

ANALYSIS, DESIGN AND EVALUATION OF A FLOATING CAPACITOR SOFT SWITCHING HIGH POWER SINGLE PHASE BOOST RECTIFIER

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Key words: Boost Converters, Soft Switching, Floating Capacitor

ABSTRACT

As the power levels of single phase boost converters used for unity power factor single phase ac rectification increases, there is need felt to employ soft switching to ameliorate the problems caused by the reverse recovery of the boost diode. This paper presents the analysis, computer simulation, and experimental evaluation of a soft switching approach for a boost power converter used for single phase power factor correction. Detailed modal analysis of the converter operation is presented in the paper followed by simulation and experimental results from a 10 kW experimental hardware prototype. A comparison of thermal performance of the approach with a hard-switched baseline using the exact same hardware platform is presented. Experimental results indicate a 30% reduction in heat sink temperature rise.

I. INTRODUCTION

Although the use of a boost converter has become well established as an approach to shape the input current drawn by single-phase ac-dc power converters, the problems caused by the reverse recovery of the diode in the converter limits its applicability at high power levels [1-3]. In order to alleviate this problem, several techniques for realizing soft switching in these converters have been introduced with varying degrees of success [1-11]. On the other hand, when the power throughput levels increase beyond several kW, advantages provided by several of soft switching topologies fail to translate into definitive performance improvements [12-13]. Use of additional number of active switching devices, additional voltage and/or current stress on main power devices, additional complexity in control and major changes in switch configuration compared to the parent hard switching topology are seen to be major impediments to realizing the potentials in performance improvements. A soft switching technique that uses a floating capacitor along with a simple coupled inductor was presented in [11] as an approach for realizing reduced switching stress for the boost converter. Preliminary inspection of the features of this approach indicated that this approach might not suffer from all of these disadvantages. Hence a detailed analytical and experimental examination of this

topology was conducted. The study included an optimized design and retrofit of a state of the art 6 kW unity power factor single phase boost ac-dc converter with a floating capacitor soft switching network. Fig. 1 illustrates the schematic of the power circuit of the approach under study. From the schematic, it is clear that the proposed approach does not require any additional active components, and the main power switch-diode configuration is maintained intact. The additional components comprise of two diodes and a resonant capacitor. The resonant inductor is coupled to the main boost inductor and hence does not require a separate magnetic core. Therefore, it can be easily retrofitted into the hard switching platform to provide reduced turn on and turn off losses, since it features both ZVS and ZCS switching properties. This paper presents the analysis, design and evaluation results of the floating capacitor soft switching approach applied to a boost converter used for unity power factor ac-dc power conversion. In the following section the topological description of the proposed converter is presented along with the modal analysis of the converter operation. The results from the modal analysis are used to develop design guidelines.. Results from the experimental evaluation of the approach implemented on a modified production level hard-switched parent converter are presented in Section IV. A summary of the evaluation study is presented in the concluding section.

II. MODAL ANALYSIS

A. Topological Description

A schematic of the switching circuit of the floating capacitor soft switching boost converter is illustrated in Fig. 1. As may be observed from the figure, the converter features no additional active device compared to the conventional boost converter. It consists of two auxiliary diodes D_r , D_c , a resonant capacitor C_r and an auxiliary inductor L_r coupled to the boost inductor L_b . L_r is used to provide zero current switching conditions for Q_b and limit its turn-on di/dt , thereby reducing the reverse recovery current of the main diode D_b . The capacitor C_r is primarily used to provide zero voltage switching conditions for Q_b

and limit its turn-off dv/dt . Furthermore, it is also used to absorb the energy stored in L_r due to persistent reverse recovery current of D_b . For the purpose of analytical description of the operating conditions, several simplifying assumptions have been made. These assumptions include: ideal switching devices with instantaneous transition periods, absence of parasitic inductances between interconnections, absence of parasitic capacitances across devices, absence of equivalent series resistance for capacitors and inductors, ideal voltage source and a constant output voltage. The only non-idealities that are considered in the analysis include the non-zero coupling coefficient between the resonant inductor and boost inductor and a non-zero reverse recovery current for the diode. Once the principal modes of operation are determined using these assumptions to develop design guidelines and the component values are known, a detailed digital computer simulation is performed that include various non-idealities to account for the effect of unmodeled elements.

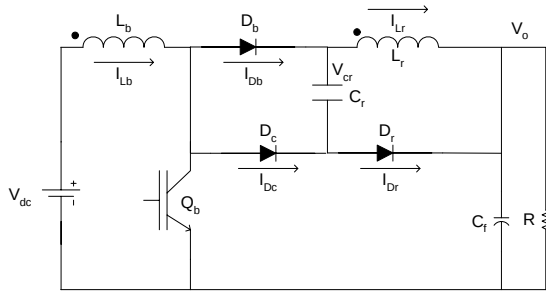


Fig. 1: Power circuit schematic of the floating capacitor soft switching boost converter

B. Operating Modes

During each switching cycle of operation of the boost converter, the converter proceeds through six operating modes. The equivalent circuits corresponding to these modes are given in Figure 2. The operation during various operating modes is described below:

a. Mode 1

During this mode, the boost inductor is connected across the source and is charged up. This corresponds to the transistor on period of the parent boost converter.

b. Mode 2

This is the resonant mode that occurs at the initial stages of the ZVS turn off of Q_b . This mode is followed by a linear transition mode for the resonant capacitor discharge (3a) or resonant inductor charge (3b) depending on the load level.

c. Mode 3(a)

This linear transition mode occurs at heavy load conditions, when the capacitor voltage is discharged before the resonant inductor current is charged up to the boost inductor current. This mode ends when the resonant inductor current reaches the boost inductor current level.

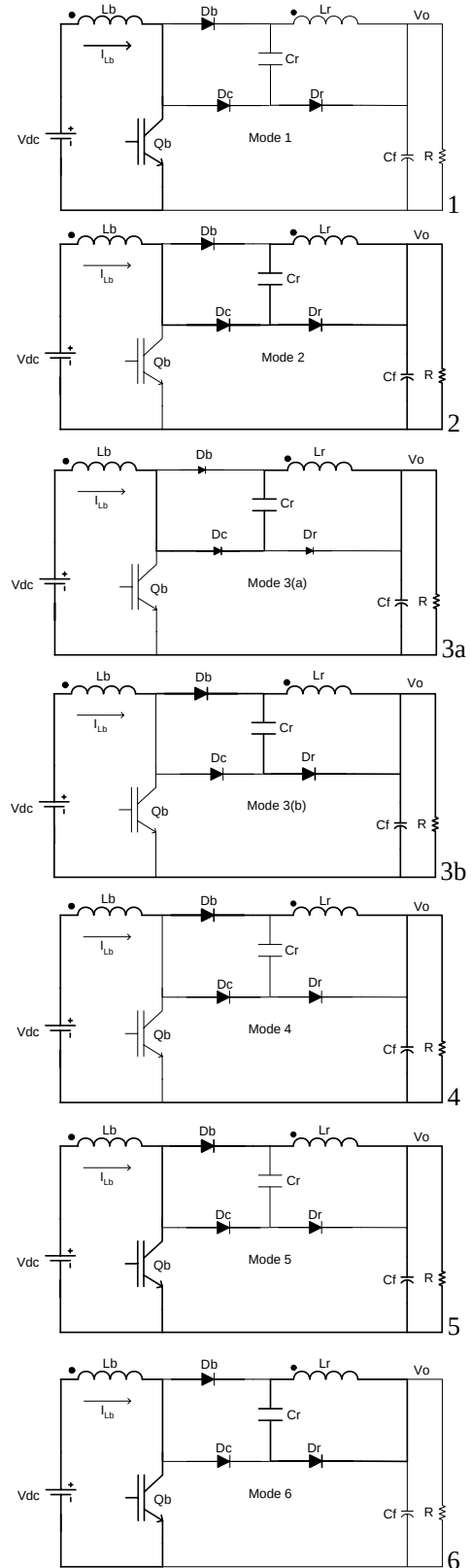


Figure 2. Equivalent circuits during the different operation modes

d. Mode 3(a)

This is the linear transition mode occurs at light load conditions, when the resonant inductor current is charged

up to the boost inductor current before the capacitor voltage is discharged completely. This mode ends when the resonant capacitor voltage reaches zero.

e. Mode 4

This is the boost inductor discharge mode, when energy is transferred to the load. The period corresponds to the transistor off period of the parent boost converter.

f. Mode 5

This is the linear transition mode when the transistor Q_b is turned on again to initiate a ZCS turn-on. This mode continues until the resonant inductor current reaches the negative reverse recovery current of D_b .

g. Mode 6

This is the resonant mode during which the energy stored in the resonant inductor due to reverse recovery current flowing through it is transferred to C_r . The mode ends when the resonant inductor current reaches zero.

Typical current and voltage waveforms that correspond to major converter elements during a complete switching illustrating various operating modes are shown in Fig. 3.

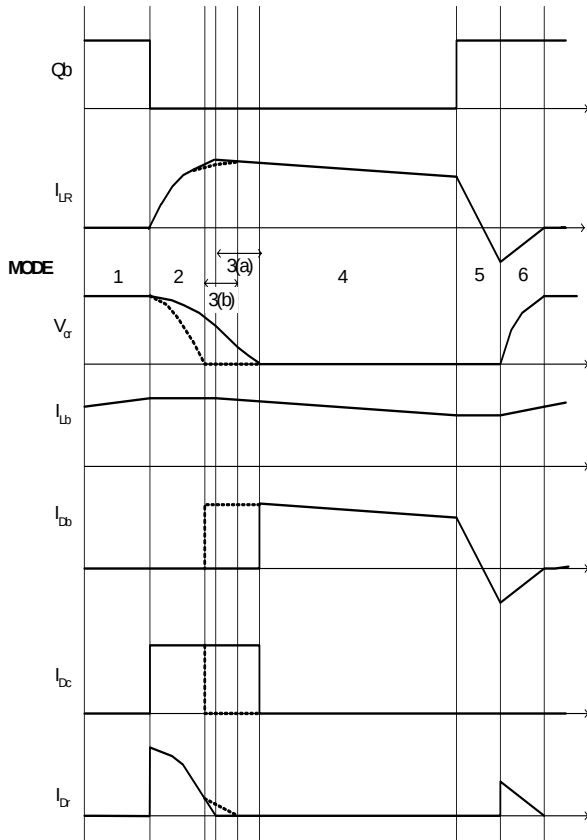


Fig. 3: Typical waveforms of the floating capacitor soft switching boost converter during various operating modes

C. Design Equations

Design considerations for soft switching converters involve complex trade-offs involving circuit operating frequency and the resonant circuit elements used for realizing soft switching [14]. The general approach uses

the analytical results from the modal analysis to determine voltage and current stress levels across various circuit elements to arrive at an optimal design. Optimal design considerations may include overall loss minimization or reduction of component size. In the present study, the design considerations were driven by the existing hard-switching converter design and a retrofit was desired. Thus, the choices of switching frequency and power circuit components were pre-constrained, thereby allowing a simple design approach. The results from the modal analysis described above were used to select the resonant elements L_r and C_r for the converter. There are two major design considerations in the choice of circuit elements (a) the peak voltage stress across the resonant capacitor (and hence auxiliary diodes), given by $I_{RRM} Z$, and (b) the peak voltage stress across the boost diode during the on-state of the boost transistor, given by $(V_o + V_{dc} N_2/N_1)$.

For a peak input voltage V_{dc} of 325 V, corresponding to a 230 V single phase input, and an output voltage of 750 V, a turns ratio $N_2/N_1 = 1/6$ gives a peak boost diode voltage stress of about 805 V. This design choice provides an adequate margin for the use of 1200 V diodes for D_b . Once the turns ratio of the coupled resonant inductor is chosen, L_r is determined as $L_b (k N_2/N_1)^2$ assuming a nominal coupling factor. For an L_b of 0.67 mH and k of 0.92, this yields an L_r of about 16 μ H.

A typical fast recovery diode with 1200V PIV, 20A average current rating is expected to have a maximum reverse recovery current I_{RRM} of about 15-20A under limited di/dt conditions. A characteristic impedance Z of about 15-20 Ω would result in peak capacitor voltage V_{cr} of about 225-400V. A choice of resonant capacitor voltage C_r to be in the range of 40 to 70 nF would realize in the desired range.

Thus a turns ratio of 6 and C_r of about 40-70 nF represents the design choices for the soft-switching circuit. The final value of the turns ratio and capacitor value are optimized further based on digital computer simulations that model the circuit parasitic elements accurately.

IV. EXPERIMENTAL RESULTS

A. Hardware description

An experimental demonstration prototype was developed from a production unit of a hard-switching single phase unity power factor rectifier rated at 6 kW. The control of the converter was performed using a dedicated integrated circuit specifically designed for controlling a single phase unity power factor boost rectifier [15]. Manufacturer's application guidelines were used to develop the various regulator control loops of the converter. This feature of being able to apply an off-the-shelf control solution without any additional control or sensor hardware is one of the attractive features of the soft-switching topology being studied. The resonant capacitor and the auxiliary

diodes were mounted in the space between the heat sink and the printed circuit board, to keep lead lengths short. All interconnects, with the exception of the auxiliary windings, were made with copper foil cut and bent to shape with a layer of adhesive backed Kapton was applied to provide insulation as necessary. Connections to the auxiliary diodes and resonant capacitor were either soldered, or screw mounted depending on the package style. Connections to the main diode and IGBT were made using a bus plane made of copper strips between the screw terminals on the switch module and the printed circuit board.

B. Switching waveforms

Due to the higher voltage stress on the clamp diodes, two different realizations of the diodes were performed in the experiments. The first set of experiments was performed using a 45A 1.2kV diode. The second set of experiments applied 47A 1.7kV diode to realize the clamp diodes. In each case the diodes were mounted onto the heat sink close to the boost IGBT (Q_b) and located to minimize conductor lengths. Heat sink compound and insulating pads and bushings were applied to mount the auxiliary devices as necessary to fit the package and isolation requirements. Selected waveforms from the experimental prototype are illustrated in Figs. 4-5. Resonant inductor current and resonant capacitor voltage waveforms over a complete switching cycle are illustrated in Fig. 4.

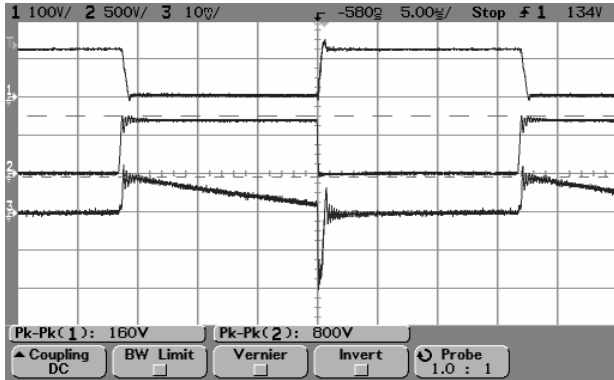


Fig.4: Waveforms obtained from the experimental prototype of the floating capacitor soft switching boost converter

Fig. 5 illustrates an expanded view of the waveforms during turn on and turn off intervals. The excellent correspondence of the experimental results to the simulation results illustrated in Fig. 4-5 may be readily observed.

C. Thermal measurements

Since one of the major motivations to use the soft switching approach was to reduce the thermal stress on the device the temperature rise of the devices were measured. The boost IGBT was equipped with a thermocouple mounted on the base plate. Ambient temperature was measured with a second thermocouple

mounted near the intake of the cooling fan. Each thermal test began with the heat sink at or near room temperature and lasted approximately 15 minutes, with temperature readings taken at 10 second intervals. A baseline run was made with the converter in hard-switched mode with results are shown in Fig. 6. The temperature rise experiment was performed under the same input, output, and switching frequency conditions as the hard-switched converter. The temperature rise curve for the soft switching converter is shown in Fig. 7. Comparison of Figs. 6 and 7 indicates that the soft switching approach results in the base plate temperature reduction of about 14°C when compared to hard-switching base line.

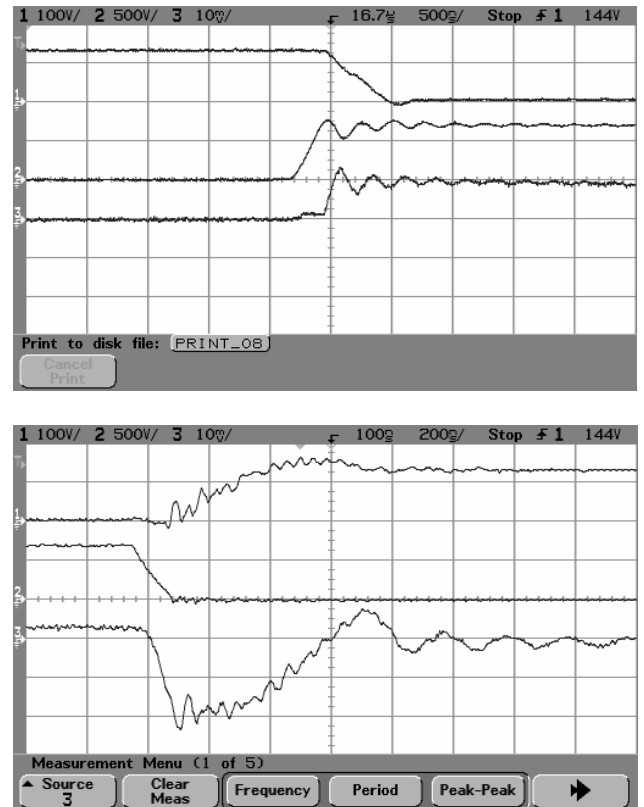


Fig. 5: Expanded view of waveforms obtained from the experimental prototype of the converter IGBT turn-off (top) and IGBT turn-on (bottom)

V. CONCLUSION

This paper has presented a detailed analysis and evaluation results from a practical soft-switching approach applicable for a high power boost converter. The approach realizes switching stress reduction during turn-on and turn-off conditions of the switching IGBT and manages the reverse recovery charge from the diode through recirculation to the load after temporary storage in a floating capacitor. Soft switching over a wide range of operating conditions is realized with the use of a resonant capacitor, two clamp diodes and a few turns of a winding coupled to the boost inductor. The soft switching converter utilizes exactly the same controller approach as

the parent boost converter applied for power factor correction for a single phase ac-dc conversion. Thus the realization of the proposed approach results in a minimal additional cost in hardware and zero additional cost in control overhead. An extra voltage penalty on the main boost diode over the baseline design is a modest 7.5%. The boost IGBT sees no additional voltage penalty. The auxiliary diodes conduct current only for a small portion of the switching cycle, and therefore, their current ratings can be very relaxed as compared to the main diode and IGBT.

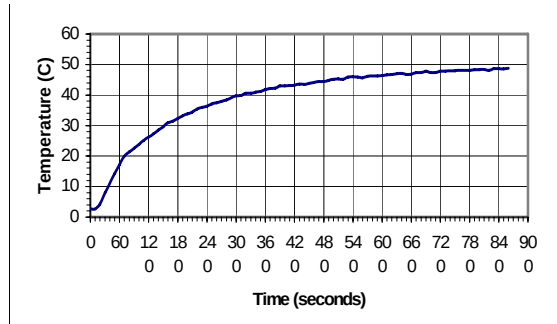


Fig. 6: Temperature rise characteristics of the IGBT base-plate under hard switching mode of operation

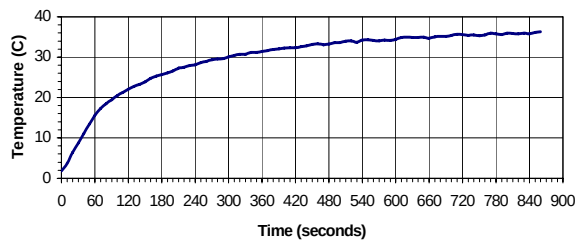


Fig. 7: Temperature rise characteristics of the IGBT base-plate under soft switching mode of operation

The analysis presented for the converter operation was verified through a retrofit of a production converter with the soft switching network. Experimental investigations have demonstrated a 30% reduction in temperature rise when compared to the baseline hard-switching mode of operation. This reduction in temperature can lead to a combination of possible advantages depending on design optimization objectives: (a) ultimate increase in lifetime and reliability of the converter with no change in thermal management, (b) reduced heat sink size, weight and cost (c) increased switching frequency of operation and hence reduced reactive components used as filter elements in the converter, (d) reduced size of power semiconductor switching devices.

Detailed analysis of the modes have been carried and differential equations that are valid in these modes have been derived. However, this analysis, along with the simulation results has been left out of the paper due to the space limitations.

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