

Zero Voltage Switching Converters

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ABSTRACT

In this paper zero voltage switching converters are investigated. The investigation starts by discussing the RCD charge-discharge snubber. The concept of resonant and quasi-resonant DC link converters is discussed. One of the most promising quasi-resonant DC links reported in the literature is implemented and tested in a battery charger application. Simulated resonant link voltage and current waveforms are analyzed. IGBT switching waveforms under zero voltage conditions are investigated. Measured waveforms are shown and the converter and the overall battery charger efficiency are measured.

Keywords: IGBT, resonant converter, snubber, zero voltage switching.

INTRODUCTION

Several problems associated with hard switching are reported in the literature. The main problems are the semiconductor losses due to the finite duration of the switching transients and the electromagnetic compatibility (EMC) problems associated with the high voltage derivative with respect to time, occurring especially at the turn-off transient. Power electronic converter manufacturers strive towards increased switching frequencies in order to omit the audible noise and reduce the output current harmonic content. For such high switching frequencies, the switching losses dominate, at least if insulated gate bipolar transistor (IGBT) technology is employed. IGBT technology is the most common choice for mid-power converters due to its ease of drive, high ruggedness and favorable combination of

moderate conduction and switching losses. In this paper, different means to achieve zero voltage switching (ZVS) are discussed. The aim is to perform the switching transients at, or close to, zero voltage across the semiconductor devices. At a first glance, this would give zero, or low, switching losses. However, this is not entirely true in the case of IGBTs and this is also discussed. The discussion treats the IGBT switching behavior at hard-switched conditions, and with RCD charge-discharge snubbers, intended to provide zero voltage transistor turn-off. The resonant DC link (RDCL) converter investigated suffers from two severe drawbacks, both of which are highlighted.

HARD SWITCHING

One of the most basic transistor bridge configurations for power electronic applications is the step down converter. It consists of a voltage source (DC link capacitor), a power transistor (IGBT in this case) and a freewheeling diode, see Fig.2.1 Since this is a voltage source converter, the load is a current source, i.e. inductive. When the switch state is changed from on to off (turn-off) or from off to on (turn-on), the transition will take a finite time in the non-ideal case.

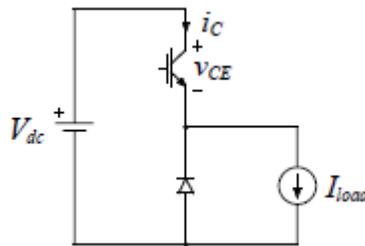


Fig. 2.1. The basic step down converter used in the analysis.

Fig. 2.2 shows typical collector current and collector-emitter voltage for an IGBT, when used in the step down converter above. Note that the collector current and collector-emitter voltage are normalized with base values selected as the rated maximum continuous collector current, I_C , and the maximum collector-emitter voltage that can be sustained across the device, V_{CES} .

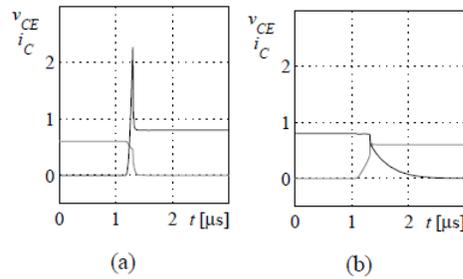


Fig. 2.2 Normalized transistor current (black) and voltage (grey) at (a) turn-on and (b) turn-off of the power transistor in the step down converter.

In Fig. 2.2, the IGBT is exposed to a current spike at turn-on due to reverse recovery of the freewheeling diode. It is seen that the IGBT is exposed to simultaneously high current and voltage during the switching transients. This causes high switching losses, especially at turn-off since the IGBT exhibits a collector current tail there.

SOFT SWITCHING BY MEANS OF SNUBBERS

To partly overcome the previously mentioned problems and to use the semiconductor devices in a more efficient way, snubber circuits are introduced. Various snubber circuits are used for different purposes, for example to reduce the semiconductor switching losses. One such snubber is the RCD (resistor, capacitor, and diode) charge-discharge snubber. From now on, this snubber is referred to as the RCD snubber.

Step down Converter

Fig. 3.1 shows the step down converter with a RCD snubber connected across the IGBT. At turn-off, this snubber behaves as a pure capacitor. It is sometimes claimed that this type of snubber circuit provides turn-off under ZVS conditions, or soft switched conditions. This refers to the fact that when the turn-off sequence is initiated, the collector-emitter voltage is approximately zero. However, at the end of the current fall interval the collector-emitter voltage is high, ideally equal to the DC link voltage V_{dc} .

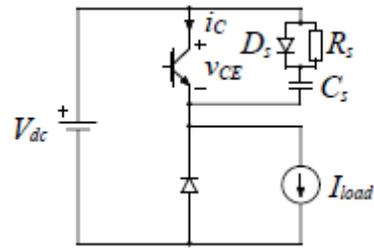


Fig. 3.1. The step down converter with the RCD snubber connected across the device output terminals.

Fig. 3.2 shows the time signals of the transistor collector current and collector-emitter voltage. The snubber resistor value is selected in such a way that the snubber capacitor peak discharge current do not exceed the peak reverse recovery current of the freewheeling diode. From Fig. 3.2 it is seen that the snubber capacitor affects the turn-off waveforms in such a way that the turn-off losses do indeed decrease. Also, the derivative of the collector-emitter voltage is controlled, which can be an important aspect by means of EMC.

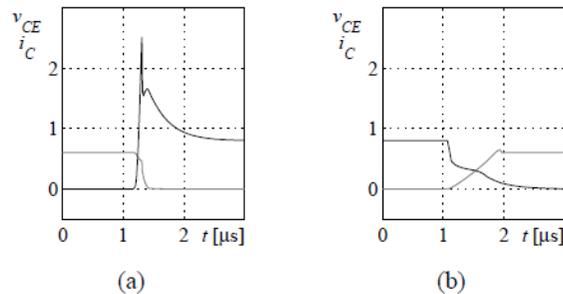


Fig 3.2 Transistor current (black) and voltage (grey) at (a) turn on and (b) turn-off of the power transistor in the step down converter with a full RCD charge-discharge snubber across the power transistor.

Half Bridge Converter

To investigate the switching waveforms for a three-phase converter with RCD snubbers, one across each IGBT, an entire half bridge has to be considered, see Fig. 3.3. The upper and lower RCD snubber provide soft turn-off for the upper and lower IGBT, respectively. The simulated collector current and collector-emitter voltage are shown in Fig. 3.4. Note the high current peak at transistor

turn-on. The occurrence of this current peak is due to the capacitive current path seen from the IGBT output terminals,. At turn-on of the upper IGBT, the collector-emitter voltage should decrease for the upper IGBT and increase for the lower. This means that the upper snubber capacitor in Fig. 3.3, denoted C_{s1} , should be discharged and the lower, denoted C_{s2} , should be charged. The snubber resistor R_{s1} limits the discharge current of C_{s1} as in the previous case but the charging current of C_{s2} is not limited by any other component.

Furthermore, the only path possible for the charging current is through the upper IGBT. In this way, the charging current of the lower snubber capacitor gives a large contribution to the collector current of the upper IGBT, at turn-on.

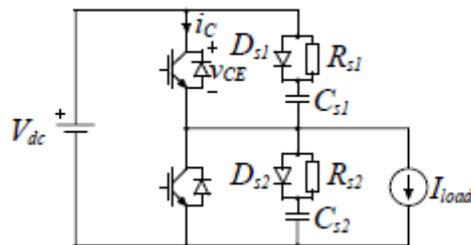


Fig. 3.3 a half bridge with one RCD snubber connected across each transistor.

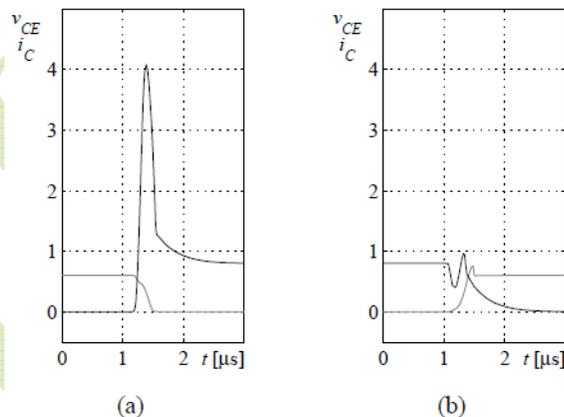


Fig. 3.3 Transistor collector current (black) and collector-emitter voltage (grey) at (a) turn-on and (b) turn-off of the upper IGBT in the converter consisting of a bridge leg. One RCD snubber is used across each IGBT. Note the high collector current peak at turn-on. Also note the poor behavior at turn-off.

One of the main problems related with soft switching appears due to poor understanding of power semiconductor physics, since it is assumed that data sheet information is still valid for soft switching. However, data sheet information for IGBTs is in most cases given for inductively

clamped load, i.e. constant load current during the switching transients. Also, the information is only valid for certain constant DC link voltage. In the literature, several problems associated with soft switching is discussed.

One of the most frequently discussed phenomena is the current tail bump occurring at IGBT zero voltage turn-offs. In Fig. 6 the current tail bump is clearly seen. According to, the reason for this bump is that during ZVS turn-off the excess carriers stored in the drift region are not forced out by the expanding depletion region, as is the case for hard-switched turn-off. Consequently, after the channel is removed, the collector current continues its decrease and no current tail is observed until the IGBT collector-emitter voltage begins to increase. The current tail bump results in higher losses for ZVS turn-off than expected from data sheet information. Nevertheless, the turnoff losses are lower for ZVS than for hard switching.

THE RESONANT DC LINK CONVERTER

An important step in resonant converter technology was taken in 1986 when the resonant DC link converter was invented. For the resonant DC link converter, one resonant circuit is used to provide soft switching for the entire converter. As the name resonant DC link indicates the DC link is forced to oscillate. The basic three phase resonant DC link converter is shown in Fig. 4.1.

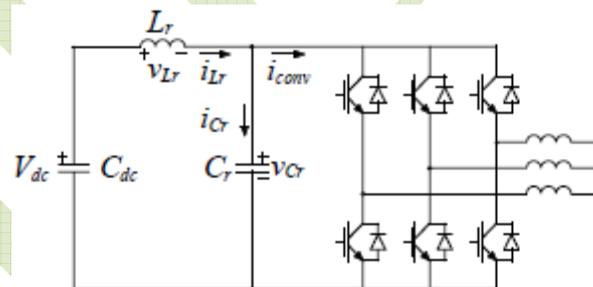


Fig. 4.1 The basic three phase resonant DC link converter.

The idea of the resonant DC link converter is that the switch state of the converter only should be changed at, or close to, zeros link voltage. The resonant circuit is formed by the resonant inductor L_r and the resonant capacitor C_r . Since the DC link capacitor C_{dc} has a much higher capacitance than C_r , it does not affect the resonance behavior. Assume that a resonant cycle starts at a capacitor voltage equal to twice the DC link voltage V_{dc} . Due to the resonant properties of this circuit, the capacitor voltage decreases towards zero. When the capacitor voltage reaches zero, it will be clamped to this

level since the load current freewheels through the freewheeling diodes, at least if the resonant inductor current is lower than the DC link current, i.e. the current drawn by the converter. As soon as the inductor current reaches the level of the DC link current, the capacitor voltage starts to ramp up. In the case where the DC link current is not changed, the capacitor voltage reaches the starting point of the analysis, which equals twice the DC link voltage.

The normalized resonant link waveforms for the case of changing DC link current are shown in Fig. 4.2. From Fig. 4.2 some observations are made. Firstly, when the DC link current i_o is decreased due to a change of the converter switch state, the resonant DC link voltage resonates to a peak value considerably higher than twice the DC link voltage V_{dc} . Secondly, when the DC link current is increased, the zero voltage interval is prolonged and the resonant capacitor voltage increases, with a moderate derivative, to twice the DC link voltage V_{dc} .

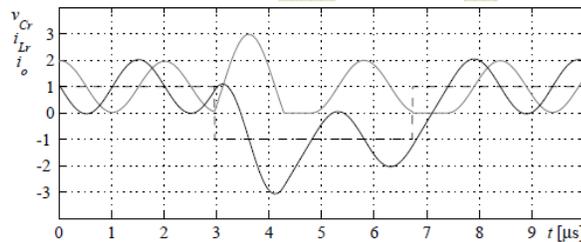


Fig. 4.2 Normalized inductor current (black) and resonant link voltage (grey) for a resonant DC link converter. The current fed to the converter is also shown (dashed). Note the resonant link voltage peak resulting from a decrease of the converter current.

In the first case, there is excess energy stored in the resonant inductor due to the previously high current through L_r , corresponding to the DC link current. This energy must decrease to meet the new DC link current, which implies that the energy must be transferred to the resonant capacitor C_r . In the second case, a too small amount of energy is stored in the inductor, which results in a prolonged zero voltage intervals. The length of the zero voltage intervals is determined by the time needed for the inductor current to reach the same level as the converter current. When the inductor current reaches the level of the converter current, the resonant capacitor is charged, since the inductor current continues to increase. Another problem of this circuit is that carrier wave pulse width modulation (PWM) cannot be used since the possible switching instants are determined by the resonant circuit. Instead, other modulation strategies must be applied. However, these modulation strategies require that the resonance frequency is much higher than the switching

frequency, in order to obtain a result comparable to carrier based PWM by means of output current spectrum.

CONCLUSIONS

Zero voltage switching converters are investigated. The quasi-resonant converter was introduced to cope with problems of ZVS converters based on snubbers or resonant links. The quasi-resonant DC link converter investigated at first seems promising since it can be triggered on demand, and operates without excessive over voltage due to the clamping network. However when implemented, measurements show that the converter losses increase compared to the hard-switched counterpart at a switching frequency of 5 kHz. Despite the low switching frequency, the measurements show that the commanded switching's are delayed, causing low order harmonics

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