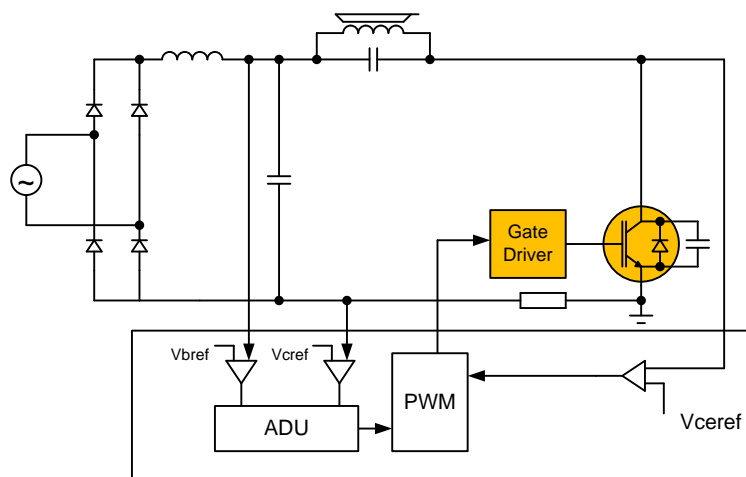


Figure 1.3: Single-Ended induction cooking application schematic and operation

2 Technology

Infineon provides a specific family for induction cooking that is optimized for the operation of resonant inverters. The reverse conduction (RC) technology provides an IGBT in TRENCHSTOP™ technology with a monolithically integrated powerful reverse diode. Due to this technology an additional anti-parallel diode can be avoided. On cell of the IGBT shown in

Figure 2.1: Vertical cross section of the RC IGBT

is based on two major principles, which are the fieldstop layer and the trench gate structure. This structure combination leads to a widely improved saturation voltage and very low turn-off energies. Compared to previous generations based on the NPT-cell design thinner wafer substrates can be used to increase the conduction and switching performance. Furthermore new trade-offs between the turn-off energy and the saturation voltage can be reached, which was not possible with planar cells in common IGBT technologies, such as non-punch trough NPT or punch through PT technologies. Due to the relatively large reverse recovery charge compared to discrete diodes the IGBT is only suited for soft-switching. The benefits over a classical two chip solution are higher power density of the devices and a full nominal current rated diode since the IGBT and the diode are using the same die area.

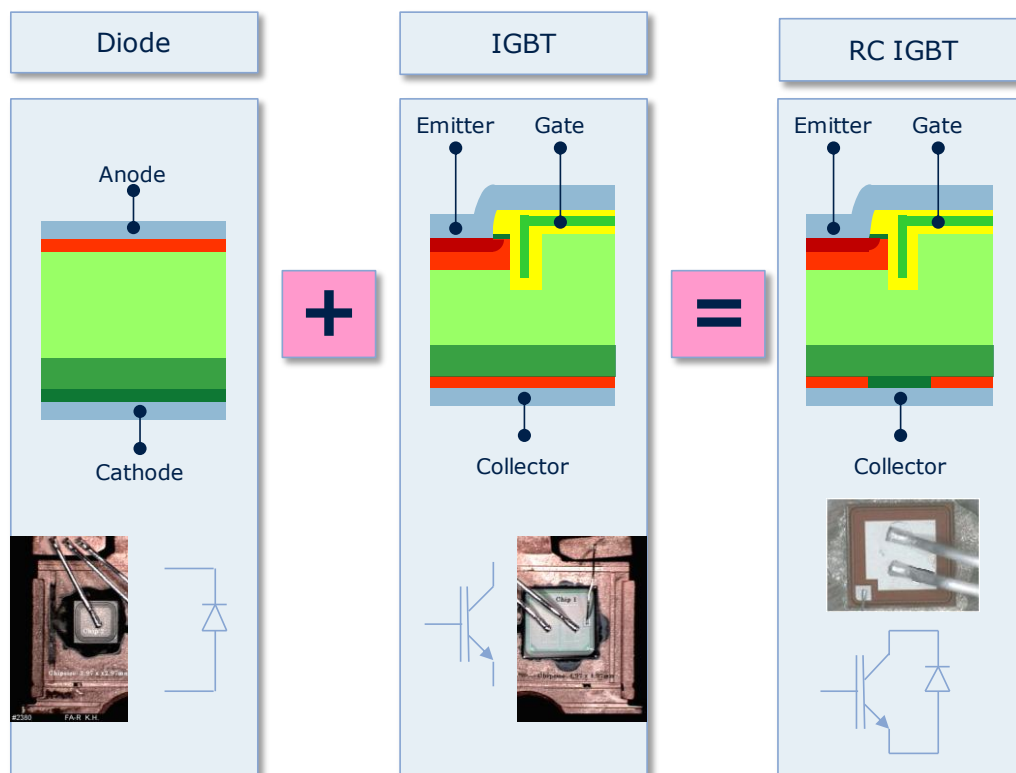


Figure 2.1: Vertical cross section of the RC IGBT

3 Operation conditions of the reverse conducting IGBT

For the IGBT usage in applications there are typically two main operation principles hard switching and soft switching. Typical applications are shown in Table 3.1. Infineon offers a wide portfolio for the different needs of these switching conditions.

Soft-Switching	Hard Switching
Inverterised Microwave	Inverterised major home appliances: Washing machines, dishwashers, fridges, air-conditioning
Induction heating cooker	General purpose inverters
Induction heating rice-cooker	Solar Inverters
Laser printers	PFC stages
	Break IGBTs
	UPS/welding

Table 3.1: Typical applications for soft- and hard switching

Soft switching can reduce the switching losses of the IGBT significantly. The operation of soft switching can be divided into two main operations ZVS-mode (zero-voltage-switch) and ZCS-mode (zero-current-switch). During commutation time (t_k) the DC-link voltage drop over the current-carrying switch causes considerable power losses in the IGBT. While soft switching is either 0V with a positive collector current or 0A collector current with a positive collector emitter voltage. During the current commutation time (t_k) the power losses are almost neglect able. This enables the usage of the IGBT for a wide range of switching frequencies up to 100kHz. Since the reverse-conduction IGBTs are designed for soft switching they cannot be used in hard switching application. The diode is not commutation proof since it's optimized for a low V_F , with a slow reverse recovery and relatively long current tails. The power dissipation at IGBT turn-on in hard switching

conditions would be unacceptably high and would eventually lead to device failure. The typical waveforms for hard switching are shown in **Error! Reference source not found.** for the turn-off and Figure 3.1 for the turn-on.

Figure 3.2 shows an example of a soft switching where the voltage rises with a very low dV/dt resulting in minimal

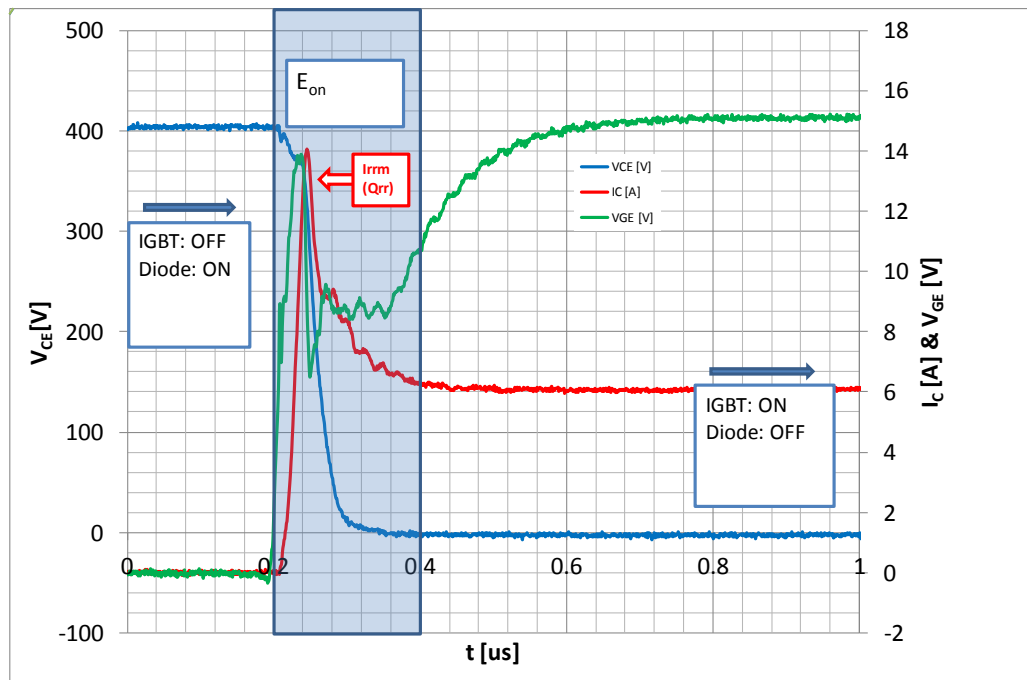


Figure 3.1: Hard switching turn-on waveform

If the single ended application is running in over-resonant mode the output power can be reduced. This operation is limited due to the reason that the V_{CE} is not going down to zero anymore. The energy stored in the resonant circuit capacitor is not going down to zero and is discharged over the IGBT this effect is displayed in Figure 3.3.

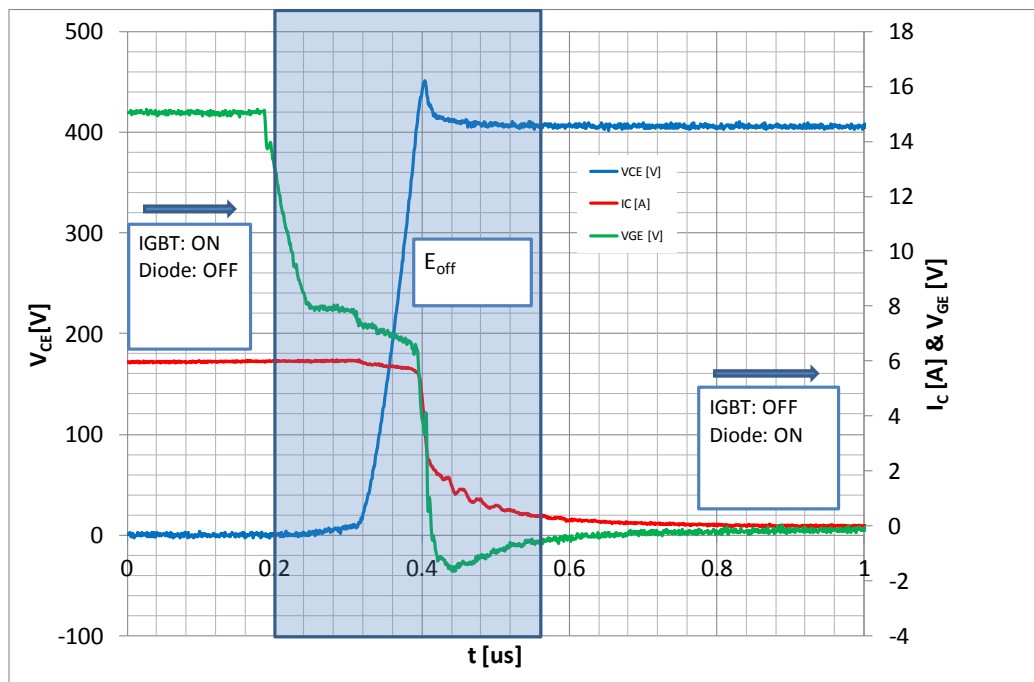


Figure 3.2: Single-Ended topology Zero-voltage turn-off example

$$E = \frac{1}{2} C_{res} V_{CE}^2 \quad (1)$$

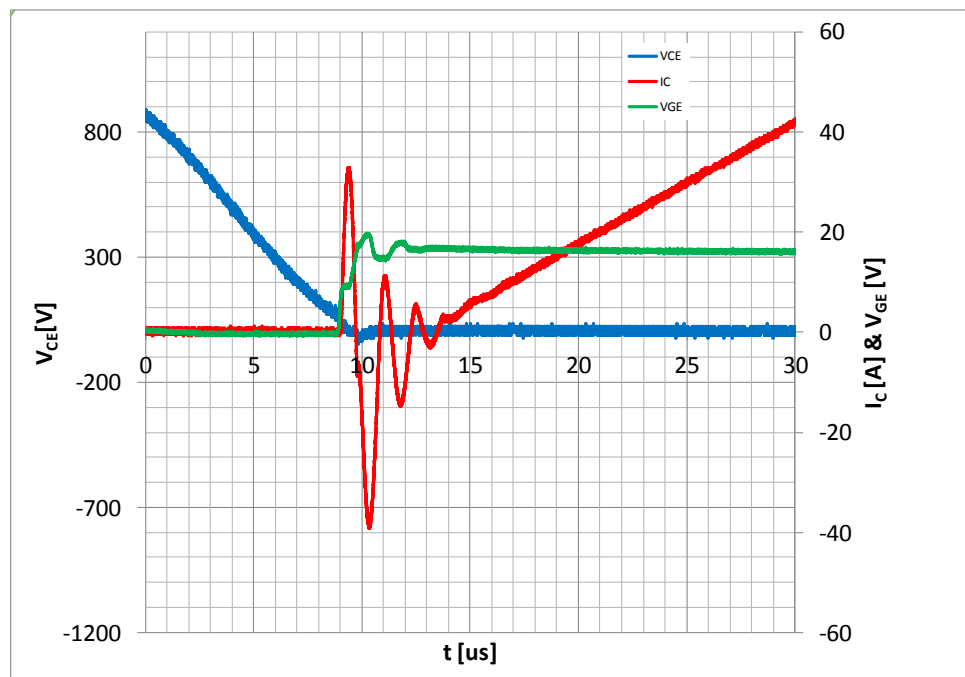


Figure 3.3: Zero current (ZCS) and near Zero-voltage (ZVS) turn-on

4 IGBT selection

For half-bridge operation Infineon provides IGBTs for medium frequency induction heaters that are in a range of 8 to 20kHz operation for the highest power range. These IGBTs are available for hard- and soft-switching conditions (T-Series and R-series). Furthermore a high speed series of the 600V RC-IGBT (F) versions is available for switching frequencies from 20kHz to 100kHz. A detailed list of the IGBTs is shown in **Error! Reference source not found..**


Revolutionary Application Specific – Induction Heating Series IGBTs						
Continuous Current I_C $T_C=100^\circ\text{C}$		TO-247				
						
IGBT and RC-Diode		650 V	1100 V	1200 V	1350 V	1600 V
	15 A			IHW15N120R3		
	20 A	IHW20N65R5		IHW20N120R3 IHW20N120R5	IHW20N135R3 IHW20N135R5	
	25 A			IHW25N120R2		
	30 A		IHW30N110R3	IHW30N120R3	IHW30N135R3	IHW30N160R2
	40 A	IHW40N65R5		IHW40N120R3	IHW40N135R3	
	50 A	IHW50N65R5				

Table 4.1: Product portfolio

5 Simulation

The reverse conduction capability of the RC-IGBT is provided by an appropriate short structure of the IGBT anode. Due to this structure the cathode pn-junction starts injecting minority carriers into the base region of the IGBT when a reverse voltage appears across the IGBT.

The forward voltage condition leads to a slightly different behavior of the RC-IGBT compared to the conventional IGBT. Some fraction of the MOS current is by-passing the emitter which will lead to a delayed minority carrier injection from the anode emitter. This situation is schematically shown in Figure 5.1. In order to set up an RC-IGBT virtual prototype on a SPICE like simulator, a model based on the sub-circuit structure was developed. Two sub models, one of an IGBT, the other of a diode are connected together. The outside connection points of both models are anode and cathode. Internally, both models interact via the laterally flowing currents through an effective coupling lateral resistor.

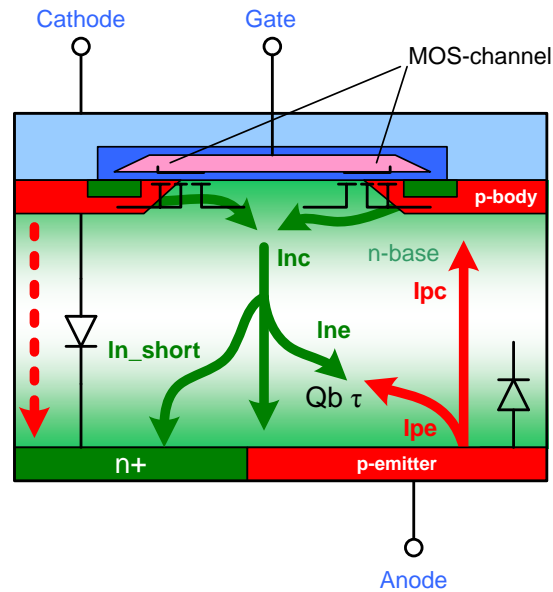


Figure 5.1: Hard switching turn-off waveform

The underlying models of both the IGBT and the diode are physics based and have been published elsewhere. These physics based sub models account for the relevant device phenomena, as there is the charge injection via anode and cathode pn-junctions, the dynamic conductivity modulation of the base region, the cathode site specific hole current extraction and the temperature dependence of the electrical parameters from the geometrical structure of the device and from technology data. This enables parameterized simulations in order to optimize the RC-IGBT behavior inside the application.

The model is completed by a thermal sub-model which generates temperature dependent changes. The thermal model consists of either one of a CAUER or FOSTER representation of a thermal RC chain. Its model parameters are to be extracted from conventional transient thermal impedance measurements or simulations. The model can be downloaded from the Infineon website.

6 Application

6.1 Single-Ended induction heating topology

With an optimal load the IGBT is switched on at zero current and near zero voltage. For all switching conditions the IGBT turn-off is always a soft switching since the voltage ramps up sinusoidal. A fast switching is preferred since the turn-off losses are reduced. Due to layout constraints e.g. stray inductance a fast switching leads to oscillations on the gate voltage and could potentially damage the IGBT. An optimal R_G would be as small as possible without causing oscillations on V_G .

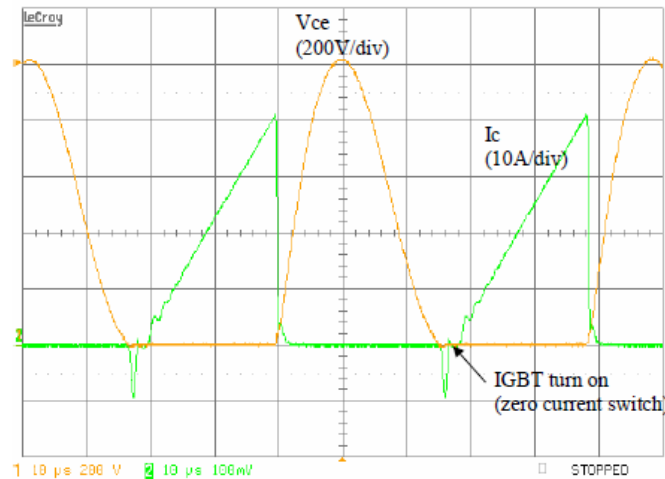


Figure 6.1: Optimal Switching Waveform with near Zero-Voltage and Zero-Current turn-on

7 Capacitive load application

In the case of a non-optimal load the IGBT will no longer be switched at zero voltage although still at zero current. During turn-on of the IGBT there is a large current spike due to the fast discharge of the resonant capacitor and the stray inductance of the inductor. If this discharge current exceeds the I_{Cpuls} value that is specified in the datasheet the effect of thermo-transient has to be considered. The turn-on spike can be limited by the usage of a lower gate voltage e.g. 10 V the height of the pulse will be lower resulting in a better EMI behavior of the system. A voltage step from the turn-on to the optimal gate-voltage should be considered in the system to have an increased current capability of the system.

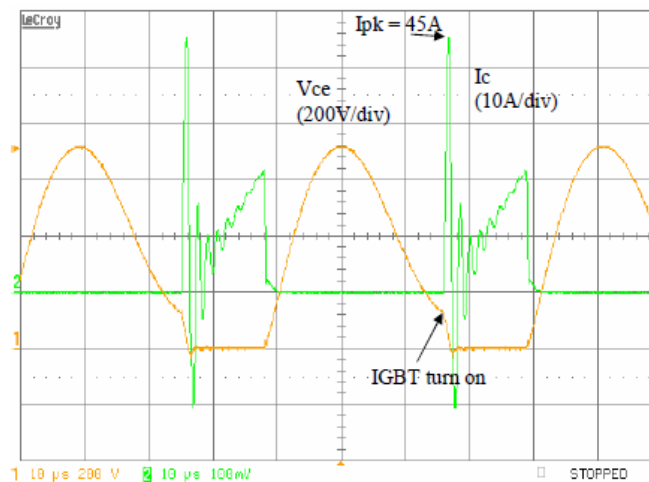


Figure 6.2: Over-resonant application with capacitive load

8 Overvoltage protection

A serious problem in the single-ended topology is the case of an overvoltage that cannot be filtered. To reduce the voltage surge a varistor is commonly used, but it does not absorb the whole energy. To avoid a destruction of the IGBT protection features should be integrated in the circuit. Also the voltage safety margin of the IGBT should be chosen high enough to avoid avalanche destruction. To suppress an overvoltage surge the IGBT can be turned on actively with a series of zener diodes connected to the collector and the gate. Other possibilities to clamp the collector-emitter voltage are shown in Figure 3.

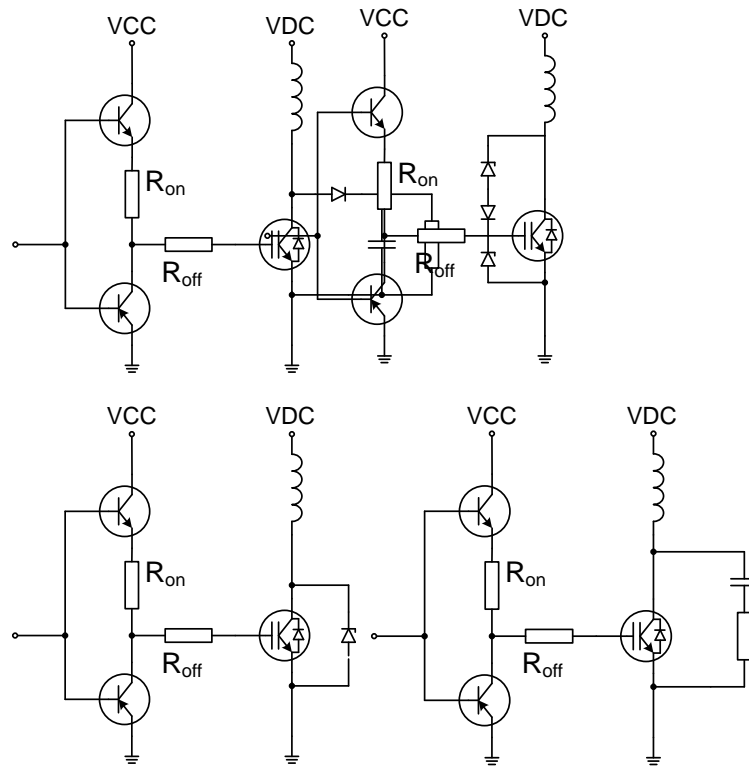


Figure 6.3: Possibilities of clamping the collector-emitter voltage

9 Half bridge topology

In the half-bridge topology ZVS and ZCS turn-on is achieved by turning on the IGBT during the diode turn-on period. The resonant circuit itself is based on a series resonance. The ZVS condition during turn-off should be realized with a lossless snubber with capacitors connected in parallel to the IGBTs. If there is no snubber the RC-IGBT can potentially be destroyed due to excessive power losses in the switch. It is recommended to use a snubber between 10...20nF to lower the dV/dt resulting in a reduction of the losses in the IGBT.

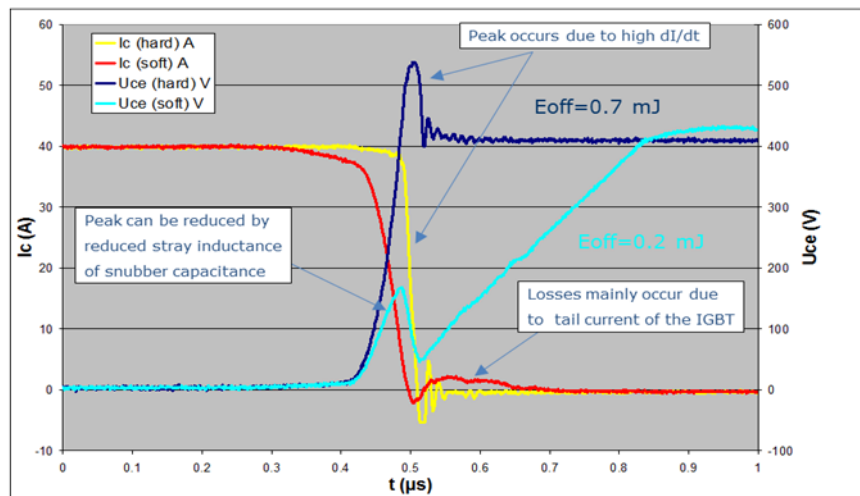


Figure 6.4: IGBT turn-off losses with- and without snubber

Due to the dependence of the forward voltage drop (V_F) of the integrated diode and the applied gate-voltage off the IGBT it is recommended to increase the dead-time of the driver voltage to turn-on the IGBT near the zero-crossing of the collector current. This reduces the on state power losses of the diode during reverse conduction. A diagram showing the dependency of V_F versus V_{GE} is shown in Figure

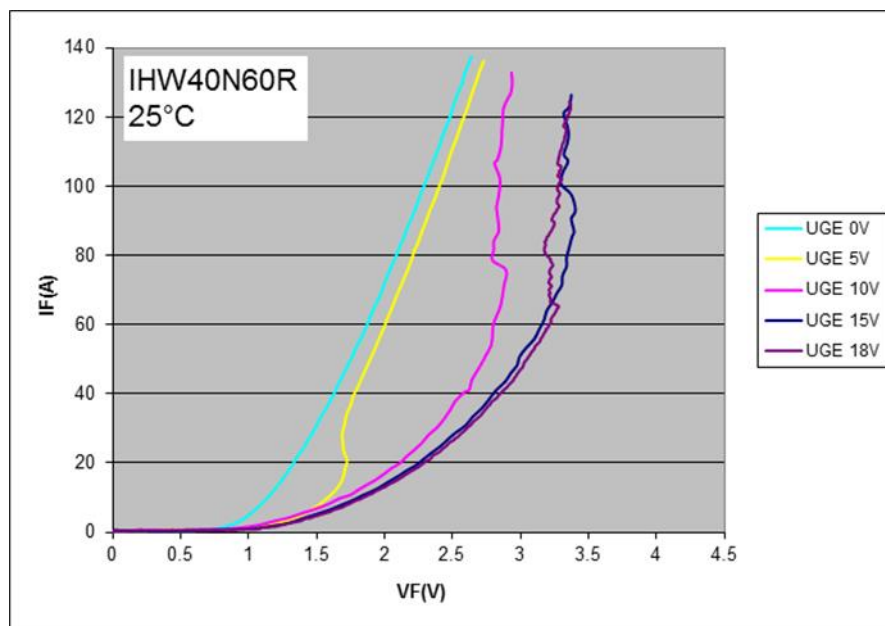


Figure 6.5: $V_F(I_C)$ of the diode versus the V_{GE} applied to the IGBT

For optimal driving of the IGBT the Infineon EICEDRIVER™ is recommended. The driver is suitable for single-phase supplied cookers or in case of isolation between the phases in a three-phase system according to Figure.

10 Conclusions

The Infineon reverse conduction IGBT is well suited for applications that are using a soft switching based topology. The device-family offers application specific optimization for lowest conduction losses and moderate switching losses the RC-H series and the switching loss optimized RF series. If hard switching is required the TRENCHSTOP™ co-pack family can be used.

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