

Regenerative Undeland Snubber Using a ZVS PWM DC–DC Auxiliary Converter Applied to Three-Phase Voltage-Fed Inverters

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Abstract—This paper proposes an energy regeneration circuit for three-phase voltage-fed inverters using a modified Undeland snubber. The proposed system uses a quasi-square-wave zero voltage switching dc–dc auxiliary converter to regenerate the energy from snubber capacitor to the dc bus. The regenerative circuit uses a single active switch, and it operates independently of the three-phase inverter. Operation stages, theoretical waveforms, and a design methodology are presented. Experimental results based on a 4.5-kVA three-phase inverter prototype are included to validate the proposed topology.

Index Terms—Regenerative snubber, soft commutation, three-phase inverter.

I. INTRODUCTION

THREE-PHASE voltage-fed inverters operating at high-switching frequencies have been widely used in several applications, such as uninterruptible power systems, ac power sources, and distributed generation systems. The main motivations to increase the switching frequency are the reduction of size, weight, and volume of passive filters and the synthesis of signals with high-order harmonics [1]–[3]. On the other hand, high-switching frequencies increase the switching losses and electromagnetic interference.

Many studies have been carried out focusing on the development of techniques to reduce switching losses in voltage-fed inverters, using active or passive auxiliary commutation circuits.

In active schemes, soft commutation is achieved by using controlled switches in the auxiliary commutation circuit [4]–[27]. These topologies usually require the use of special pulsewidth modulation (PWM) schemes to synchronize the auxiliary switches to the main switches, increasing the complexity of the control circuits.

On the other hand, passive techniques do not have controlled switches in the auxiliary commutation circuit [28]–[33]. In these schemes, soft commutation is performed with passive snubbers based on diodes, resonant elements, and resistors. Passive techniques have industry preference because they are more robust, simple, cheap, and because it is possible to use conventional PWM schemes.

Among several passive topologies, Undeland snubbers have been widely used in voltage-fed inverter applications due to their good performance, simplicity, and robustness [28], [29], [31], [33], [34]. These snubbers reduce the switches' losses by extracting the commutations' energy to a storage capacitor. However, the Undeland snubbers do not increase the inverter efficiency because they dissipate the energy on a resistor.

Consequently, several papers with regenerative circuits have been published [35]–[47] as an attempt to minimize the losses in passive snubbers. Most of these topologies use high-frequency isolation transformers, which have low efficiency and limited switching frequency due to the stray inductances and saturation of magnetic core.

In addition, some papers introduced some modifications in the Undeland snubber to regenerate the switching losses to the input dc bus by using dc–dc converters [35], [36], [39], [43]–[46]. Among them, the circuit proposed by Fregien *et al.* [43] uses self-oscillating dc–dc push-pull converters to regenerate the energy from switching losses to the input dc bus. The main disadvantage of this topology is the use of two isolated converters, which usually have high volume and low efficiency, caused by the leakage inductances of the transformers. A nonisolated dc–dc converter was proposed in [35] to regenerate the energy stored in the snubber. This circuit has been implemented in high-power drives used in some European trains. Nevertheless, this regenerative circuit has a large number of components.

A similar solution was proposed in [39], using a dc–dc buck converter to regenerate the stored energy to the dc bus, reducing the number of additional elements. Moreover, Xiangning *et al.* [44], [45] proposed a new dc–dc converter to regenerate the energy from switching losses. This auxiliary circuit is simple, but it must be synchronized with the main switches, making its command circuit complex.

Recently, a modified Undeland snubber (MUS) was proposed [48], [49] to use a low voltage capacitor to store the energy from switching losses. This modification allowed the inclusion of a buck–boost converter in discontinuous conduction mode

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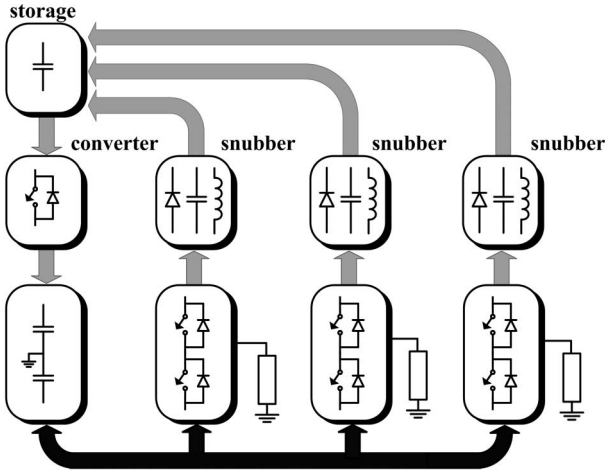


Fig. 1. Simplified block diagram of the proposed inverter.

for energy regeneration [50]. This solution is attractive due to its simple command circuit and reduced number of additional components. However, there are voltage and current oscillations during the free-wheeling diode turn off.

Aiming to reduce the aforementioned problems, this paper proposes the MUS for three-phase voltage-fed inverters with a single regenerative converter. The MUS uses only one voltage clamping capacitor with reduced voltage rating to store the commutations' energy from all inverter switches. The proposed regenerative circuit transfers energy from the snubber storage capacitor to the dc bus capacitor using a quasi-square-wave (QSC) zero voltage switching (ZVS) buck-boost dc-dc converter [51]. This converter operates with fixed duty cycle, which is independent of main switches, and it employs one inductor and one active switch. The ZVS operation of the regenerative circuit is highly desirable to obtain high efficiency and reduce electromagnetic emissions.

This paper is organized as follows: Section II presents the proposed regenerative snubber using a modified Undeland circuit. Section III describes the operation principle of the QSC-ZVS buck-boost converter. A detailed methodology is included in Section IV to design the MUS and the QSC-ZVS buck-boost converter. A design example for a 4.5-kVA three-phase inverter is presented in Section V. Simulation and experimental results are shown in Sections VI and VII, respectively.

II. PROPOSED REGENERATIVE SNUBBER

Fig. 1 presents a block diagram representation of a scheme to reduce switching losses in PWM inverters. In this structure, passive snubbers are used to transfer the energy from switching losses to a storage capacitor.

Consequently, one can reduce the power dissipation in main switches. However, it is necessary to include a discharge circuit to guarantee the power balance of the storage capacitor. The simplest solution is to connect a resistor to discharge this capacitor, but the efficiency of the overall system is penalized. On the other hand, if the energy stored in this capacitor is regenerated to the dc bus, as shown in Fig. 1, the overall inverter efficiency can be increased.

Based on this concept, a regenerative snubber is proposed here to transfer the energy from switching losses of a three-phase voltage-fed inverter to its dc bus, as shown in Fig. 2.

The MUS is used to transfer the energy from switching losses of a well-known three-phase four-wire voltage-fed inverter to a clamping capacitor C_s . It has some important advantages, such as the utilization of only one inductor, which is common to all inverter legs, and the clamping capacitor is connected above the dc bus. By comparing it with the original Undeland snubber, the number of magnetic elements is reduced as well as the voltage across the clamping capacitor. On the other hand, when a single inductor is used to limit di/dt in a three-phase operation, it is possible to have a small overcurrent through the snubber diodes due to the commutations of the other legs.

A QSC buck-boost converter is proposed to recover the energy stored in the clamping capacitor, and it is connected as shown in Fig. 2. This buck-boost converter can be designed to operate under soft commutation (ZVS), which increases its efficiency and reduces its electromagnetic interference.

III. QSC-ZVS BUCK-BOOST CONVERTER

A simplified circuit of the buck-boost dc-dc converter to regenerate the snubber energy is shown in Fig. 3. In order to simplify the analysis, one can assume the following.

- 1) Voltage across the capacitor C_s has small variations in a switching period so that it can be considered as an ideal dc voltage source V_{Cs} .
- 2) Voltages across C_{dc1} and C_{dc2} have small variations in a switching period so that they can be assumed as a single ideal dc voltage source V_{dc} .
- 3) D_{r2} and S_{r1} have intrinsic capacitances.
- 4) D_{r2} presents a significant reverse recovery charge.

As the MUS is designed to work with an almost constant clamping voltage and bulky dc bus capacitors, the hypotheses 1) and 2) are always ensured.

The hypothesis 3) must be ensured because the intrinsic capacitances of these components are fundamental to obtain ZVS operation of the QSC-ZVS buck-boost converter.

A discrete capacitor may be included in parallel of these switches if their intrinsic capacitances are negligible. The hypothesis 4) is included because this converter uses the reverse recovery of the diode D_{r2} to charge the inductor L_r in one operation stage.

The operation of this converter in QSC-ZVS mode can be described in five operation stages. The equivalent circuit of each stage can be seen in Fig. 5, and the main waveforms are shown in Fig. 4.

First Stage ($t_0 \leq t < t_1$): The equivalent circuit of this stage is shown in Fig. 4(a). This stage begins when S_{r1} is turned on and the inductor current is zero. The source V_{Cs} transfers energy to the inductor L_r so that the inductor current increases linearly with rate V_{Cs}/L_r .

Second Stage ($t_1 \leq t < t_2$): The equivalent circuit of this stage is shown in Fig. 4(b). At time t_1 , the switch S_{r1} is turned off. The inductor current remains almost constant during this stage and flows resonantly through C_{r1} and

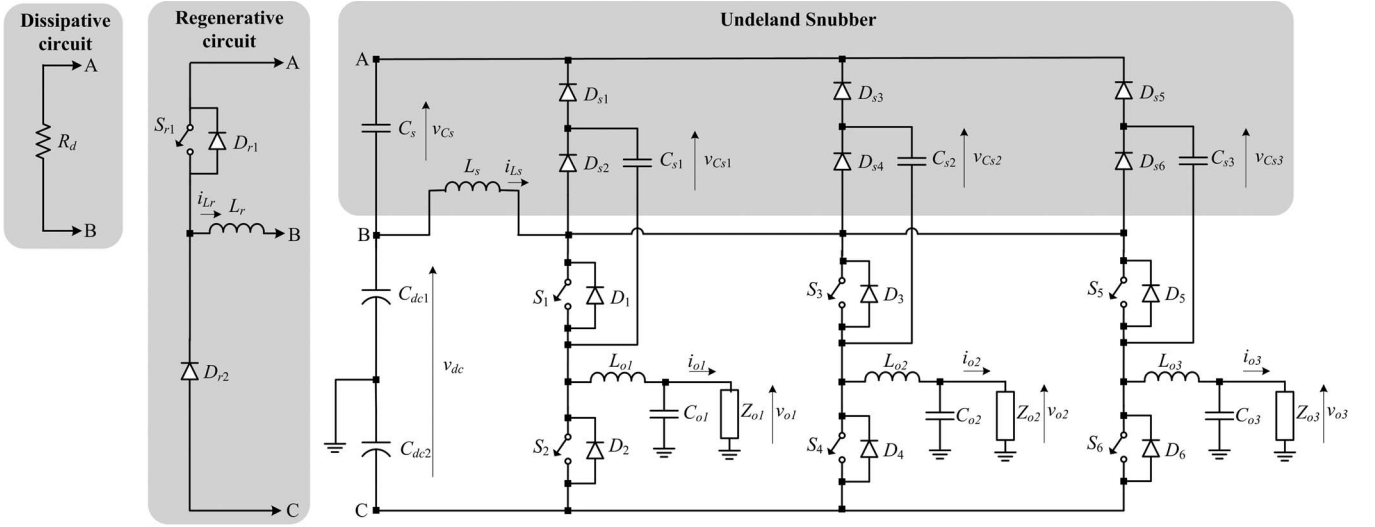


Fig. 2. MUS applied to a three-phase inverter.

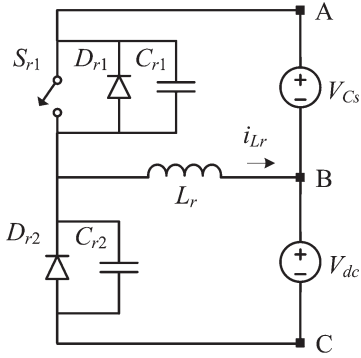


Fig. 3. Equivalent circuit of the buck-boost QSC-ZVS converter.

C_{r2} . The voltage across C_{r2} decreases linearly to zero, and the voltage across C_{r1} increases up to $V_{dc} + V_{Cs}$ at $t = t_2$.

Third Stage ($t_2 \leq t < t_3$): The equivalent circuit of this stage is shown in Fig. 4(c). At t_2 , the voltage across diode D_{r2} is zero. Therefore, the inductor current flows through the diode D_{r2} to the source V_{dc} , decreasing linearly until zero with rate $-V_{dc}/L_r$. From this instant, the diode reverse recovery energy is transferred to the inductor, and the inductor current becomes negative. At $t = t_3$, all reverse recovery energy is transferred to the inductor; the current reaches the maximum negative value $-I_R$, and the diode turns off.

Fourth Stage ($t_3 \leq t < t_4$): The equivalent circuit of this stage is shown in Fig. 4(d). After diode D_{r2} turns off, the inductor current flows resonantly through C_{r1} and C_{r2} . During this stage, the inductor current remains almost constant. The voltage across C_{r1} decreases to zero, and voltage across C_{r2} increases up to $V_{dc} + V_{Cs}$ at $t = t_4$.

Fifth Stage ($t_4 \leq t < T_s$): The equivalent circuit of this stage is shown in Fig. 4(e). At t_4 , the voltage across diode D_{r1} reaches zero, and the inductor current circulates through diode D_{r1} , transferring the inductor energy to the source V_{Cs} . The inductor current increases linearly with rate

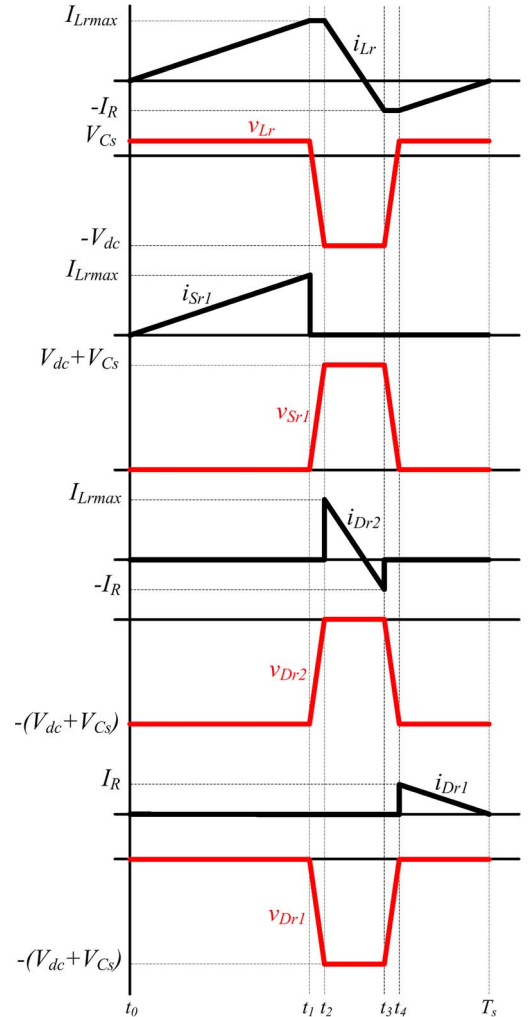


Fig. 4. QSC-ZVS buck-boost theoretical waveforms.

V_{Cs}/L_r reaching zero at $t = T_s$. During this stage, the switch S_{r1} must be turned on to guarantee a zero voltage commutation.

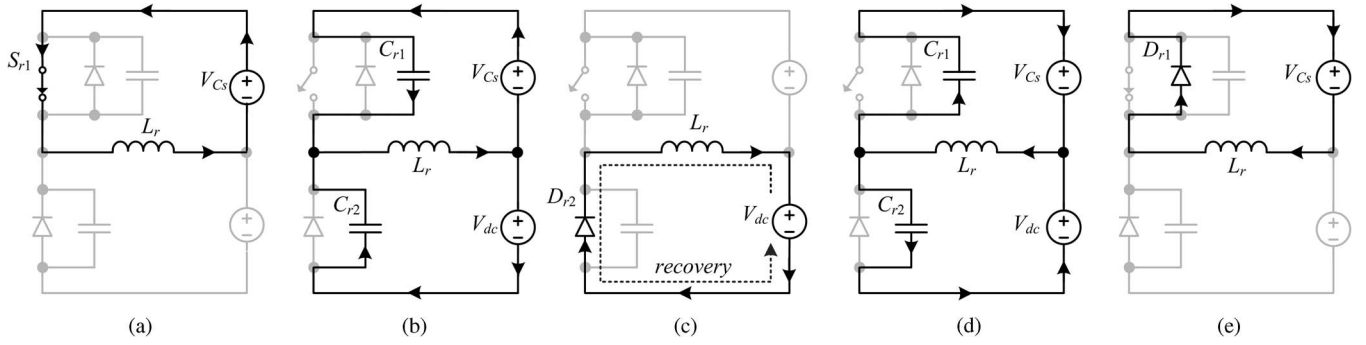


Fig. 5. QSC-ZVS buck-boost converter operation. (a) First stage. (b) Second stage. (c) Third stage. (d) Fourth stage. (e) Fifth stage.

IV. DESIGN CONSIDERATIONS

This section presents some guidelines to design the auxiliary commutation circuits of the proposed inverter.

A. Design of the MUS

The design methodology for the MUS considers the following specifications:

- V_{dc} nominal dc bus voltage;
- $di_s/dt|_{\max}$ maximum rate of current change of the main switches;
- $dv_s/dt|_{\max}$ maximum rate of voltage change across the main switches;
- I_p peak current in the converter legs;
- ΔV_{C_s} maximum clamping capacitor voltage ripple;
- f_s switching frequency of the main switches.

From these specifications one can design the MUS as follows:

Step 1—Definition of the clamping voltage of the MUS at nominal operating point. The following range is usually considered:

$$0.05 V_{dc} \leq V_{C_s} \leq 0.1 V_{dc}. \quad (1)$$

Step 2—Determination of the inductance L_s that limits the rate of current change of the main switches

$$L_s = \frac{V_{dc}}{di_s/dt|_{\max}}. \quad (2)$$

Step 3—Determination of the capacitances C_{s1} , C_{s2} , and C_{s3} that limit the rate of voltage change across the main switches

$$C_{s1} = C_{s2} = C_{s3} = \max(f_1, f_2) \quad (3)$$

$$f_1 = \frac{1}{2(dv_s/dt|_{\max})^2} \left[\frac{V_{dc}^2}{L_s} + \sqrt{\frac{V_{dc}^4}{L_s^2} + (dv_s/dt|_{\max})^2 I_p^2} \right] \quad (4)$$

$$f_2 = \left(\frac{V_{dc}}{dv_s/dt|_{\max} \sqrt{L_s}} \right)^2. \quad (5)$$

Step 4—Calculation of the maximum power P_{C_s} processed from switching losses to the clamping capacitor C_s in a switching period. The analytical computation of P_{C_s} is

extremely complex due to its interdependence with several circuit parameters. Therefore, one can obtain a reliable estimate of P_{C_s} by simulating the overall circuit, assuming the following.

- 1) Three-phase inverter processes the maximum power level, i.e., the nominal load is connected to the output.
- 2) C_s is replaced by a dc voltage source V_{C_s} .
- 3) All models used to describe the behavior of the semiconductors are accurate (SPICE model).
- 4) The simulation of at least one complete cycle of a low-frequency reference signal is performed.

Step 5—Determination of the minimum value of the clamping capacitor C_s to limit its voltage ripple.

The analytical computation of C_s depends on i_{C_s} , which cannot be easily solved analytically. Therefore, the easiest and most efficient way to determine a reliable estimate of this current is through simulation of the overall circuit. Other than the simulation conditions described in Step 4, one can also assume the following.

- 1) V_{C_s} is replaced by the capacitor C_s , whose capacitance is determined using iterative simulations. An initial estimate for this capacitance, to start the iterations, can be given by

$$C_s = \frac{P_{C_s}}{\Delta V_{C_s} f_s V_{C_s}}. \quad (6)$$

- 2) The equivalent series resistance of the capacitor C_s is included in its model.
- 3) The resistor R_d , shown in Fig. 2, is connected in parallel to the capacitor C_s to dissipate the energy stored in this capacitor. The resistance can be obtained by

$$R_d = \frac{V_{C_s}^2}{P_{C_s}}. \quad (7)$$

It is important to emphasize that C_s used in practice may be greater than the value obtained from the simulations. A larger capacitance does not affect the snubber performance but results in smaller clamping capacitor voltage ripple. In practical applications, the design of this capacitor is closely related to thermal restrictions. Thus, it may be necessary to connect several capacitors to satisfy this condition.

B. Design of the Buck–Boost QSC-ZVS Regenerative Converter

The design methodology for the buck-boost QSC-ZVS converter, which is utilized to regenerate the energy stored in the clamping capacitor, is based on [51]. In addition to the specifications imposed on the MUS, one must specify the clamping capacitor voltage V_{Cs} and the maximum power P_{Cs} from the snubber design.

Therefore, one can design the main components of the regenerative circuit as follows:

Step 1—Definition of the diode D_{r2} , whose peak voltage is $V_{dc} + V_{Cs}$ and the average current is given by

$$I_{Dr2avg} = \frac{P_{Cs}}{V_{dc}}. \quad (8)$$

The reverse recovery time (t_{rr}), the rate of change of current used in the reverse recovery test (di_d/dt), reverse recovery charge (Q_{rr}), and the junction capacitance (C_{r2}) are obtained from the datasheet of the chosen diode. From these values, it is possible to obtain the peak value of the reverse recovery current, given by

$$I_R = \frac{2Q_{rr}}{t_{rr}}. \quad (9)$$

Step 2—Determination of the nominal duty ratio

$$D_{nom} = \frac{V_{dc}}{V_{dc} + V_{Cs}}. \quad (10)$$

Step 3—Determination of L_r

$$L_r = (a - \sqrt{a^2 - b})V_{dc}(1 - D_{nom})^2 \quad (11)$$

where

$$a = \frac{1}{2f_s I_{Dr2avg}} + \frac{4Q_{rr}}{6I_{Dr2avg}^2} \quad (12)$$

$$b = \frac{1}{4f_s^2 I_{Dr2avg}^2}. \quad (13)$$

Step 4—Determination of the peak current through inductor L_r

$$I_{Lrpk} = \frac{D_{nom} \cdot V_{Cs}}{f_s \cdot L_r} - I_R. \quad (14)$$

Step 5—Calculation of the rms current in D_{r2}

$$I_{Dr2rms} = \sqrt{\frac{L_r}{3 \cdot V_{dc} \cdot T_s} \cdot (I_R^3 + I_{Lrpk}^3)}. \quad (15)$$

Step 6—Definition of the switch S_{r1} , whose peak voltage is $V_{dc} + V_{Cs}$, and the average current is given by

$$I_{Sr1avg} = \frac{V_{Cs} f_s}{2L_r} t_{sw}^2 \quad (16)$$

$$t_{sw} = \frac{D_{nom}}{f_s} - \frac{I_R L_r}{V_{Cs}}. \quad (17)$$

TABLE I
INVERTER SPECIFICATIONS

$v_{dc} = 600$ V	Nominal dc bus voltage
$v_{o1} = v_{o2} = v_{o3} = 127$ V _{rms}	Output phase to neutral voltage
$P_o = 4.5$ kVA	Total output power
$f_s = 50$ kHz	Switching frequency
$L_{o1} = L_{o2} = L_{o3} = 560$ μ H	Output filter inductance
$C_{o1} = C_{o2} = C_{o3} = 5$ μ F	Output filter capacitance

TABLE II
SNUBBER SPECIFICATIONS

$di_s/dt _{max} = 120$ A/ μ s	Maximum rate of current change
$dv_s/dt _{max} = 4000$ V/ μ s	Maximum rate of voltage change
$I_p = 16.7$ A	Output peak current
$\Delta V_{Cs} = 1.5$ V	Maximum voltage ripple across the clamping capacitor

Step 7—Calculation of the rms current in S_{r1}

$$I_{Sr1rms} = \frac{V_{Cs}}{L_r} \cdot \sqrt{\frac{T_{sw}^3}{3T_s}}. \quad (18)$$

The output capacitance of the selected switch (C_{r1}) is obtained from the datasheet. This value is used in the following step.

Step 8—Verification of the soft-commutation condition, which is given by

$$Q_{rr} > \frac{3(C_{r1} + C_{r2})(V_{dc} + V_{Cs})^2}{4V_{dc}}. \quad (19)$$

If this condition is not satisfied, the regenerative circuit operates in dissipative mode. In this case, to obtain a ZVS converter, it is necessary to return to Step 1) and repeat the design procedure with another diode D_{r2} , which should have a larger reverse recovery time.

Step 9—Determination of the duty ratio of S_{r1} , which should satisfy the following condition:

$$D_{min} < D < D_{nom} \quad (20)$$

where

$$D_{min} = D_{nom} - \frac{f_s}{V_{Cs}} \sqrt{\frac{4}{3} L_r V_{dc} Q_{rr}}. \quad (21)$$

This duty ratio interval corresponds to the conduction period of D_{r1} , in which the switch S_{r1} must be turned on to guarantee ZVS.

V. DESIGN EXAMPLE

This section presents a design example for the proposed regenerative snubber circuit. The main specifications of the three-phase inverter are given in Table I. Table II presents additional specifications that were considered to design the MUS.

TABLE III
MAIN COMPONENTS OF MUS

$V_{Cs} = 30$ V	Nominal clamping voltage
$P_{Cs} = 150$ W	Power transferred to C_S
$L_S = 5$ μ H	Snubber inductance
$C_{S1} = C_{S2} = C_{S3} = 4.7$ nF	Snubber capacitances
$C_S = 940$ μ F	Snubber clamping capacitor

TABLE IV
REGENERATIVE CONVERTER SPECIFICATIONS

$V_{Cs} = 30$ V	Input voltage
$V_{dc} = 600$ V	Output voltage
$P_{Cs} = 150$ W	Output power
$f_s = 50$ kHz	Switching frequency

TABLE V
SPECIFICATIONS OF D_{r2} AND S_{r1}

$t_{rr} = 164$ ns	Reverse recovery time of D_{r2}
$Q_{rr} = 680$ nC	Reverse recovery charge of D_{r2}
$di_d/dt _{\max} = 200$ A/ μ s	Maximum rate of change of reverse recovery current in D_{r2}
$C_{r2} = 27$ pF	Junction capacitance of D_{r2}
$C_{r1} = 200$ pF	Output capacitance of S_{r1}

TABLE VI
QSC-ZVS BUCK-BOOST PARAMETERS

$D_{nom} = 0.95$	Nominal duty-cycle
$D_{min} = 0.74$	Minimum duty-cycle
$L_r = 30$ μ H	Buck-boost inductance
$I_{Lrmax} = 10.7$ A	Maximum current in L_r
$I_{Dr2avg} = 0.25$ A	Average current in D_{r2}
$I_{Dr2rms} = 1.22$ A	Rms current in D_{r2}
$I_{Sr1avg} = 2.9$ A	Average current in S_{r1}
$I_{Sr1rms} = 4.5$ A	Rms current in S_{r1}

From these specifications, one can design the MUS using the methodology proposed in Section IV-A, whose results are presented in Table III.

The next step is the design of the regenerative converter, using the methodology presented in Section IV-B. The main specifications to design this converter are shown in Table IV.

Table V presents additional information that was considered to design the QSC-ZVS buck-boost converter. This information was obtained from datasheets of diode HFA16TB120 and switch IRG4PF50WD, which were chosen to implement D_{r2} and S_{r1} , respectively.

From these specifications, it is possible to obtain the design results for the QSC-ZVS buck-boost converter, which are shown in Table VI.

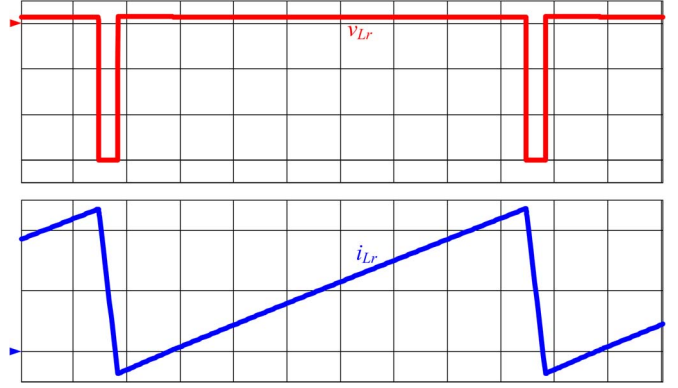


Fig. 6. Voltage and current waveforms of the buck-boost inductor L_r (200 V/div, 5 A/div, 5 μ s/div).

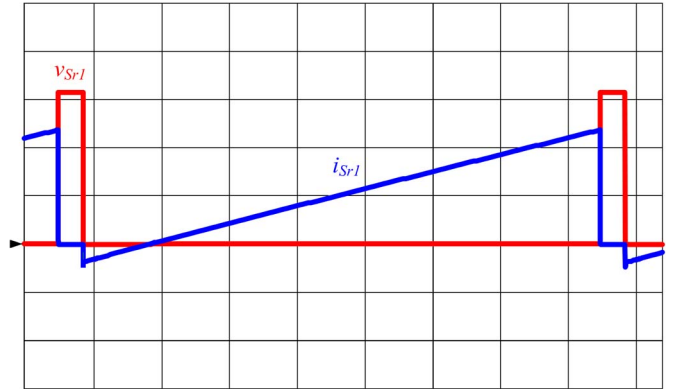


Fig. 7. Collector-emitter voltage and current waveforms of the auxiliary switch S_{r1} (200 V/div, 5 A/div, 2.5 μ s/div).

VI. SIMULATION RESULTS

This section presents some simulation results obtained from PSPICE for the QSC-ZVS buck-boost converter, using the parameters shown in Section V.

Fig. 6 shows the voltage and current waveforms of the inductor L_r . One can observe that these waveforms agree with theoretical waveforms (Fig. 4), with a quasi-square voltage waveform and triangular current waveform. Moreover, the maximum and minimum values of the inductor current were similar to the values computed in Section V.

Fig. 7 shows the collector-emitter voltage and current waveforms of the auxiliary switch S_{r1} . As expected, it is possible to see that S_{r1} commutates under zero voltage.

VII. EXPERIMENTAL RESULTS

This section presents some experimental results obtained with a 4.5-kVA three-phase inverter prototype, shown in Fig. 8 and whose parameters are presented in Table VII.

Fig. 9 shows the sinusoidal phase-to-neutral output voltages of the three-phase inverter. Fig. 10 shows one output phase-to-neutral voltage and its respective current waveform for nominal resistive load.

Figs. 11 and 12 show the turn-on and the turn-off commutations of the main switch S_4 . One can see that the turn-on and turn-off losses are reduced due to the utilization of



Fig. 8. Implemented prototype.

TABLE VII
MAIN COMPONENTS OF THE PROTOTYPE

$S_1 - S_6, S_{r1}$	IGBT switch: IRG4PF50WD
$D_1 - D_6, D_{r1}$	IGBT anti-parallel diode: IRG4PF50WD (ultrafast, soft recovery)
$D_{S1} - D_{S6}, D_{r2}$	Diode: HFA16TB120 (ultrafast, soft recovery)
$C_{s1} - C_{s3}$	Polypropylene capacitor: 4.7 nF
C_{dc1}, C_{dc2}	Electrolytic capacitor: 680 μ F
C_s	Electrolytic capacitor: 2 x 470 μ F
C_o	Polypropylene capacitor: 5 x 1 μ F
L_{o1}, L_{o2}, L_{o3}	Toroidal iron powder inductor: 560 μ H
L_r	Ferrite inductor: 28 μ H
L_s	Ferrite inductor: 15 μ H

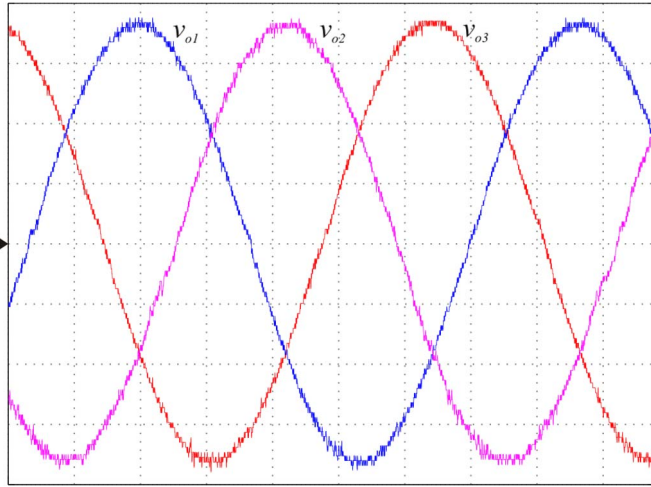


Fig. 9. Phase-to-neutral output voltages (50 V/div, 2.5 ms/div).

the regenerative snubber. In this case, commutation energy is transferred to the clamping capacitor C_s .

The auxiliary regenerative circuit does not modify the operation of MUS. The regenerative converter is dynamically decoupled from the snubber due to large capacitance of the dc bus capacitors C_{dc1} and C_{dc2} and the storage capacitor C_s . Moreover, the voltage V_{C_s} is designed to be equal to the dissipative snubber. As a result, all waveforms of MUS with auxiliary regenerative circuit are similar to the dissipative solution.

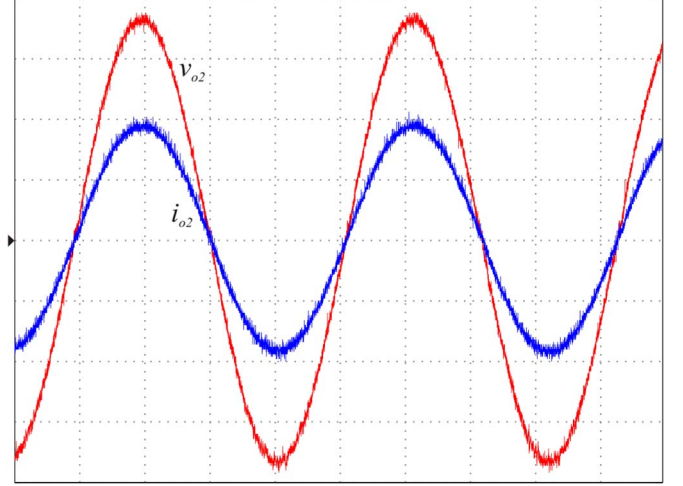
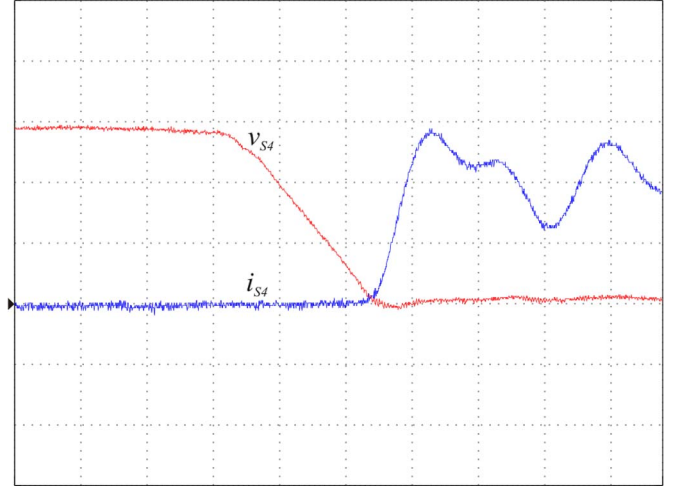
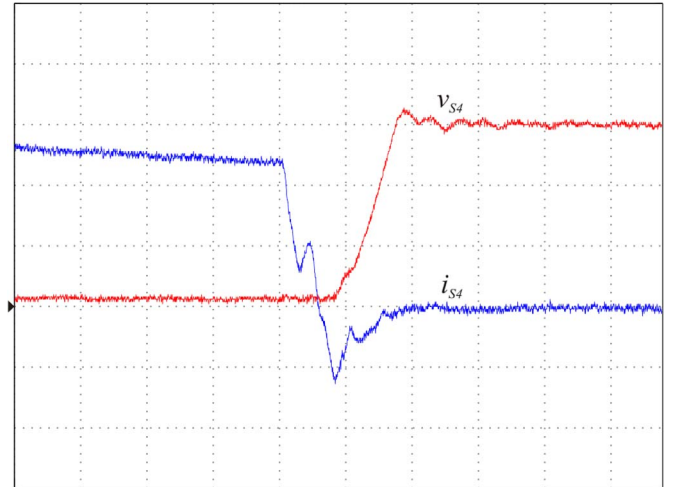


Fig. 10. Phase-to-neutral output voltage and output current for nominal resistive load (50 V/div, 10 A/div, 5 ms/div).

Fig. 11. Turn-on commutation of the main switch S_4 (200 V/div, 10 A/div, 100 ns/div).Fig. 12. Turn-off commutation of the main switch S_4 (200 V/div, 5 A/div, 250 ns/div).

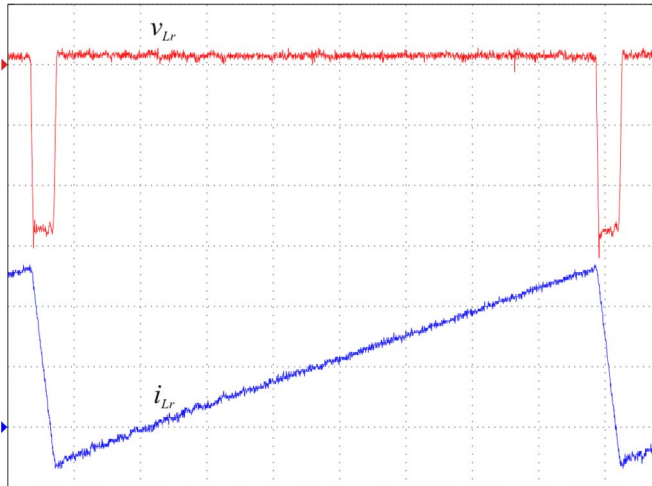


Fig. 13. Voltage and current waveforms of the buck-boost inductor L_r (200 V/div, 5 A/div, 5 μ s/div).

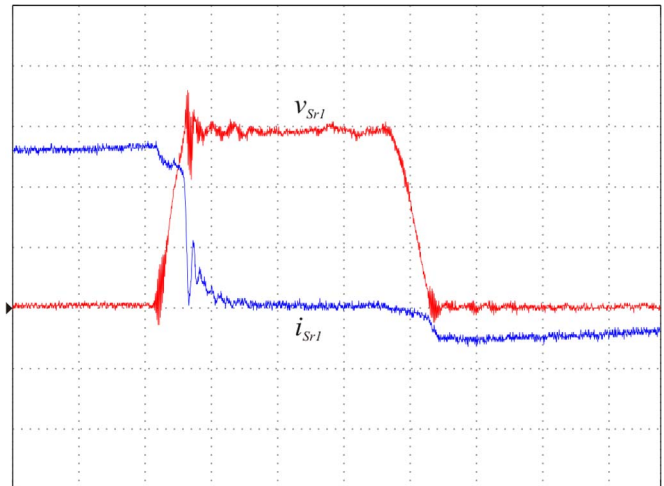


Fig. 15. Detailed commutation of auxiliary switch S_{r1} (200 V/div, 5 A/div, 250 ns/div).

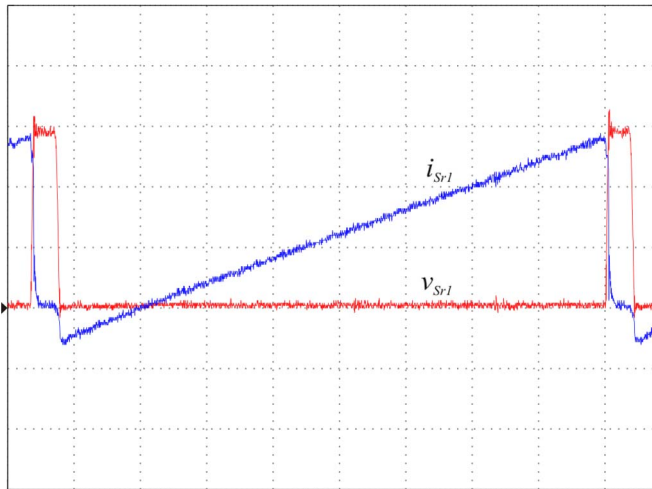


Fig. 14. Collector-emitter voltage and current waveforms of the auxiliary switch S_{r1} (200 V/div, 5 A/div, 2.5 μ s/div).

Figs. 13 and 14 show the voltage and current waveforms of the inductor L_r and switch S_{r1} of the regenerative converter, respectively.

The commutation of the auxiliary switch S_{r1} can be observed in detail in Fig. 15. As can be seen, there is a good similarity between experimental and theoretical waveforms. When the switch is turned off, the intrinsic output capacitance of S_{r1} is charged, and its collector-emitter voltage rises almost linearly until the current falls to zero. As can be seen, there is a tail current due to the utilization of an insulated gate bipolar transistor (IGBT) switch.

On the other hand, the switch S_{r1} is turned on when diode D_{r1} is conducting, which ensures zero voltage switching. Fig. 16 shows the voltage across the snubber clamping capacitor C_s . As can be observed, its steady-state value is close to the value obtained by simulation (30 V). This voltage waveform also presents some spikes due to inverter and regenerative converter commutations.

Finally, the efficiency of the inverter using the proposed QSC-ZVS buck-boost regenerative converter was compared to a dissipative snubber, using a resistor R_d to dissipate the energy

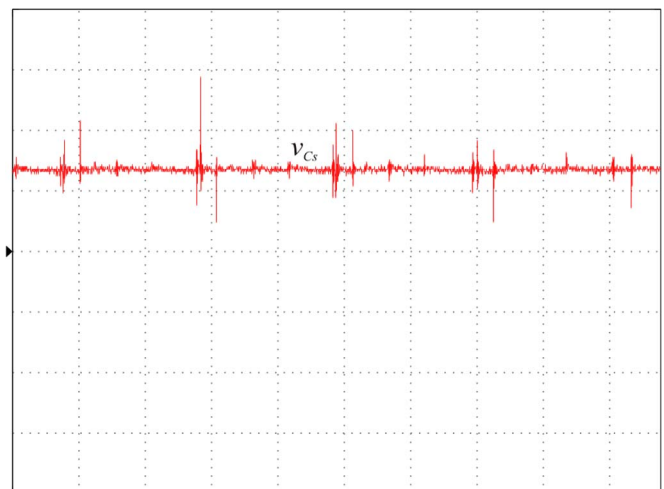


Fig. 16. Voltage across snubber clamping capacitor (20 V/div, 10 μ s/div).

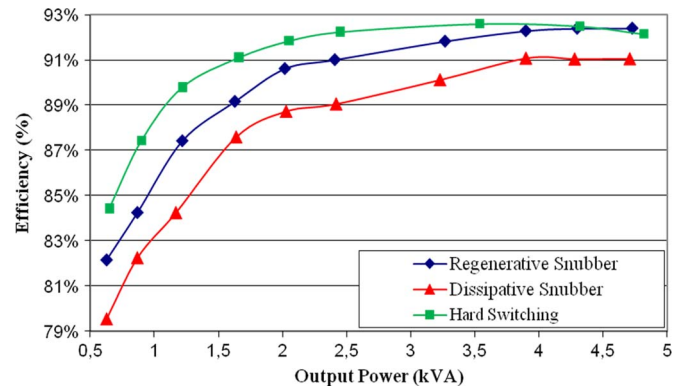


Fig. 17. Efficiency curves.

from the MUS. In order to obtain a fair comparison, the energy processed by dissipative or regenerative schemes is the same in all load conditions. As can be seen in Fig. 17, the use of regenerative snubber improves the efficiency up to 2% over a wide output power range.

Fig. 17 also includes an efficiency curve of the three-phase inverter operating with hard switching. As mentioned before,

the dissipative Undeland snubber reduces the losses dissipated on the switches and reduces the electromagnetic interference, but it does not increase the overall efficiency of the inverter because the switching losses are dissipated on a resistor. In some cases, as in this prototype, the overall efficiency decreases with a dissipative snubber, due to the conduction losses of the auxiliary components. By using the proposed circuit to regenerate the energy stored in the snubber capacitor, the overall efficiency of the inverter increased considerably, and it is higher than the efficiency obtained with hard switching for nominal load.

Moreover, the proposed regenerative circuit enables one to increase the switching frequency of inverters using IGBT switches, which are usually limited to operate in few kilohertz due to their high turn-off switching losses.

Consequently, it is possible to reduce the volume/weight of magnetic elements and to increase the bandwidth, which is very important for some applications.

By comparing the proposed circuit with other topologies found in the literature, to regenerate the energy stored in the snubber capacitor of the Undeland snubber, mentioned in the introduction, one can observe the following advantages:

- 1) reduced number of components;
- 2) simple command circuit;
- 3) higher efficiency, due to the ZVS commutation;
- 4) smaller electromagnetic and radio interferences.

The regenerative circuit proposed here is composed of only three additional components: one switch (with its respective antiparallel diode), one diode, and one inductor. The command signal of auxiliary switch has constant duty ratio, and it can present the same switching frequency of the main switch, using the same high-frequency carrier. The auxiliary switch operates under ZVS commutation, resulting in low switching losses and low electromagnetic interference levels.

VIII. CONCLUSION

The proposed circuit to regenerate the energy from the MUS presents few components (inductor, switch, and diode), and it has an easy design methodology. In addition, it has a simple command circuit with a constant duty cycle and uses the same triangle carrier employed for the three-phase inverter. Another important advantage is that the proposed circuit can regenerate the energy from n -leg converters with a single converter, which operates under ZVS.

Moreover, the proposed regenerative snubber has higher efficiency compared to dissipative snubbers. The experimental results show that the proposed regenerative snubber improves the efficiency up to 2% over a wide output power range. Furthermore, the proposed topology presents some advantages in relation to other soft-commutation cells:

- 1) low clamping voltage across the switches;
- 2) robust structure with a single auxiliary active switch;
- 3) operation of auxiliary switch with independent PWM at constant duty cycle;
- 4) simple design procedure with few parameter restrictions.

The proposed regenerative circuit enables one to increase the switching frequency of the main inverter; thus, it is possible

to reduce the magnetic components and increase the bandwidth, which is essential for some applications, such as active filters, unified power quality conditioners, digital voltage restorers, class-D amplifiers, and ac power sources.

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