Abstract— This paper proposed a method to reduce the switching losses in a direct-current-direct-current boost converter. The proposed method uses a capacitor switched regenerative snubber circuit to reduce the turn-off losses of the IGBT in the boost converter, and thus it improves the overall efficiency of the converter. The circuit uses no additional magnetic components and enjoys a simple control strategy. Two 500W prototypes, that is one with and the other without the regenerative snubber have been tested to evaluate and demonstrate the impact of the proposed regenerative snubber circuit.

Index Terms—Regenerative snubber,DC-DC boost converter, Switching loss,IGBT.

I. INTRODUCTION

Boost converter is one of the most important and widely used devices of modern power applications. Till now Boost converters with snubber circuits are used where switching losses are dissipated in external resistors leading to higher switching losses and low overall efficiency. Modern Boost converters use IGBT switches which have the following properties such as high current and voltage rating, fast switching, low power gate drive. These properties lead to following disadvantages such as at high blocking voltage the switching frequency is reduced to low values and due to high switching speed, the rate of change of current and voltages become high. Also hard switched boost converter suffers from severe diode reverse-recovery problem in high-current high-power applications. So whenever the main switch is turned on a shoot through of the output capacitor to ground causes a large current spike through the diode and main switch. It will cause significant turn-off and turn on losses of the main switch and also causes severe electromagnetic interference (EMI) emission. Reverse Recovery problem is more significant for high switching frequency at high power level. Therefore, the hard-switched boost converter is not capable to achieve high efficiency and high power density at high power level.

In order to reduce the size and weight of switching converters and increase power density, a high switching frequency is required. However, in hard-switching converters, as the switching frequency increases, switching losses and electromagnetic interference increase. To solve this problem, soft-switching converters are indispensable. In recent years, great amount of research is done to develop soft-switching techniques in dc–dc converters. There are different topologies have been proposed to reduce switching losses in DC/DC converters. The devices are turned off and/or turn on at zero voltage or zero current of a resonant mode in resonant and quasi-resonant converters [1],[2]. But it requires careful matching of the operating frequency to the resonant tank component values, and operation failure can occur in the case of any magnetic saturation or unexpected drift in resonant frequency. Also, it can be difficult to design filters and control circuits because of the wide range of switching frequency variations.

Passive soft-switching methods [3]-[8] use only passive components to achieve zero-voltage or zero-current switching at a constant switching frequency. The auxiliary circuits can be complicated and require numerous extra components, including extra inductors, which can again partially or fully offset the mass reduction benefits of using a higher switching frequency. The main disadvantage of using passive soft switching method is it can cause higher component stresses and have generally been shown to provide only marginal reductions in switching losses.

Active soft-switching methods [9]-[19] use one or more auxiliary switches in addition to passive components to achieve zero-voltage or zero-current switching. The disadvantages of active methods include control complexity and limitations in terms of voltage-boost and load ranges. Also, a large number of proposed active methods focus on the reverse-recovery losses at turn-on of the main switch, even though this problem can now be easily remedied through the use of Sic boost diodes. Finally, some active methods have hard switching of the auxiliary switches, and many have a high component count, including heavy extra inductors.

There is a need for a simple and efficient method for increasing the switching frequency of high-power
boost converters. Marshall and M.Kazerani [20] introduced a new lossless active snubber for a high-power boost converter. The auxiliary switches are switched at zero-voltage and hence introduce no switching losses to the converter. The turn-off losses of the main switch are drastically reduced. But the snubber circuit is controlled by a complex control strategy and requires additional sensors or feedback.

The literature review reveals that there is a need for a simple and efficient method for increasing the switching frequency of high-power boost converters without adding heavy extra inductors, so that the converter mass can be reduced. Thus, this project provides an in-depth examination of the capacitor switched regenerative snubber for high-power boost converters. The circuit is simple, is highly efficient, operates effectively over the entire load range, requires no additional inductors, and enjoys a straightforward control strategy. The only additional components required are two IGBTs (which are connected as a leg and can be easily implemented by a dual IGBT module), two diodes, and one snubber capacitor.

I. GENERAL DESCRIPTION OF THE PROPOSED SYSTEM

A. CIRCUIT DESIGN

An analysis is performed on a high-power hard-switched boost converter in order to compare the turn-on and turn-off losses of the switch. The switch turn off loss is generally greater than switch turn on loss in high power based IGBT. The much higher value of turn-off losses in an IGBT can be explained by the fact that there is a significant current tail as the voltage across the switch rises rapidly during turn-off. Hence, the capacitor-switched regenerative snubber circuit described here in focuses on reducing the turn-off losses of the IGBT. However, the design of the present invention, in one aspect silicon-carbide diodes is used to reduce the turn-on losses and hence improve the overall efficiency of the converter at high switching frequencies. Silicon-carbide diodes reduce turn-on losses in a boost converter because they exhibit nearly zero reverse recovery current when turning off.

The circuit diagram of a conventional boost converter is shown in Fig. 1, complete with input and output filters to smooth current and voltage ripple. One particular implementation of the regenerative snubber circuit is shown in Fig. 2. The idea is to charge the snubber capacitor \(C_s\) at one turn-off and then discharge the snubber capacitor at the next turn-off. With this operation, the voltage rise across the switch is slowed down and the current tail through the switch is reduced at each turn-off, and virtually all of the energy used to accomplish this is returned to the output circuit.

![Fig 1. Conventional Hard Switched Converter](image1)

![Fig 2. Boost Converter With Proposed Regenerative Snubber Circuit](image2)

To realize this operation, the connection of the snubber capacitor to the main switch \(S_1\) must be reversed for every turn-off, so that the charging and discharging actions are bringing the voltage across the snubber capacitor from 0 V to \(V_{out}\) and vice versa. The details of the circuit operation are described below.

At the first turn-off of \(S_1\), \(S_3\) is on and \(S_2\) is off so that current flows through \(D_2\) and \(S_3\) to charge the snubber capacitor \(C_s\) from 0 V to the output voltage \(V_{out}\). This charging action slows down the voltage rise across switch \(S_1\), greatly reducing the losses while the current in the switch \(S_1\) falls quickly. At the next turn-on, both \(S_2\) and \(S_3\) are off, thus the operation of \(S_1\) at turn-on is virtually unaffected by the snubber circuit. At the next turn-off of \(S_1\), \(S_2\) is on and \(S_3\) is off, thus, the current flows through \(S_2\) and \(D_3\) to discharge the snubber capacitor. Again, this action greatly slows down the voltage rise across \(S_1\) and reduces the current tail through \(S_1\). All the energy stored in the snubber capacitor is transferred to the output of the circuit, leading to a very efficient design.

B. CONTROL STRATEGY

The control strategy for operating the main and auxiliary switches is simple and can be implemented on a microcontroller. No additional
sensors or feedback are required for the auxiliary switches. FIG.3 shows required gating signals

![Switch Gating Signals](image)

The auxiliary switches must turn on before the main switch turns off and they must turn off before the main switch turns back on. The auxiliary switches have a constant duty cycle to facilitate charging (S1 on) and discharging (S2 on) of the snubber capacitor. The duty cycle of the main switch can be changed by changing the turn-on time, while keeping the turn-off time in sync with the auxiliary switch turn-on times. The boost converter is not practical for use with very high voltage boosts (due to parasitic losses) and so very high duty cycles are not usually required. Thus, the fact that the snubber capacitor must finish charging or discharging before switch S1 turns on does not pose any limitation in most practical cases. If a high voltage boost is required, the design choice of the snubber capacitor size can be made to ensure the required duty cycle is obtainable without violating the control strategy principles.

A microcontroller was programmed with the control strategy for use with the experimental prototypes. To decouple any effects caused by a closed-loop controller from the circuit behavior, open-loop control was implemented. The auxiliary switches have a constant duty cycle, which can be determined through simulation and depends on the converter current and voltage, as well as snubber capacitance. A closed-loop current or voltage control scheme can be easily implemented, as the only change would be that a software control loop would control the main switch duty cycle.

C. DESIGN CONSIDERATIONS

In general, the design of the proposed circuit is very simple because only one passive component size, i.e., $C_s$, must be determined. The capacitance of the snubber capacitor should be chosen as small as possible (to minimize conduction losses in the auxiliary components) but still large enough to slow down the voltage rise across the main switch to the extent that the turn-off losses are significantly reduced. The recommended design rule is as follows:

The desired time for voltage rise ($\Delta t_{\text{desired}}$) is equal to approximately three times the turn-off time specified in the datasheet for the particular main switch used.

If this is not possible due to limited availability of capacitor sizes, it is recommended to use the next larger capacitor size that will allow a minimum of a three times increase in turn off time. Also, the snubber capacitor should be chosen to have the lowest equivalent series resistance possible to reduce resistive losses during charging and discharging. After the designer has determined $\Delta t_{\text{desired}}$, the capacitance of the snubber capacitor ($C_s$) can be approximated by (1). In (1), $I_{C,\text{max}}$ and $V_{\text{out, max}}$ are the maximum collector current for the main switch and the maximum output voltage, respectively.

$$C_s = \frac{I_{C,\text{max}} \Delta t_{\text{desired}}}{V_{\text{out, max}}} \quad (1)$$

The constant duty cycle of the auxiliary switches should be chosen after the calculation for $C_s$ so that their on-time is slightly longer than $\Delta t_{\text{desired}}$ to allow for the snubber capacitor to become fully charged or discharged while the auxiliary switch is on. The choice of the auxiliary switches and diodes must be based on standard design practices considering peak and rms currents and peak voltage. According to PSPICE simulations, the auxiliary switches have peak currents similar to and rms currents lower than those of the main switch [20]. These results will be based on the choice of $C_s$ and will thus vary across different designs.

The rms current of each auxiliary switch can be approximated using (2), which assumes one rectangular pulse of current $I_{C,\text{max}}$ for time $\Delta t_{\text{desired}}$ within each period where the switching period of the auxiliary switch ($\tau_{\text{aux}}$) is twice that of the main switch.

$$I_{\text{rms}} = \frac{I_{C,\text{max}} \Delta t_{\text{desired}}}{\sqrt{\tau_{\text{aux}}}} \quad (2)$$

If the peak current is the constraining factor within the choices of available switches, then the auxiliary switches must be chosen to be the same type as the main switch so that the peak current (and voltage) constraint(s) is (are) met. However, if the rms current is the constraining factor, then
the following two design options are available for sizing the auxiliary switches.

1. Choose the auxiliary switches based on the simulated or calculated peak and rms currents for those switches while adhering to the maximum voltage constraint. This option is desirable if the absolute lowest cost and mass are required.

2. Choose the auxiliary switches to be the same as the main switch. This option is desirable if minimizing the number of different parts in the circuit is a high priority.

It can be seen that the design process for the auxiliary components of the regenerative-snubber circuit is simple and straightforward: 1) Calculate the time for the snubber capacitor to be fully charged or discharged \( (\Delta t_{\text{desired}}) \) based on the main switch turn-off time; 2) calculate \( C_s \) using (1); and 3) choose the auxiliary switches and diodes based on the required current and voltage ratings (or use the main switch type for the auxiliary switches to minimize the number of different parts in the circuit).

II. ANALYSIS OF LOSSES

The reason why there are switching losses in any switch mode power converters is that when the switching element turns on or off, high voltage and current are present simultaneously in the switch. This leads to very high instantaneous power loss in the switch resulting in a low efficiency of the converter. The switching loss in any semiconductor switch varies linearly with switching frequency \( f_s \) and the delay times. Such a power converter is therefore unsuitable for operation at high frequencies above 30 kHz. Although switching stresses can be reduced by using simple dissipative snubbers across the switch the efficiency of the converter is not improved as the switching power loss shifts from the switch to the snubbers. Switching losses can be reduced by two methods:

1. By reducing the turn-on and turn-off delay times. This is done by using faster and more efficient switches in the converter.

2. By making the current or voltage across the switch zero before turning it on or off. Soft switching converters are based on this concept.

Simulations were performed using MATLAB to characterize the behavior of a 5-kW prototype of the present invention. Table 1 shows the main parameters of the simulation system. The results shown in FIG. 1 (a) and 1(b) illustrate the voltage and current through the main switch of the hard switched boost converter. The voltage and current through the main switch is around 220V and 40A. FIG. 2(a) and (b) also shows the voltage and current through the main switch of the proposed system. The results shows that the switching stress across the main switch both in terms of current and voltage are equal at two different frequencies. The switching frequency for the hard-switched converter prototype was chosen to be 30 kHz and the proposed system was chosen to be 60kHz. That is switching loss across the main switch is minimum in the proposed system compared to the hard switched boost converter.

Table 1. Simulation parameters of the boost converter
Simulation results show that the current rise and voltage rise obtained across the main switch in the proposed system and the hard switched boost converter is almost same. And also we can see that the transient response is improved in the proposed converter system.

IV. EXPERIMENTAL prototype

In order to perform a comprehensive comparison between the capacitor-switched regenerative snubber boost converter and the hard-switched boost converter in terms of mass, switch stress, and efficiency, two 500-kW boost converters, one with and the other without the snubber circuit, were designed, built, and tested. Using the best switches available on the market ensures the comparison between the two converters is relevant. The control strategy for operating the boost converter is implemented on a microcontroller. The hard-switched converter and the capacitor-switched regenerative snubber converter use the exact same IGBTs, drivers, diodes (silicon carbide diodes to reduce turn-on losses), filter capacitors, and boost capacitors. The input filter inductors and boost inductors were custom-made for each converter. The input LC filter for each converter uses a 220µF electrolytic capacitor, and the inductor values were determined based on choosing the filter's resonant frequency to be approximately one decade below the switching frequency of each converter. The inductance of the main boost inductors for each converter was chosen to make the inductor current ripple approximately 2 A (10%) at full power. Equation (1) is used to determine the size of the snubber capacitor in the prototype: \( V_{\text{out,max}} = 250 \text{V}, \) \( I_{\text{c,max}} = 24 \text{A}, \Delta t_{\text{desired}} = 0.5 \mu\text{s}. \) Thus \( C_S = 0.1 \mu\text{F}. \) The output L-C filter was omitted to simplify the prototype construction. However, the same IGBTs were used for the auxiliary and main switches to minimize the number of different parts required.

A. EXPERIMENTAL RESULTS

The experimental results verify the operation of the regenerative snubber circuit and match well with the MATLAB simulation results.
Fig 4(b) shows the current through the main switch of the regenerative snubber converter. During the turn off time of the main switch current is made to zero and achieved zero current switching condition.

Fig 5(a) and 5(b) shows the voltage and current through the main switch of the regenerative snubber converter. During the first turn off event of the main switch, Snubber capacitor is charged because a current is passed through the auxiliary switch S3. From the analysis we can say that during the turn on time of the auxiliary switch S3, current is passed through the switch and off time the voltage is present in the auxiliary switch and current stays to zero. The auxiliary switch S3 shows zero current switching and so there is no switching loss across the switch. The oscillations during turn off and turn on are due to the parasitic inductances and capacitances in the circuit.

Fig 6 shows the switching loss in the auxiliary switch S3. Here switching loss is negligible because the auxiliary switches achieves zero voltage (ZVS) and zero current switching (ZCS)

Fig 7 shows the comparison of switching loss in the hard switched and regenerative snubber converter of the main switch. It implies that the switching loss in the main switch is less in the regenerative snubber converter than the hard switched converter. So it improves the overall efficiency of the regenerative converter.

V. CONCLUSION

An improved control strategy, experimental results, design considerations and extensive analysis of the switching and power loss for capacitor switched regenerative snubber converter was proposed in this paper. The snubber circuit is controlled by a simple control strategy that is easily implemented and requires no additional sensors or feedback. Here the auxiliary switches are switched under zero voltage and zero current switching. The two 500W prototype converters have been shown experimentally to reduce the voltage stress, power loss and thus improved the efficiency of the converter.
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