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Design of Bootstrap Power Supply for Half-Bridge Circuits using Snubber Energy Regeneration

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ABSTRACT

This paper deals with a design of a bootstrap power supply using snubber energy regeneration, which is used to power a high-side gate driver of a half-bridge circuit. In the proposed circuit, the energy stored in the low-side snubber capacitor is transferred to the high-side bootstrap capacitor without any magnetic components. Thus, the power dissipation in the *RCD* snubber can be effectively reduced. The operation principle and design method of the proposed circuit are presented. The experimental results are also provided to show the validity of the proposed circuit.

Keywords: Bootstrap circuit, charge pump technique, gate driver, half-bridge circuit, snubber, energy regeneration

1. Introduction

A half-bridge topology is used as a basic building block for power conversion circuits such as single- and three-phase full-bridge converters. However, two isolated power supplies are generally required to control the gates of both high- and low-side power switches because the high-side switch has a floating ground. This is a problem of significance in miniaturizing power converter circuits. The bootstrap and charge pump techniques have been considered as possible solutions to overcome this problem [1]-[5].

A *RCD* snubber has been used to relieve switching stress of a power semiconductor device during a turn-off transition. Its configuration is simple but the power dissipation in the snubber resistor may degrade the efficiency of the power converter. Non-dissipative snubber circuits using energy regeneration have been presented [6], [7]. However, these circuits need additional magnetic components, such as transformers, for energy regeneration from the snubber capacitor.

This paper deals with a bootstrap power supply using snubber energy regeneration for the high-side gate driver of a half-bridge circuit. In the proposed circuit, the snubber capacitor in the low-side power semiconductor switch is utilized for charge pumping to a bootstrap capacitor as well as its original snubbing action. Thus, a simple floating power supply for the high-side switch can be implemented without any magnetic components. Moreover, the power dissipation in the *RCD* snubber can be reduced by the snubber energy regeneration. The operation principle, characteristic analysis and design method of the proposed circuit are presented. The experimental results are also provided to show the validity of the proposed circuit.

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2. Proposed Circuit

2.1 Circuit configuration

Fig. 1 shows a half-bridge leg with the proposed power supply circuit, which consists of the *RCD* snubber (R_s, C_s and D_s), bootstrap circuit (C_b and D_b), zener diode (D_z) and initial charging circuit (D_i and R_i). The MOSFETs are considered for the power semiconductor switches (S_1 and S_2). The low-side gate driver is supplied from the independent DC source (V_{DC}) with a common ground. The details of the low-side circuit are omitted for simplicity.

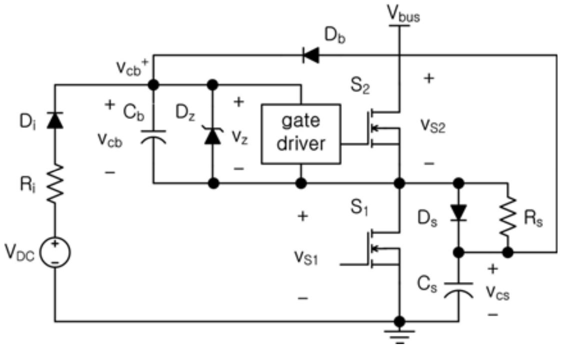


Fig. 1. Configuration of proposed circuit.

2.2 Operation of proposed circuit

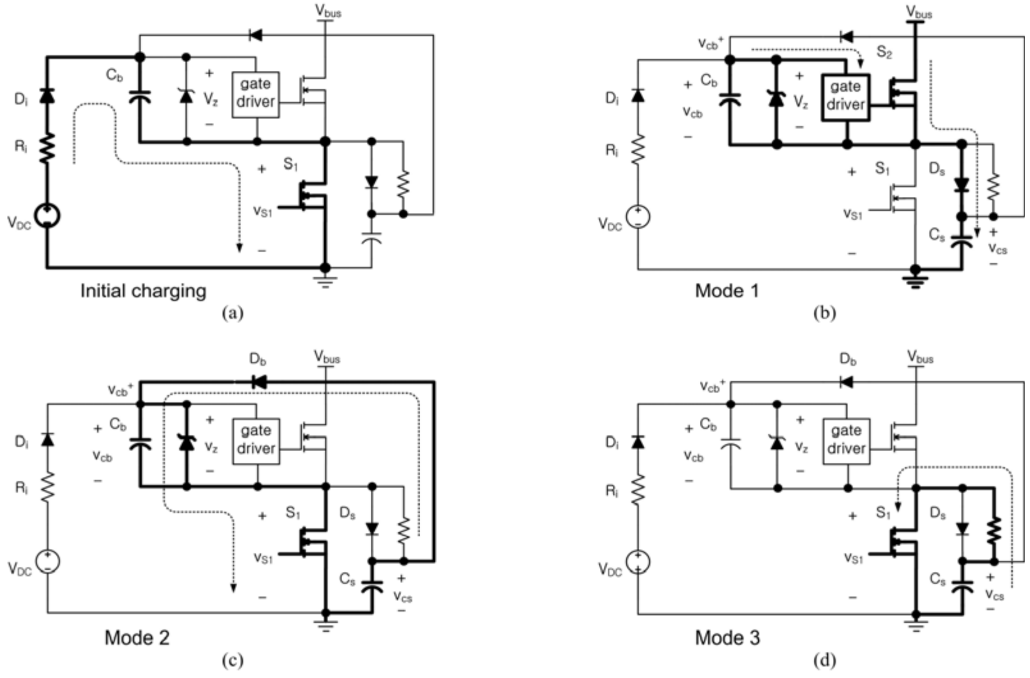
The operation of the proposed circuit can be explained using four operating modes as shown in Figs. 2 and 3. Each operating modes are as follows:

- **Initial charging:** If the bootstrap and snubber capacitors (C_b and C_s) are initially uncharged, it is required to charge one of two capacitors for starting up. As shown in Fig. 2(a), the low-side switch S_1 is first turned-on and C_b is charged by the current supplied from the power supply V_{DC}. The voltage across C_b after the initial charging is given as

$$V_{cb,init} = V_{DC} - V_{Di} - V_{S1(on)} \,. \tag{1}$$

where V_{Di} and $V_{S1(on)}$ denote the on-state voltage drops of the diode D_i and MOSFET switch S_1, respectively.

- **Mode 1 (snubber capacitor charging)**: After S_1 is turned-off, S_2 can be turned-on by using the energy stored in C_b as shown in Fig. 2(b). The voltage across C_b is abruptly dropped as shown in Fig. 3 because the gate charge of S_2 is supplied from C_b. The voltage drop due to the gate charge of S_2 is represented as



(a) (b) (c) (d)

Fig. 2 Four operating modes of proposed circuit. (a) Initial charging. (b) Mode 1. (c) Mode 2. (d) Mode 3.

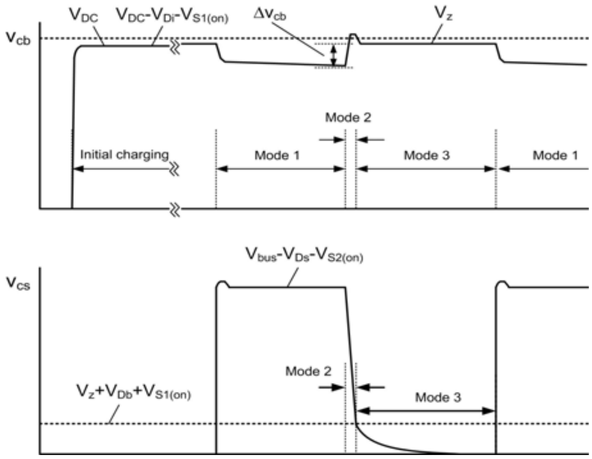


Fig. 3 Voltage waveforms of the bootstrap and snubber capacitors.

$$\Delta v_{cb1} = \frac{Q_g}{C_b} \tag{2}$$

where Q_g is the gate charge of S_2. The capacitor C_s is operated as a snubber during the turn-off transition of S_1 and charged by the bus voltage. The stored charge in C_s is given as

$$Q_{cs} = C_s v_{cs} \tag{3}$$

where v_{cs} denotes the voltage across the snubber capacitor. As the voltage across S_1 increases to the bus voltage, a bootstrap action occurs. The voltage potential at the top of C_b (v_{cb}^+) is highest in the whole circuit. The current to sustain the on-state of S_2 should be supplied from C_b during this mode. Thus, vcb is slightly decreased until the end of this mode due to the leakage and quiescent currents of the connected devices.

- **Mode 2 (charge pumping)**: As shown in Fig. 2(c), S_2 is turned-off and S_1 is turned-on in this mode. The bootstrap capacitor C_b is abruptly recharged by charge pumping from C_s through D_b. The voltage v_{cb} is limited by a zener breakdown voltage V_z. The charge stored in C_b in this mode is given as

$$Q_{cb} = C_b V_z \,. \tag{4}$$

- **Mode 3 (snubber capacitor reset)**: The energy transfer from C_s to C_b is completed when the voltage across C_s is down to $v_{cs} = V_z + V_{Db} + V_{S1(on)}$ and the diode D_b is turned-off. After that, the charge remained in C_s is entirely dissipated to R_s for the next snubbing action.

In the operation of the proposed circuit, the initial charging is needed once, only for starting up. Then, the Modes 1, 2 and 3 are repeated. After the initial charging, V_{DC} is disconnected from the proposed circuit if the zener breakdown voltage V_z is chosen to be satisfied for the condition given as

$$V_z > V_{DC} - V_{Di} - V_{S1(on)} \,. \tag{5}$$

3. Design of Proposed Circuit

3.1 Bootstrap and snubber capacitor values

The values of the bootstrap and snubber capacitors can be calculated using the required charges and leakage currents of the high-side circuit. The amount of the charge required in C_b to sustain the on-state of S_2 during Mode 1 is represented as [1], [2]

$$\Delta Q_{cb} = Q_g + Q_{ls} + \frac{I_{qbs} + I_{lgs} + I_{lcb} + I_{zk}}{f} \,. \tag{6}$$

where Q_{ls} is the charge required in the level shifter of the gate driver. The symbols I_{qbs}, I_{lgs}, I_{lcb}, I_{zk}, and f denote the quiescent current of the gate driver, gate-source leakage current of S_1, leakage current of C_b, bias current of D_z, and switching frequency, respectively. The minimum value of C_b can be determined using (6) as

$$C_b \geq \frac{\Delta Q_{cb}}{\Delta v_{cb}} \,. \tag{7}$$

where Δv_{cb} is the desired ripple voltage in C_b during Mode 1 defined by $\Delta v_{cb} = V_z - V_{cb,\min}$. It is known from (7) that large value of C_b is needed for small ripple voltage. The minimum voltage $V_{cb,\min}$ should be greater than a turn-off threshold voltage of S_2.

Since the charge of C_b is supplied from C_s during Mode

2, the amount of the charge required in C_s can be represented as

$$\Delta Q_{cs} = \Delta Q_{cb} + \frac{I_{lcs}}{f} . \tag{8}$$

where I_{lcs} is the leakage current of C_s. The minimum value of C_s can also be determined using (8) as

$$C_s \geq \frac{\Delta Q_{cs}}{\Delta v_{cs}} \tag{9}$$

where

$$\Delta v_{cs} = V_{bus} - V_{S2(on)} - V_{Ds} - V_{Ds} - V_z - V_{S1(on)} . \tag{10}$$

The symbols V_{Ds} and V_{Db} denote the forward voltage drops of the snubber and bootstrap diodes. The value of C_s also satisfies the snubber requirement. The design of the *RCD* snubber is discussed in [8] and the value of C_s can be given as

$$C_s \geq \frac{I_L t_f}{2V_{bus}} \tag{11}$$

where I_L and t_f denotes the on-state current and turn-off time of the low-side MOSFET switch S_1, respectively.

3.2 Diode ratings

Under the above design, the charge supplied from C_s to the high-side circuit is given as

$$\Delta Q_{cs}' = C_s \Delta v_{cs} \geq \Delta Q_{cs} . \tag{12}$$

Since the charge consumed in the high-side circuit during Mode 1 is ΔQ_{cb}, the excess charge not stored in C_b can be represented as

$$\Delta Q_e = \Delta Q_{cs}' - \Delta Q_{cb} . \tag{13}$$

This charge is dissipated to D_z and S_1. The average power loss by the dissipation of ΔQ_e in D_z and S_1 can be calculated as

$$P_z = \Delta Q_e f \cdot V_z . \tag{14}$$

$$P_{S1(on)} = \Delta Q_e f \cdot V_{S1(on)} = \left(\Delta Q_e f\right)^2 \cdot R_{DS1(on)} . \tag{15}$$

The average currents of the bootstrap and snubber diodes D_b and D_s can be derived, respectively, as

$$I_{Db} = \Delta Q_{cs}' f \tag{16}$$

$$I_{Ds} = Q_{cs} f . \tag{17}$$

The peak current rating is important for the initial charging diode D_i, which is calculated as

$$I_{Di,peak} = \frac{V_{DC} - V_{Di}}{R_i + R_{DS1(on)}} . \tag{18}$$

The peak inverse voltages of D_b, D_s and D_i can also be derived, respectively, as

$$V_{Db,PIV} = V_z + V_{Ds} \tag{19}$$

$$V_{Ds,PIV} = V_{bus} - V_{S2(on)} - V_{S1(on)} . \tag{20}$$

$$V_{Di,PIV} = V_{bus} - V_{S2(on)} + V_z - V_{DC} . \tag{21}$$

3.3 Snubber resistor

In Mode 3, the charge remained in C_s is entirely dissipated in R_s and $R_{DS1(on)}$. Since the value of R_s is much higher than that of $R_{DS1(on)}$, almost all charge remained in C_s is dissipated in R_s. The time constant for resetting the snubber capacitor is given as R_sC_s and generally chosen as five times smaller than the MOSFET on time t_{on} as [8]

$$R_s \leq \frac{t_{on}}{5C_s} \tag{22}$$

The power loss in R_s can be calculated as

$$P_{Rs} = \frac{1}{2} C_s \left(V_z + V_{Db} + V_{S1(on)}\right)^2 \cdot f \tag{23}$$

It is noted that the power loss in R_s is independent to the bus voltage V_{bus}.

4. Experimental Verifications

4.1 Simulation and experimental conditions and device parameters

The experimental study was carried out to show the validity of the proposed circuit. The MOSFET IXFH58N20 and fast recovery diode DSEI8 by IXYS were used for the power switches (S_1 and S_2) and diodes (D_i, D_b and D_s), respectively. The dual gate driver IR2110 by International Rectifiers was used for the gate drivers of S_1 and S_2. The device parameters used in the simulation and experiment are summarized in Table 1.

The capacitor values can be calculated from (6) through (11) as $C_b \geq 93.3$nF and $C_s \geq 9.7$nF for Δv_{cb} = 3V and I_L = 5A. The standard capacitor values with a margin were used in the simulation and experiment as C_b = 100nF and C_s = 22nF. Since metalized polyester capacitors with a small equivalent series resistance (ESR) were used for C_b and C_s, the leakage currents were neglected in this calculation. However, if electrolytic capacitors with a large ESR are used, the leakage currents should be considered. The power dissipation in the snubber resistor R_s is calculated as 0.03W and the resistor of 100Ω/0.25W was used.

Table 1 Experimental conditions and device parameters

	Item	Value
Experimental conditions	f	10 kHz
	V_{bus}	50 V
MOSFET	Q_g	225 nC
	I_{lgs}	100 nA
	$R_{DS(on)}$	40 mΩ
	t_f	90 ns
Zener diode	V_z	15 V
	I_{zk}	250 uA
Fast recovery diode	t_{rr}	35 ns
	V_{Di}, V_{Db}, V_{Ds}	1.0 V
Gate driver	I_{qbs}	230 uA
	Q_{ls}	5 nC

4.2 Experimental results

Figs. 4 through 6 show the experimental results for the proposed circuit. Fig. 4 shows the experimental results when a duty ratio of the high-side switching signal is 50% It is shown in this figure that the proposed circuit operates

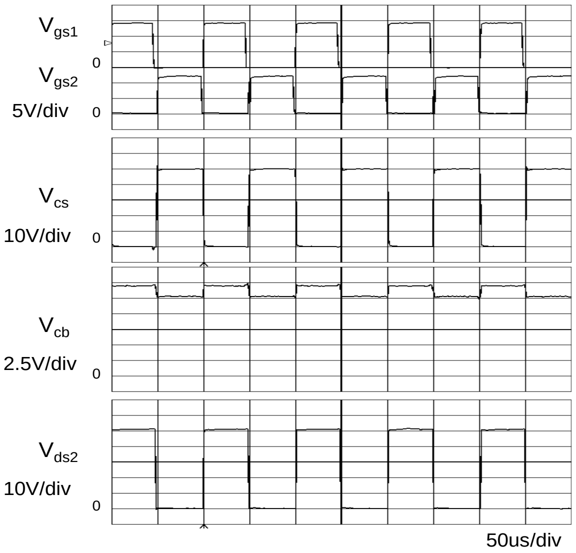


Fig. 4 Experimental results for proposed circuit (duty = 50%)

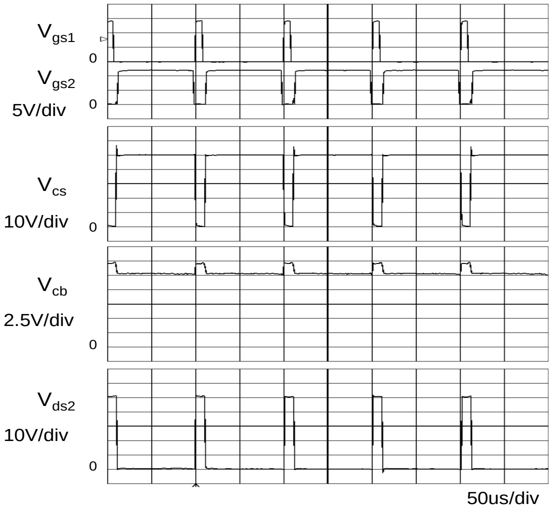


Fig. 5 Experimental results for proposed circuit (duty = 90%)

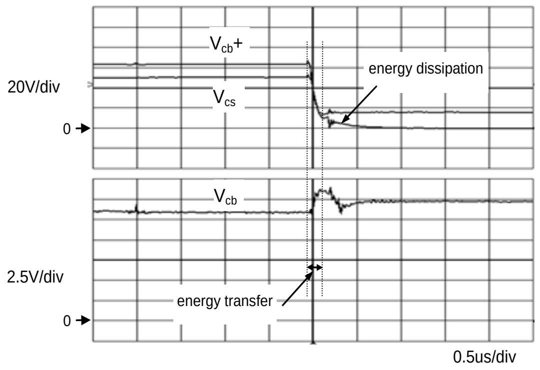


Fig. 6 Energy transfer from the snubber to bootstrap capacitors

well as predicted in the simulation result. The voltage down in C_b is dominant at the turn-on transition of S_2. Thus, it can be known that the gate charge Q_g is the most important parameter in the design of the proposed circuit. It is impossible for bootstrapped power supplies to achieve a duty of 100% because the low-side switch must be turned-on to charge the bootstrap capacitor for one switching interval. Therefore, the operation under a high duty ratio is important for this type of power supply. Fig. 5 shows the experimental results under a duty ratio of 90%. Fig. 6 shows the energy transfer from C_s to C_b during the turn-on transition of S_1, where v_{cb}^+ means the voltage between the top of C_b and common ground. It is shown in this figure that C_b is charged during Mode 2 and Cs is reset during Mode 3.

4.3 Power analysis

The total energy stored in the snubber capacitor for one switching interval is given as

$$W_{cs} = \frac{1}{2}C_s v_{cs}^2 = \frac{1}{2}C_s\left(V_{bus} - V_{s2(on)} - V_{Ds}\right)^2 . \tag{24}$$

In the conventional *RCD* snubber, since the stored energy is fully dissipated to R_s, the snubber power loss P_{ls} can be represented as

$$P_{ls} = P_{cs} = \frac{1}{2}C_s v_{cs}^2 \cdot f = \frac{1}{2}C_s\left(V_{bus} - V_{s2(on)} - V_{Ds}\right)^2 \cdot f . \tag{25}$$

However, the power loss of the proposed circuit is given as

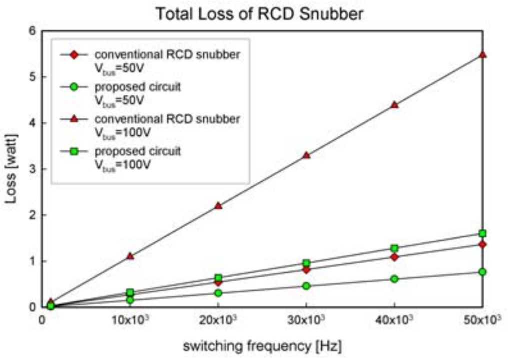


Fig. 7 Losses of conventional *RCD* snubber and proposed circuit (C_s = 22nF)

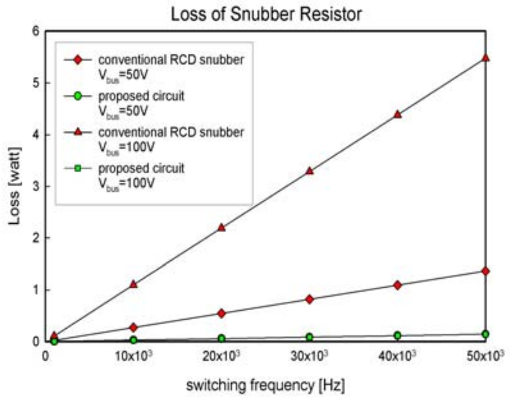


Fig. 8 Losses of snubber resistors in the conventional *RCD* snubber and proposed circuits (C_s = 22nF)

$$P_{lp} = P_{cs} - P_g = P_{R_s} + P_z + P_{S1(on)} . \tag{26}$$

where P_g denotes the power consumption of the high-side gate drive circuit.

Since a part of the stored energy in the snubber capacitor is used for the high-side gate driver, the power loss can be reduced in the proposed circuit. Moreover, the power rating of the snubber resistor is smaller than that of the conventional *RCD* snubber because the only remaining energy is dissipated to the snubber resistor as shown in (23). Fig. 7 shows the loss of the *RCD* snubber and proposed circuit for various switching frequencies and bus voltages. It is shown that the snubber loss is remarkably reduced in the proposed circuit. Fig. 8 shows the loss dissipated in the snubber resistor for both schemes. It is noted that the loss in the snubber resistor is independent from the switching frequency and bus voltage in the proposed circuit because the only remaining charge after the energy regeneration is dissipated to the snubber resistor.

In the proposed circuit, the power losses P_z and $P_{S1(on)}$ are caused by the excess charge ΔQ_e as shown in (14) and (15). Thus, these losses can be reduced by selecting the smaller C_s and a compromise between the efficiency and snubbing effect is needed for the optimum design.

5. Conclusions

The design of a bootstrap power supply for a half-bridge circuit, using energy regeneration from the snubber capacitor, has been considered. The proposed circuit can be simply implemented without any magnetic components. Moreover, the power dissipation in the *RCD* snubber can be reduced by the energy regeneration to the high-side supply. Since the power dissipation in the snubber resistor is remarkably reduced, the power ratings of the snubber resistor can also be minimized. The operation and design method of the proposed circuit were presented and its validity was proved by the simulations and experiments. It is, therefore, expected that the proposed circuit will be used for small-sized and low cost power conversion circuits employing a half-bridge topology.

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