A Composite Soft-Switching Inverter Configuration with Unipolar Pulsewidth Modulation Control

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Abstract—This paper presents a new composite soft-switching configuration for single-phase inverters where power bridge leg modules are used. The presented configuration consists of only one inductor and one capacitor as well as two low-power-rated switches/diodes for full-bridge circuits. It can realize snubber functions and/or resonant zero-current switching at any load current for switches in power inverters with unipolar sinusoid pulsewidth modulation control. The idea presented here is that soft-switching processes at turn-on and -off for each active switch in inverters can be different. The detailed circuit operational processes, simulation waveforms, and experimental results are included.

Index Terms—Power inverter, pulsewidth modulation control, snubber, soft switching.

I. INTRODUCTION

The use of either lossless snubber circuits or resonant zero-voltage-switching and zero-current-switching (ZVS and ZCS) techniques increases the efficiency of power converters and inverters, and reduces electromagnetic interference (EMI) and noise[1], [2], caused by stray inductance, parasitic capacitance, and other imperfections in practical circuits and devices.

In the case of a snubber, the switch current increase is delayed at turn-on and the switch voltage rising is delayed at turn-off, avoiding an overlap of supply voltage and load current in the switching period. Passive components are normally used, although lossless snubbers incorporate complications associated with energy recovery [3]–[6]. In contrast, with ZVS the switch voltage is forced to zero before the switch current rises at turn-on. In the case of ZCS the switch current is forced to zero before the switch voltage rises at turn-off. Extra active devices and control circuitry are needed to achieve these objectives, which results in complicated inverter bridges [7]–[10]. Most published papers on soft-switching techniques discussed ZVS and ZCS, or lossless snubbers separately, there being difficulties in overcoming the shortcomings of each individual technique.

This paper presents a new composite soft-switching configuration for single-phase inverters, which combines the advantages of snubber functions and resonant ZCS circuits, with few additional switches. The proposed composite soft-switching technique eliminates the need for energy recovery circuits and simplifies inverters with switching aid circuits. The operational processes of the configuration with unipolar sinusoid pulsewidth modulation (SPWM) inverter control are analyzed in detail, and simulations and experimental results are presented.

II. SOFT-SWITCHING FULL-BRIDGE INVERTER

A. General Description

The single-phase inverter with the proposed soft-switching circuit is shown in Fig. 1. Main devices T1–T4 and D1–D4 comprise two insulated gate bipolar transistor (IGBT) bridge leg modules, and T5, T6, D5, and D6 are auxiliary devices. Ls and Cs are common passive snubber components, and only one inductor and capacitor are needed in this case.

When T1 and T4 turn on, the current increase in both T1 and T4 is controlled by Ls. Then, full-load current flows through T1 and T4 while D3 and D2 are off. Before T1 turns off, T5 turns on and Ls and Cs resonate, transferring T1 current to T5. T1 turns off under a zero-current condition. Simultaneously, Cs with an initial voltage of −Vdc reverses its charge until VCs = Vdc and the load current, transferring from T5, flows through D2. Then, T5 turns off under a zero-current condition. At the same time, T4 turns off with Cs acting as a turn-off snubber and the load current flows through D6. Finally, Cs discharges resonating with Ls and reversing charges through T3 and D6.
until \( V_{C6} = -V_{dc} \) when \( T3 \) and \( T2 \) turn on. Here, \( T3 \) and \( T2 \) turn on according to the complementary control pulses for \( T1 \) and \( T2 \), and for \( T3 \) and \( T4 \). Figs. 2 and 3 show current flow paths during \( T1 \) and \( T4 \) turn-on and turn-off processes. Similar turn-on and turn-off operational processes can be found for \( T3 \) and \( T2 \) if load current flows from node 5 to node 2 (\( I_m < 0 \)), which are shown in Figs. 4 and 5. \( T6 \) will turn on and off instead of \( T5 \), to realize soft switching for \( T3 \) and \( T2 \).

**B. Circuit Operational Equations**

In order to simplify analysis so as to obtain an analytical solution, it is assumed that the switches \( T1-T6 \) are ideal and the load current \( I_m \) is constant during turn-on and -off periods. The circuit analytical waveforms are given in Fig. 6.

1) \( T1 \) and \( T4 \) Turn-On (see Figs. 2 and 6): \( t < t_0 \) [Fig. 2(a)]—The load current flows through \( D2, D3 \), and \( L_n \).
Fig. 3. (Continued.) Circuit operational processes at T1 and T4 turn-off.

\[ t_0 - t_1 \text{ [Fig. 2(b)] — The current } i_{T1} \text{ and } i_{T4} \text{ increase linearly, that is,} \]
\[ i_{T1}(t) = i_{T4}(t) = \frac{V_{dc}}{2L_s}(t - t_0), \quad (1) \]

\[ t_1 - t_2 \text{ [Fig. 2(c)] — T1 and T4 turn-on completes and } i_{T1} = i_{T4} = I_m. \]

2) T1 and T4 Turn Off (see Figs. 3 and 6): \( t < t_2 \) [Fig. 3(a)] — This is as in Fig. 2(c).

\[ i_{T1}(t) = I_m - \frac{V_{dc}}{Z_R} \sin[\omega_s(t - t_2)] \]
\[ i_{T5}(t) = I_m - i_{T1}(t) \quad (2) \]

where

\[ \omega_s = \frac{1}{\sqrt{L_s C_s}} \quad Z_s = \sqrt{\frac{L_s}{C_s}}. \quad (3) \]
Fig. 5. Circuit operational processes at $T3$ and $T2$ turn-off.

$t_3 - t_4$ [Fig. 3(c)] — $T1$ is off and $D1$ is on with

$$ i_{T5}(t) = \frac{V_{dc}}{Z_a} \sin[\omega_a(t - \tau_2)]. $$

$t_4 - t_5$ [Fig. 3(d)] — $I_m$ charges $C_a$ until $v_{C_a}(t_5) = V_{dc}$

$$ v_{C_a}(t) = \frac{I_m}{C_a}(t - t_4) - V_{dc} \cos[\omega_a(t_4 - t_2)] $$

$$ i_{T5}(t) = I_m. $$

$t_5 - t_6$ [Fig. 3(e)] — $D2$ is on and $i_{T5}(t) = 0. T5$ turns off. Then, $T4$ turns off and $D6$ is on with $C_a$ acting as a turn-off snubber capacitor

$$ v_{T4}(t) = \frac{I_m}{C_a}(t - t_5). $$

$t_6 - t_7$ [Fig. 3(f)] — $T3$ and $T2$ turn on (complementary control
pulse), and \( C_s \) discharges, that is,

\[
i_{CS}(t) = -I_m - \left( \frac{V_{dc}}{Z_s} - I_m \omega_s(t - t_g) \right) \sin(\omega_s(t - t_0)). \tag{7}
\]

\( t_{3-g} \) [Fig. 3(g)]—The load current transfers from \( C_s \) to \( L_s \). If \( u_{CS}(t) \) is assumed as constant in the period

\[
i_{CS}(t) = \frac{V_{dc}}{I_m} (t - t_{3-g}). \tag{8}
\]

\( t > t_{3-g} \) [Fig. 3(h)]—\( i_{CS}(t) = I_m \) and \( u_{T3}(t) = V_{dc} \), the same as in Fig. 3(a).

3) \( T3 \) and \( T2 \) Turn-On and Turn-Off (see Figs. 4 and 5): The circuit analytical equations of \( T3 \) and \( T2 \) turn-on and turn-off are the same as that given in the above parts 1) and 2), by replacing 1, 4, and 5 with 3, 2, and 6, respectively, for switches \( T \) and diodes \( D \), according to the circuit operation in Figs. 4 and 5, which are comparable to Figs. 2 and 3. Analytical waveforms at \( T3 \) and \( T2 \) turn-on and turn-off are, therefore, readily obtained. The analysis shows that \( T1, T3, T5, \) and \( T6 \) are ZCS at turn-off with a turn-on snubber which is similar to the soft switchers in dc–dc converters presented in [11], but \( T2 \) and \( T4 \) are operated with snubber functions for both turn-on and turn-off. Therefore, the active switches in this proposed single-phase inverter are operated with different soft-switching processes at their turn-on and turn-off [12]. In fact, the snubber energy-recovery circuits are replaced by a simple ZCS configuration.

III. DISCUSSIONS

The passive components \( L_s \) and \( C_s \) in the configuration, as the snubber devices, are designed based on initial current and voltage limits \( di/dt = V_{dc}/L_s \) and \( de/dt = I_m/C_s \) for the appropriate power switches. However, according to (2), the following requirement has to be met for \( T1 \) or \( T3 \) to turn off under a ZCS condition:

\[
V_{dc} \sqrt{\frac{C_s}{L_s}} > I_m. \tag{9}
\]

As mentioned above, \( T5 \) turns on and off only with \( I_m > 0 \) and \( T6 \) turns on and off only with \( I_m < 0 \). However, it is not necessary to measure the direction of the load current \( I_m \) to turn \( T5 \) or \( T6 \) on in practical circuits. Instead, the voltage across \( T2 \) and \( T4 \) can be used to determine if trigger signals should be applied to \( T5 \) or \( T6 \), making the control circuit simpler and reliable. That is, if \( u_{T2} > V_0, T5 \) can turn on if necessary, and if \( u_{T4} > V_0, T6 \) can turn on if needed, and generally \( V_0 \gg 0 \). Both \( T5 \) and \( T6 \), including \( D5 \) and \( D6 \), are operated with a low duty cycle, hence, lower power rated devices may be used.

Fig. 7 shows control signals for each active switch in the inverter. The relationship between the control pulses assumes normal SPWM control with modification of the time parameters \( S_1, S_2, S_3, \) and \( S_4 \). \( T5 \) (T6) turn-on pulse must lead the \( T1 \) (T3) turn-off pulse \( S_1 \) which is the resonant interval taken by \( T5 \) to relieve \( T1, T5 \) (T6) on time is \( S_3 \) to allow \( C_s \) charged to \( V_{dc} = V_{dc} \). \( T1 \) and \( T4 \) (T3 and T2, also) turn on at the same time, but \( T4 \) (T2) must turn off after a short delay \( S_2 \) which makes \( C_s \) a good turn-off snubber, after \( T1 \) (T3) turns off. The deadtime between \( T4 \) (T2) turn-off and \( T3 \) (T1) turn-on is \( S_4 \), which is usually seen in normal SPWM control.

The scheme is suitable for power inverters operated under unipolar SPWM control, and

\[
S_1 = \frac{\pi}{2} \sqrt{L_sC_s}, \quad S_2 > S_1, \quad S_1 + S_2 \leq S_3 \leq S_1 + S_2 + S_4. \tag{10}
\]

\( C_s \), as either a snubber capacitor for \( T4 \) and \( T2 \) or a ZCS component for \( T1, T3, T5, \) and \( T6, \) has to completely charge and reverse its charge in each cycle. Unipolar PWM control allows sufficient energy in \( C_s \) to comply with this requirement at both high- and low-load current. During switch turn-on and turn-off transitions there will be a voltage of less than twice dc rail voltage applied on some switches in the inverter, but the proposed configuration realizes a turn-on snubber function and turn-off under a ZCS condition at any load current level.

It should be pointed out that the equations for \( S_1 - S_4 \) given in (10) are used for the control circuit design. However, values can vary provided (9) is met, which is the usual case in practice.
Fig. 8. Simulations at $T_1$ and $T_4$ (a) turn-on and (b) turn-off with load current of 30 A.

Fig. 9. Simulations at $T_1$ and $T_4$ (a) turn-on and (b) turn-off with load current of 3 A.
Fig. 10. Simulations at T3 and T2 (a) turn-on and (b) turn-off with load current of 30 A.

Fig. 11. Experimental results at T1 and T4 (a) turn-on and (b) turn-off with load current of 30 A (time: μs).
It means that the proposed configuration has a wide parameter tolerance which is a weakness of many ZCS and ZVS circuits.

IV. SIMULATION AND EXPERIMENTATION

The simulation waveforms for T1-T6 at turn-on and turn-off are shown in Figs. 8–10, including high- and low-load current cases. The results in Figs. 8 and 9 show ZCS achieved at turn-off for T1 and T5, and a snubber function at turn-on for T1 and T5 and at turn-on and turn-off for T4, with load current of 30 and 3 A, respectively. This advantage of the proposed circuit allows a wide operational range of load current. Fig. 10 shows the waveforms of T3 and T2 at turn-on and turn-off with load current of 30 A. Compared with Fig. 8, it can be seen that T1 and T4 turn-on and turn-off processes are the same as those for T3 and T2, which confirms the circuit analysis. Fig. 11 shows the experimental waveforms for T1 and T4 at turn-on and turn-off with load current of 27 A, and shows that they correspond to the simulation results. Circuit parameter values are: \( V_{dc} = 300 \) V; \( L_s = 9 \) \( \mu \)H; and \( C_s = 0.1 \) \( \mu \)F. The turn-off processes shown in the simulations and experimental results are lengthy, based on (10), but the turn-on processes are fast and there is no overcurrent stress in the main power switches. The comparison of efficiency from a single-phase IGBT inverter system in the laboratory with and without the proposed soft-switching circuit is given in Fig. 12. The soft-switching inverter has its efficiency of 90% at an output power of 1100 W, and it is greatly improved compared with the hard-switched inverter. A small \( R-C \) snubber is used across T1 or T3 in the experiment to protect power devices and its effects on the proposed circuit can be ignored.

V. CONCLUSIONS

This paper has presented a new composite soft-switching single-phase inverter. The proposed configuration realizes snubber functions or resonant ZCS operation for the main and auxiliary switches at any load current. The idea presented here is that soft-switching processes at turn-on and turn-off for each active switch in inverters can be different. The configuration has the advantages of fewer active switching devices and passive components, compared with existing resonant ZCS or ZVS circuits and passive lossless snubbers for dc/ac inverters. Simulations confirmed by experimental results show that the circuit can achieve good protection performance at turn-on and turn-off of all switches. The circuit is suitable for inverter bridge leg modules using a unipolar SPWM control scheme.

This paper has described a new composite soft-switching circuit for a turn-on snubber and ZCS, and a composite configuration of resonant ZVS and lossless turn-off snubber is also possible for power inverters based on the duality principle.

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REFERENCES

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