

# 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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Manuscript received July 20, 2007; revised August 14, 2007

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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

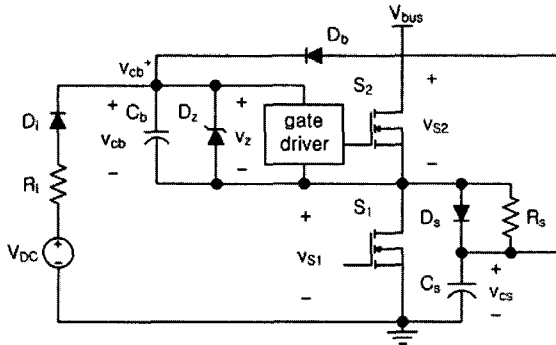


Fig. 1. Configuration of proposed circuit.

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.

### 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

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

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

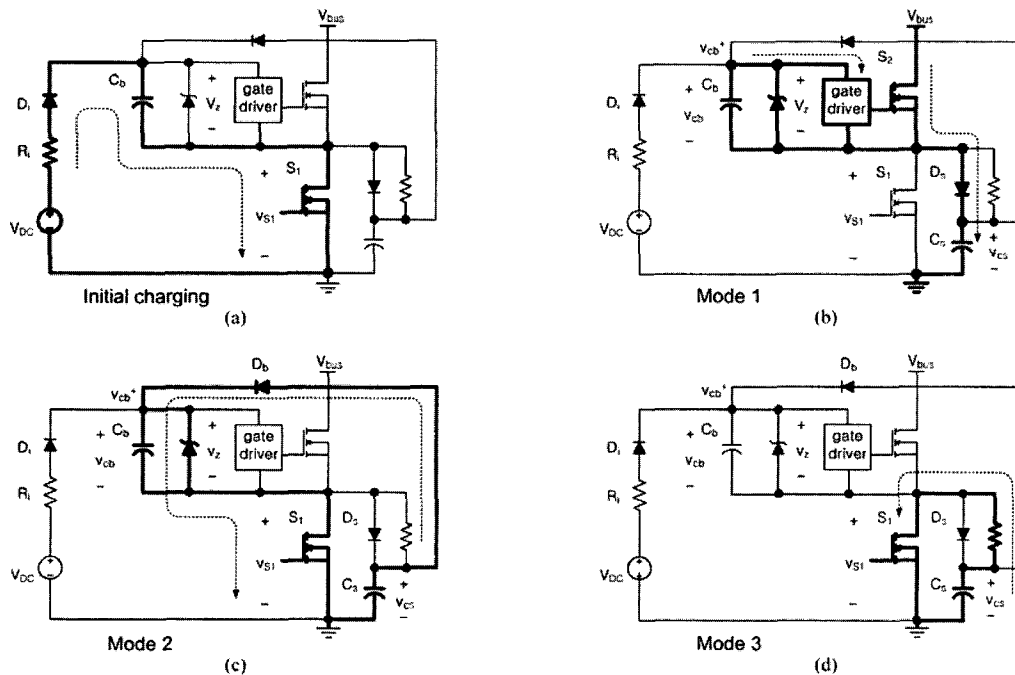


Fig. 2 Four operating modes of proposed circuit. (a) Initial charging. (b) Mode 1. (c) Mode 2. (d) Mode 3.

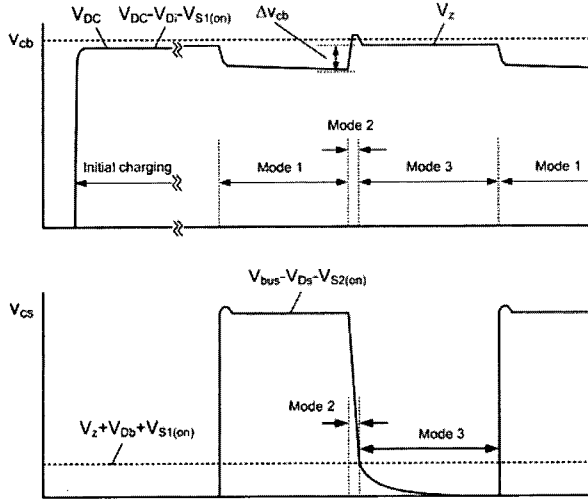


Fig. 3 Voltage waveforms of the bootstrap and snubber capacitors.

$$\Delta v_{cb1} = \frac{Q_g}{C_b} \quad (2)$$

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

$$Q_{cs} = C_s v_{cs} \quad (3)$$

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,  $v_{cb}$  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

$$Q_{cb} = C_b V_z \quad (4)$$

• **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

$$V_z > V_{DC} - V_{Di} - V_{S1(on)} \quad (5)$$

### 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 <sup>[1], [2]</sup>

$$\Delta Q_{cb} = Q_g + Q_{ls} + \frac{I_{qbs} + I_{lgs} + I_{lcb} + I_{zk}}{f} \quad (6)$$

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

$$C_b \geq \frac{\Delta Q_{cb}}{\Delta v_{cb}} \quad (7)$$

where  $\Delta v_{cb}$  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

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

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

$$C_s \geq \frac{\Delta Q_{cs}}{\Delta v_{cs}} \quad (9)$$

where

$$\Delta v_{cs} = V_{bus} - V_{S2(on)} - V_{D_s} - V_{D_b} - V_z - V_{S1(on)} . \quad (10)$$

The symbols  $V_{D_s}$  and  $V_{D_b}$  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

$$C_s \geq \frac{I_L t_f}{2V_{bus}} \quad (11)$$

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

$$\Delta Q_{cs}' = C_s \Delta v_{cs} \geq \Delta Q_{cs} . \quad (12)$$

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

$$\Delta Q_e = \Delta Q_{cs}' - \Delta Q_{cb} . \quad (13)$$

This charge is dissipated to  $D_z$  and  $S_1$ . The average power loss by the dissipation of  $\Delta Q_e$  in  $D_z$  and  $S_1$  can be

calculated as

$$P_z = \Delta Q_e f \cdot V_z . \quad (14)$$

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

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

$$I_{D_b} = \Delta Q_{cs}' f \quad (16)$$

$$I_{D_s} = Q_{cs} f . \quad (17)$$

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

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

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

$$V_{D_b,PIV} = V_z + V_{D_s} \quad (19)$$

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

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

### 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  $R_s C_s$  and generally chosen as five times smaller than the MOSFET on time  $t_{on}$  as [8]

$$R_s \leq \frac{t_{on}}{5C_s} \quad (22)$$

The power loss in  $R_s$  can be calculated as

$$P_{R_s} = \frac{1}{2} C_s (V_z + V_{D_b} + V_{S1(on)})^2 \cdot f \quad (23)$$

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.

Table 1 Experimental conditions and device parameters

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

The capacitor values can be calculated from (6) through (11) as  $C_b \geq 93.3\text{nF}$  and  $C_s \geq 9.7\text{nF}$  for  $\Delta v_{cb} = 3\text{V}$  and  $I_L = 5\text{A}$ . The standard capacitor values with a margin were used in the simulation and experiment as  $C_b = 100\text{nF}$  and  $C_s = 22\text{nF}$ . 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  $0.03\text{W}$  and the resistor of  $100\Omega/0.25\text{W}$  was used.

#### 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

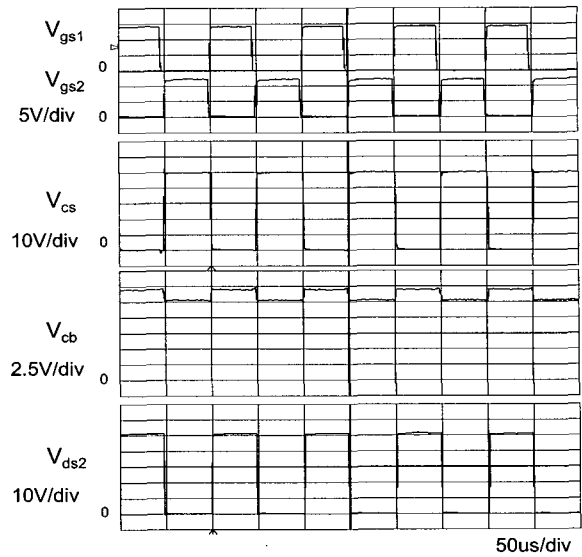


Fig. 4 Experimental results for proposed circuit (duty = 50%)

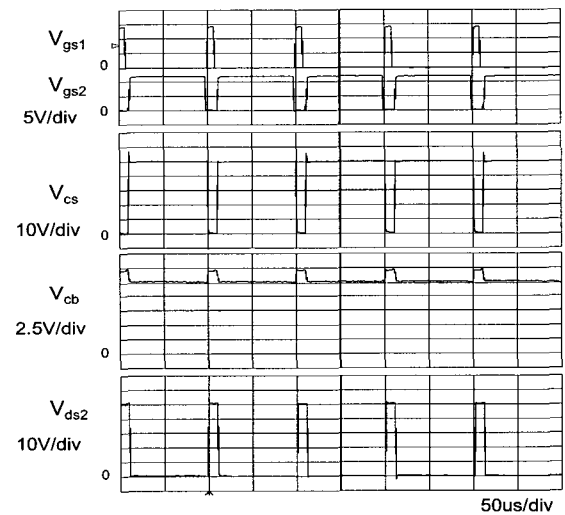


Fig. 5 Experimental results for proposed circuit (duty = 90%)

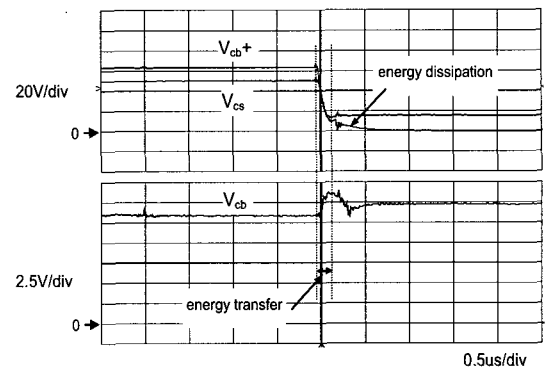


Fig. 6 Energy transfer from the snubber to bootstrap capacitors

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  $C_s$  is reset during Mode 3.

### 4.3 Power analysis

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

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

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

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

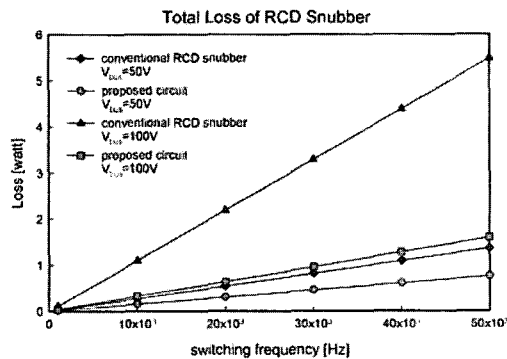


Fig. 7 Losses of conventional *RCD* snubber and proposed circuit ( $C_s = 22nF$ )

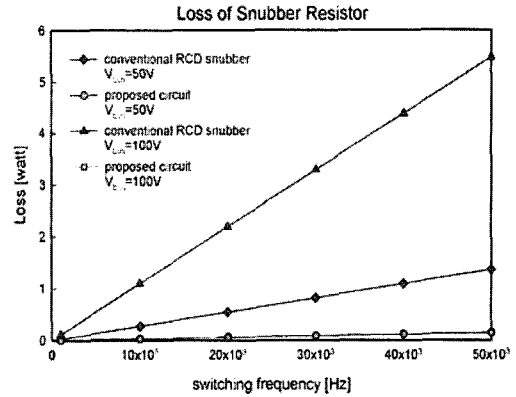


Fig. 8 Losses of snubber resistors in the conventional *RCD* snubber and proposed circuits ( $C_s = 22nF$ )

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

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

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  $\Delta Q_e$  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.

## Acknowledgment

This work was financially supported by MOCIE through the IERC program. The simulation and CAD tools used in this work were supported by IDEC.

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