A Simple Energy Recovery Circuit for High-Power Inverters With Complete Turn-On and Turn-Off Snubbers

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Abstract—This paper presents and analyzes an active energy recovery circuit for the inductive turn-on snubber and capacitive turn-off snubber used on high-power gate-turn-off thyristor inverters. The circuit performs as a simple switched-mode power supply and recovers the inductive and capacitive snubbers energy induced in power inverters back into the dc rail with the aid of an extra switch. The features and operation of the proposed circuit are given and supported by PSpice simulations and experimental results.

Index Terms—Energy recovery, gate-turn-off (GTO) thyristor, inverter, snubber.

I. INTRODUCTION

POWER insulated gate bipolar transistor (IGBT) and gate-turn-off (GTO) thyristor inverters are widely used in various industrial equipments such as power supplies and motor drives. High-power GTO thyristor inverters mandatorily incorporate both an inductive turn-on snubber and capacitive turn-off snubbers. The capacitive turn-off snubber, with \( C_s \) typically 1–4 \( \mu F \), is necessary for safe GTO turn-off. An inductive turn-on snubber, with \( L_s \) typically 5 to 20 \( \mu H \), not only controls GTO \( di/dt \), hence, turn-on loss, but also controls freewheel diode reverse recovery. The energy stored in the turn-on snubber inductor is related to the load current magnitude, \( I_m \), according to \( 1/2 L_s I_m^2 \), while the energy stored in the turn-off snubber capacitor is related to the supply voltage, \( V_{dc} \), according to \( 1/2 C_s V_{dc}^2 \).

The capacitance is usually specified by the GTO thyristor manufacturer, while the turn-on inductor limits the turn-on \( di/dt \) to about 200–400 A/\( \mu s \), according to \( L_s = V_{dc}/di/dt \). Traditionally, the stored energies are dissipated as heat in resistors [1], [2]. In the case of a three-phase inverter the total energy loss for three legs, including diode recovery current \( I_r \) losses, is given by

\[
E_t = \frac{3}{2} C_s V_{dc}^2 + \frac{3}{4} I_m^2 L_s + \frac{3}{2} I_r^2 R_s.
\]  

The total power loss will be significant because it is proportional to the switching frequency. With high voltages at just a modest frequency this power loss also becomes unacceptable because of the loss dependence on \( V^2 \). Numerous snubber configurations have been proposed which attempt to reduce the losses. Those that dissipate the energy are best represented by the Undeland snubber [2], [3], were a judicious circuit arrangement minimizes the energy to be dissipated. However, energy recovery circuits for turn-on and turn-off snubbers of high power GTO inverters are important in further decreasing losses of industrial equipments.

Effective passive recovery snubbers for GTO thyristor inverters are few in number. Some published possibilities exist and they all use a high-frequency transformer to transfer recovered energy into the dc voltage rail [4]–[7]. Recovery into the load seems an unlikely viable possibility since operations would become undesirably load current magnitude dependant. This is because the snubber capacitor energy is fixed by the dc supply and independent of the load current. The major problem for the passive snubber energy recovery in an inverter is the configuration complexity and more power components would be required if the improvements for high frequency transformer saturation or for high secondary diode reverse voltage are made [8], which limit applications of the circuits.

This paper presents a simple circuit for recovering the inductive and capacitive snubber energies, which only require the addition of an extra switch which forms part of a simple switched-mode power supply (SMPS). The features and detailed operational processes of the proposed circuit are given and the PSpice simulations and experimental results are included.

II. ENERGY RECOVERY SNUBBER CIRCUIT

The complete energy recovery turn-on and turn-off snubber for a full-bridge GTO thyristor inverter to be considered, is shown in Fig. 1, which is based on the Undeland snubber. In the Undeland circuit the snubber energy is dissipated in the resistive element \( R_s \), which may be inductive and located remotely although it is possible that only one turn-on inductor be used for three bridge legs. Until now no full passive recovery solutions for the Undeland snubber have been proposed, most probably due to the fact that the temporary stored energy voltage is outside the supply voltage rail limits. Fig. 2 is a bridge leg configuration with a simplified circuit for the proposed snubber, which will be used in analysis. One switch, two diodes, and one inductor form a SMPS in Fig. 2 and snubber energy is transferred into the dc rail. The capacitor \( C_o \) acts as an intermediate store.
for snubber energy. In the case of the active recovery circuit, the magnitude of the capacitance determines which of two possible modes, recovery occurs in. For small $C_o$, the capacitor is discharged to the rail voltage on a cycle by cycle basis, while for $C_o$ large the SMPS is operated so as to maintain a constant voltage greater than $V_{dc}$ on $C_o$ [9]. The constant capacitor voltage mode affords faster snubber reset for a given maximum switch voltage, but at the expense of high semiconductor voltages, hence, losses, at all load current levels. The circuit also requires that $C_o$ be precharged and that the voltage be monitored and maintained to be near constant at all load current levels. The one SMPS step-up inverting chopper can be used for three inverter bridge legs and the switch for this chopper too can have its own snubber energy recovery circuit [9]. The voltage requirement of $C_o$ can be reduced by reconnection to the dc rail. However, in order to fulfill the primary snubber function, with low loop inductance, $C_o$ could be split between the 0 V and dc supply rails.

By adding the diode $D_c$, smaller capacitance $C_o$ can be used, without the need of monitoring or feedback control for the SMPS switch. The operational processes at turn-on and turn-off for the top and bottom devices in the bridge leg can be analyzed in detail by using the method as in [4] and the main equations are given below.

**A. GTO G1 Turns On (see Fig. 3)**

The current in $I_{st}$ with an initial value of zero increases linearly until $i_{st} = I_{st}$, then $C_s$ discharges from an initial value of $V_{dc}$ and $C_o$ charges. The current path is shown in Fig. 3(a). The energy on $C_s$ transfers to $C_o$, causing an overshoot voltage, $V_{os1}$, on $C_o$ and $G2$, which if $C_o \gg C_s$, is given by

$$V_{os1} = \frac{C_s}{C_o} V_{dc}.$$  

The time for energy to transfer from $C_s$ to $C_o$ is

$$t_{st1} = \frac{\pi}{2} \sqrt{\frac{I_{st} C_s}{C_o}} \left( \sqrt{\frac{C_o}{C_s}} + 1 \right).$$  

Then, the SMPS switch for energy recovery turns on, shown in Fig. 3(b), $C_o$ resonates with $I_{st}$ with a peak switch current, $I_{p1}$, given by

$$I_{p1} = \sqrt{\frac{C_s}{L_t}} V_{dc}.$$  

The switch is turned on for a time of at least $t_{d1}$ which is given by

$$t_{d1} = \frac{\pi}{2} \sqrt{\frac{L_t C_o}{I_{p1}}}.$$  

The diode $D_c$ prevents $C_o$ from resonating to a voltage below the dc rail. The current $I_{p1}$ given by (4) freewheels through...
$L_d$, $D_r$ and the switch as $L_d$ maintains the energy $1/2C_sV_{dc}^2$, shown in Fig. 3(c). When the switch is turned off this energy is released into the dc rail via diode $D_r$. The current falls from that given by (4) to zero, linearly in a time $t_{r1}$, given by

$$t_{r1} = \sqrt{L_dC_s}$$

which is independent of the load current. The current path is given in Fig. 3(d).

When the inductor $L_d$ current falls to zero, controlled reverse-recovery current flows through diode $D_r$. The subsequent voltage snap is clamp by $C_o$ to $V_{dc}$ via diode $D_t$, which facilitates recovery onto $C_o$ of diode reverse-recovery energy $1/2L_dI_r^2$.

### B. GTO G1 Turns Off (see Fig. 4)

The initial values of the current in $L_s$ and voltage on $C_s$ at G1 turn-off are $I_m$ and zero, respectively. Turn-off no longer occurs at a fixed voltage and bridge switch losses are lower at all load current levels and equal at maximum load current, for a given maximum overshoot voltage $V_{os2}$ on $C_o$ at turn-off. The switch is turned on a fixed time after a leg switch is commutated, and remains on for a fixed on-period. That is, the SMPS is turned on at time $t_{s2}$ after a GTO thyristor is commutated

$$t_{s2} = \frac{\pi}{2} \sqrt{L_sC_s \left( \frac{C_o}{C_s} + 1 \right)}$$

for a time longer than $t_{x2}$ which is different from that in (5) and given by

$$t_{x2} = \frac{\pi}{2} \sqrt{L_sC_s \left( \frac{C_o}{C_s} + 1 \right)}.$$  \hspace{1cm} (8)

Note that both $t_{s2}$ and $t_{x2}$ are load current magnitude independent. During time $t_{s2}$ all the inductor snubber energy is transferred to $C_o$ and $C_s$, charging them to a voltage $V_p$

$$V_p = V_{dc} + I_m \sqrt{\frac{L_s}{C_o + C_s}}$$ \hspace{1cm} (9)

that is, the overshoot $V_{os2}$ is

$$V_{os2} = I_m \sqrt{\frac{L_s}{C_o + C_s}}.$$ \hspace{1cm} (10)

Fig. 4 shows the current path at G1 turn-off.

During the time $t_{x2}$, $C_o$ resonates with $L_d$ with a peak switch current, $I_{p2}$ given by

$$I_{p2} = I_m \sqrt{\frac{L_s}{I_{x2}}}.$$ \hspace{1cm} (11)

The diode $D_c$ prevents $C_o$ from resonating to a voltage below the dc rail. The current $I_{p2}$ given by (11) freewheels through $L_t$, $D_c$ and the switch as $L_d$ maintains the energy $1/2I_sI_m^2$. When the switch is turned off this energy is released into the dc rail via diode $D_r$. The SMPS switch must be able to commutate the current $I_{p2}$, which is usually less than the maximum load.
current, $I_m$. The current falls from that given by (11) to zero, linearly in a time $t_{r2}$, given by

$$t_{r2} = \frac{I_m}{V_{dc}} \sqrt{L_2 I_2}. \quad (12)$$

Although the reset time $t_{r2}$, unlike $t_{r1}$, is load current magnitude dependent, if necessary the SMPS switch can be turned on before this current reaches zero.

When the inductor $L_t$ current falls to zero, controlled reverse-recovery current flows through diode $D_t$. The subsequent voltage snap is clamp by $C_o$ to $V_{dc}$ via diode $D_t$, which facilitates recovery onto $C_o$ of diode reverse-recovery energy $1/2 L_4 I_2^2$, which is the same as when $G1$ turns on.

The relationship between the control pulses for the SMPS switch and GTO G1 ($V(IGBT)$ and $V(GTO)$, respectively) and the voltage on $C_o$ and current in $L_t$ ($V(C_o)$ and $I(L_t)$, respectively) is shown in Fig. 5. Similar results can be obtained from analysis of the operational processes of the bottom GTO, G2, at turn-on and turn-off.

### III. DISCUSSION

In order to allow energy transfer to $C_o$, when G1 turns on (or off), turn-on of the SMPS switch is delayed for a period $t_s$, such that

$$t_s \geq t_{s1} > t_{s2}. \quad (13)$$

In fact, considering the time $t_i = I_m I_a/V_{dc}$ at turn-on and $t_v = V_{dc} C_o/I_m$ at turn-off which are the times for snubber inductor current from 0 to $I_m$ and snubber capacitor voltage from 0 to $V_{dc}$, respectively, $t_s$ would be slightly larger than that based on (13). The on period for the SMPS switch is fixed as $t_t$ where

$$t_t \geq t_{t2} > t_{t1}. \quad (14)$$

The maximum energy recovery time $t_v$ for $L_t$, peak current $I_p$ in $L_t$ and GTO maximum over shoot voltage, respectively, can be expressed by

$$t_v = \max[t_{r1}, t_{r2}], \quad I_p = \max[I_{p1}, I_{p2}], \quad V_{os} = \max[V_{os1}, V_{os2}]. \quad (15)$$

Let

$$K_L = \frac{I_s}{I_t}, \quad K_C = \frac{C_s}{C_o}, \quad Z_s = \sqrt{\frac{L_o}{C_s}}, \quad T_0 = 2\pi \sqrt{L_o C_s}. \quad (16)$$

In practice, $I_m Z_s < V_{dc}$ and $C_o \gg C_s$ can be assumed. If $T_0$, $V_{dc}/Z_s$ and $V_{dc}$ are the bases for time, current and voltage, so the normalized maximum times, peak current and overshoot...
voltage for $t_s$, $t_t$, $t_r$, $I_{p0}$ and $V_{os0}$ of the circuit are represented by $T_s$, $T_t$, $T_r$, $I_p$ and $V_{os}$, and simply given in (17)

$$T_s = \frac{1}{4} \left( \frac{1}{K_c} + 1 \right)$$

$$T_t = \frac{1}{4} \sqrt{\frac{1}{K_t} \sqrt{\frac{1}{K_c} + 1}}$$

$$T_r = \frac{1}{2\pi} \sqrt{\frac{1}{K_t}}$$

$$I_p = \sqrt{K_t}$$

$$V_{os} = \sqrt{K_{os}}$$  \hspace{1cm} (17)

Figs. 6 and 7 show the normalized time, peak current, and overshoot voltage functions against the inductor ratio and capacitor ratio, which could be the reference for the proposed circuit design. Similar curves can be drawn if $I_{m}$, $Z_s$, $V_{os}$ be assumed.

In the simple case shown in this paper, the SMPS switch turns on with $L_t$ as the snubber inductor and turns off with $C_{os}$ as the soft-clamped capacitor. The turn-off loss for this active switch, although exists, is very small because of the low switch current $I_p$ decreased by $K_t$ value, according to (17). It is usually absorbed by the switch and could be recovered by additional circuits if necessary [9]. However, more components are needed and the circuit would be complicated.

IV. SIMULATIONS AND EXPERIMENTATIONS

Fig. 8 shows PSpice simulation results for the proposed energy recovery circuit at G1 turn-on [Fig. 8(a)] and turn-off [Fig. 8(b)], where for illustrative purposes IGBTs instead of GTOs are used as main power switching devices to confirm that the proposed circuit functions correctly. With $V_{dc} = 300$ V (rail voltage) and $I_m = 22$ A (load current), the main circuit parameters are

$$L_t = 14 \ \mu H \quad C_{os} = 0.1 \ \mu F \quad C_{t} = 1 \ \mu F \quad L_t = 480 \ \mu H$$

from which $t_s$, $t_t$, $t_r$, $I_{p0}$, and $V_{os0}$ can be derived. Fig. 9 shows simulation results at G2 turn-on [Fig. 9(a)] and turn-off [Fig. 9(b)], and both Figs. 8 and 9 are identical, which confirms the above analysis is correct. The recovered energies in one phase leg at the loads of 10 and 22 A are given in Table I, and it shows that the presented snubber recovery circuit is effective at different load conditions.

Fig. 10 shows the experimental waveforms for the circuit. Both G2 turn-on [Fig. 10(a)] and turn-off [Fig. 10(b)] wave-
forms are shown and correspond with simulations. The comparison between simulated and experimental recovery energies is given in Table II, which confirms the theoretical and analysis results very well.

V. CONCLUSION

A new active snubber energy recovery circuit for high-power inverters has been presented. The circuit uses one additional switch to form part of a SMPS and to recover the inductive and capacitive snubber energy into the dc rail. The proposed circuit configuration is simple and suitable for use in GTO thyristor full-bridge inverters, even in three-phase inverters, where the
complete turn-on and turn-off snubbers are essential. The analysis and operational processes of the circuit given in the paper show that it works effectively and has been confirmed by simulations and experimental results.

**REFERENCES**


**TABLE II**

<table>
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<tr>
<th>Im (A)</th>
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<th>Experiment</th>
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<tr>
<td>at turn-on</td>
<td>at turn-off</td>
<td>at turn-on</td>
</tr>
<tr>
<td>Snubber energy (mJ)</td>
<td>4.5</td>
<td>3.4</td>
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<tr>
<td>Recovered energy (mJ)</td>
<td>4.47</td>
<td>3.35</td>
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**Fig. 10.** Experimental results for the proposed circuit at G2 (a) turn-on and (b) turn-off. Top to bottom: $V_{C2}$ 140 V/div; $V_{C3}$ 140 V/div; $I_{Lt}$ 2 A/div.

After seven years as a Lecturer at Imperial College, University of London, U.K., he was appointed to a chair of electrical engineering at Heriot-Watt University, Edinburgh, U.K., in 1986. His teaching covers power electronics (in which he has a text published) and drive systems. His research activity includes power semiconductor modeling and protection, converter topologies and soft-switching techniques, and application of ASICs and microprocessors to industrial electronics.


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