A PASSIVE LOSSLESS SNUBBER CELL DESIGN FOR AN OHMIC LOADED PWM IGBT CHOPPER FED BY A DIODE BRIDGE FROM AC MAINS

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ABSTRACT

In this paper, it is purposed to design a passive lossless snubber cell that has simple structure, low cost and high performance, for an ohmic loaded PWM IGBT chopper that is fed by a diode bridge from AC mains. This snubber cell reduces switching losses and EMI noise and protects electronic devices against excessive voltage by restricting di/dt and dv/dt of the devices. Finally, operation principles and theoretical analysis of the DC chopper equipped with the designed snubber cell and experimental results of a prototype in the laboratory are presented.

1. INTRODUCTION

Pulse Width Modulated (PWM) DC/DC converters have been widely used in industry because of their high power capability and ease of control. In these converters, higher power density and faster transient response can be achieved by increasing the switching frequency. However, the switching frequency increases, and so do the switching losses and EMI noise [1]. In this reason, operating frequency can be increased by reducing the switching losses through so-called snubber circuits. On-state as well as off-state have a minimum duration of time due to the operating functions of the snubber components [2].

Snubber circuits are fundamentally used to reduce the switching losses and EMI noise and to protect the device against excessive voltage by restricting di/dt and dv/dt of the devices. Generally, di/dt of the current through the switch is limited by an inductor in series with the switch and dv/dt of the voltage across the switch is limited by a capacitor parallel to the switch. They are named as turn-on snubber and turn off snubber, respectively. Unfortunately, these inductor and capacitor cause an additional voltage during turn-off and an additional current during turn-on, respectively [2,3].

2. IMPORTANT FUNCTIONS OF THE DESIGNED SNUBBER CELL

The designed passive lossless snubber cell has the following important functions,

a) simple structure, low cost and high performance
b) approximately zero current switching (ZCS) turn-on and zero voltage switching (ZVS) turn-off

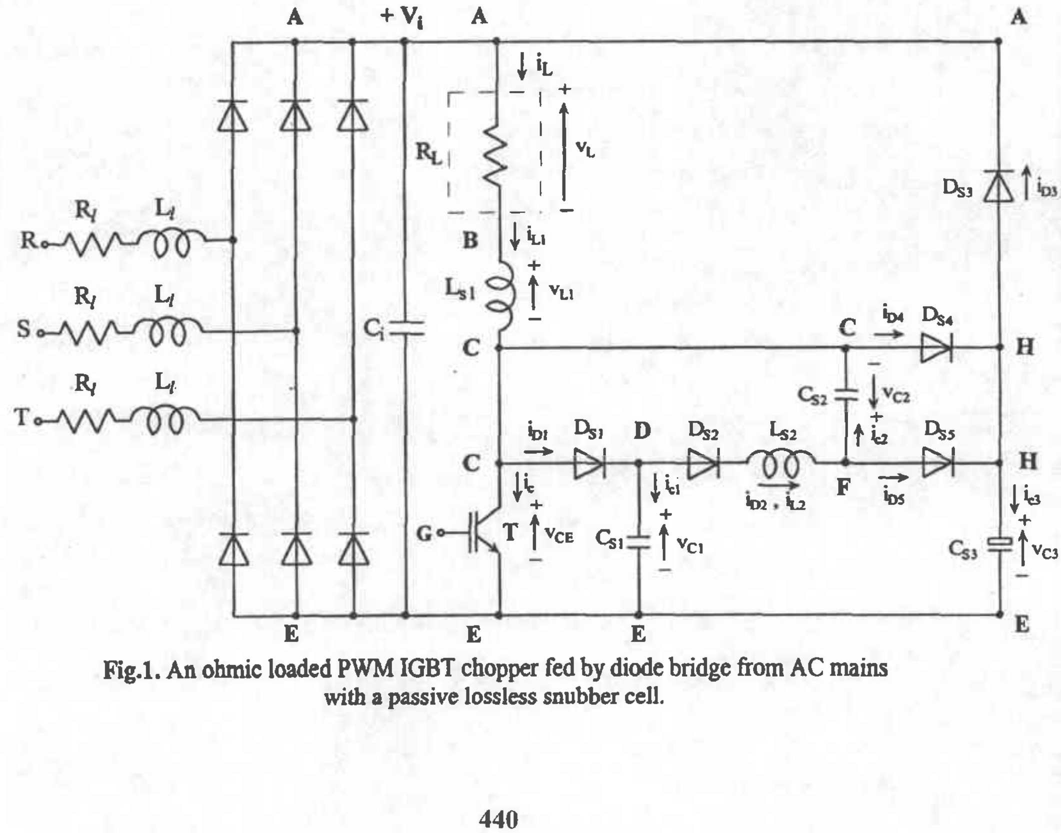

Fig.1. An ohmic loaded PWM IGBT chopper fed by diode bridge from AC mains with a passive lossless snubber cell.

c) overvoltage suppression
d) restriction of di/dt during turn-on and of dv/dt during turn-off
e) ZCS and ZVS for also snubber diodes
f) transfer of snubber energy absorbed in snubber inductor and capacitor to input
g) elimination of switching losses and EMI noise during turn-on and turn-off
h) Reduction of minimum on-state and off-state duration of time
i) possibility of operation at higher frequencies
j) possibility of operation of PWM DC chopper fed from AC mains without problems [3,4,5,6,7].

3. OPERATION PRINCIPLE AND ANALYSIS OF THE DC CHOPPER WITH THE DESIGNED SNUBBER CIRCUIT

The ohmic loaded PWM IGBT chopper fed by a diode bridge from AC mains, which is established with the designed passive lossless snubber cell is shown in Fig.1. Equivalent circuits of this chopper are given for a switching cycle in Fig.2. In Fig.3 operation waveforms for the analyzed DC chopper is given.

$t_0 < t < t_3$ Interval

At $t = t_0$, with the application of drive signal to IGBT, two independent circuits are formed. One of them is load and the other is resonance circuit. Between t_0 and t_3, in Fig.2(b), (c) and (d) circuits, the sum of the load current i_L and resonance current i_{R1}'in flows through IGBT.

In load circuit, $V_{C30} > V_i$, so the capacitor C_{S3} with high value begins to feed the load through the diode D_{S3} first (a). When $V_A \approx V_{C3} < V_i$, the source begins to take on the load current (b). When $V_A > V_{C3}$, diode D_{S3} turns off and the source completely feeds the load (c). Here, the rate of rise of the AC mains current is soft, besides that inductor L_{s1} restricts the rate of rise of the load current.

$V_A = V_i$ can be accepted because of capacitor C_i, so

$$i_L = \frac{V_i}{R_L}(1 - e^{-t/\tau}) \tag{1}$$

$$\tau = \frac{L_{S1}}{R_L} \tag{2}$$

equations can be written. It can be accepted that load current reaches its steady state value about in 3τ time. On the other hand, from C_{S1}-D_{S2}-L_{S2}-C_{S2}-T resonant path, assuming the conditions are ideal,

$$i_{R1} = \frac{V_{C10}}{\omega_{10}.L_{S2}}.\sin\omega_{10}t \tag{3}$$

equation and by accepting $\omega_1 = \omega_{10}$ and $\frac{1}{2.Q_1} = 0$,

$$v_{C1} \cong V_{C10} - V_{C10}.\frac{C_{e1}}{C_{S1}}(1 - e^{-\delta_1 t}.\cos\omega_{10}t) \tag{4}$$

$$v_{C2} \cong V_{C10}.\frac{C_{e1}}{C_{S2}}(1 - e^{-\delta_1 t}.\cos\omega_{10}t) \tag{5}$$

equations can be written. Where

$$\omega_{10} = 1/\sqrt{L_{S2}.C_{e2}} \tag{6}$$

$$C_{e1} = C_{S1}.C_{S2}/(C_{S1} + C_{S2}) \tag{7}$$

$$\delta_1 = R_{e1}/(2.L_{S2}) \tag{8}$$

$$Q_1 = \omega_{10}.L_{S2}/R_{e1}. \tag{9}$$

R_{e1} is defined as equivalent resistor of resonant circuit.

In the resonance circuit, while C_{S2} is charging C_{S1} decharges. If C_{S1}=C_{S2} is taken and losses are neglected, after half resonance cycle, $V_{C13} = 0$ and $V_{C23} = V_{C10}$. In the case of loss, $V_{C23} = -(V_{C10}-V_{C13})$ and v_{C1} doesn't fall to zero. Falling of the voltage v_{C1} to zero can be guaranteed by selecting C_{S1} smaller than C_{S2}. If v_{C1} falls to zero before the half resonance cycle π, resonance continues through D_{S1} diode with C_{S2} capacitor until the energy of L_{S2} inductance becomes zero. At the end of the interval, switching energy stored in C_{S1} capacitor is transferred to C_{S2} capacitor and C_{S1} becomes ready for a new turn-off switching.

At the instant π of the resonance, for $U_{C1} = 0$, C_{S1} must be selected as,

$$C_{S1} \le C_{e1}(1 + e^{-\frac{R_{e1}}{2}.\pi.\sqrt{C_{e1}/L_{S2}}}). \tag{10}$$

At the end of this period, CS2 voltage reaches to,

$$v_{C23} = V_{C10}.\frac{C_{e1}}{C_{S2}}(1 + e^{-\frac{R_{e1}}{2}.\pi.\sqrt{\frac{C_{e1}}{L_{S2}}}}). \tag{11}$$

Half resonance period is

$$t_{R1} = \pi.\sqrt{L_{S2}.C_{e1}}. \tag{12}$$

Mininum on-state duration of time of the DC chopper is calculated as

$$t_{ONmin} = t_{R1}. \tag{13}$$

The IGBT current is

$$i_C = i_L + i_{R1} \tag{14}$$

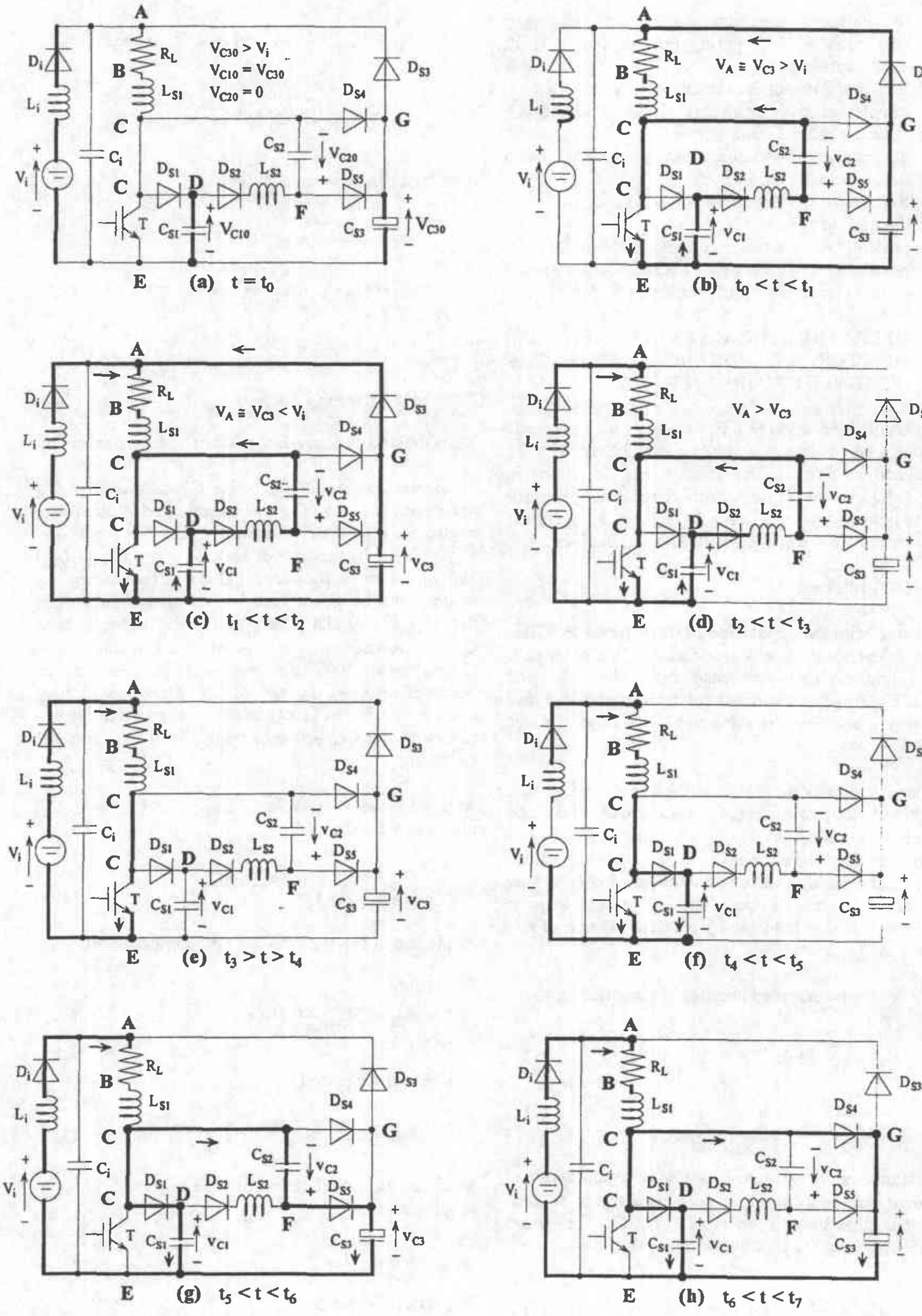

Fig.2. Equivalent circuits during one switching cycle.

and the value of this current at the end of the rise time can be calculated as

$$I_{Ctr} = i_L(tr) + i_{R1}(tr). \qquad (15)$$

This small value of current indicates that ZCS turn-on is provided for IGBT.

$t_3 < t < t_4$ Interval

Load current can be accepted to reach its steady state value, therefore, it can be written as

$$I_L = V_i / R_L. \qquad (16)$$

$t_4 < t < t_5$ Interval

In this interval, which begins with the removal of the IGBT input signal, the load current that is accepted constant in fall time t_f is commutated from IGBT to C_{S1} capacitor linearly. At the end of this interval the voltage of C_{S1} capacitor charged through D_{S1} diode reaches to

$$V_{C15} = \frac{I_L}{2.C_{S1}}.t_f \qquad (17)$$

value and IGBT turns off. This very small voltage value shows that ZVS turn-off is provided for IGBT.

$t_5 < t < t_6$ Interval

In this interval C_{S1} and C_{S2} capacitors become parallel and a new resonance circuit occurs via V_i-R_L-L_{S1}-D_{S1}-C_{S1} and V_i-R_L-L_{S1}-C_{S2}-D_{S5}-V_{C32} paths. In this resonance circuit, C_{S3} capacitor is accepted as voltage source and the amount of voltage changes in the C_{S1} and C_{S2} capacitors are the same. This operation period stops when the CS2 voltage becomes zero, D_{S5} turns off and D_{S4} turns on. At the end of this interval, turn-off switching energy, which is transferred from C_{S1} to C_{S2} before, is transferred from C_{S2} to C_{S3} now.

Expressions of the resonance circuit current i_{R2} and C_{S2} capacitor voltage V_{C2} is given as

$$i_{R2} = e^{-\delta_2 t}\left[\left(\frac{V_{C23}}{\omega_2.L_{S1}} - \frac{I_L}{2.Q_2}\right).\sin\omega_2 t + I_L.\cos\omega_2 t\right] \qquad (18)$$

$$v_{C2} = e^{-\delta_2 t}\left[V_{C23}.\cos\omega_2 t + \left(\frac{V_{C23}}{2.Q_2} - \frac{I_L}{\omega_2.C_{e2}}\right).\sin\omega_2 t\right]. \qquad (19)$$

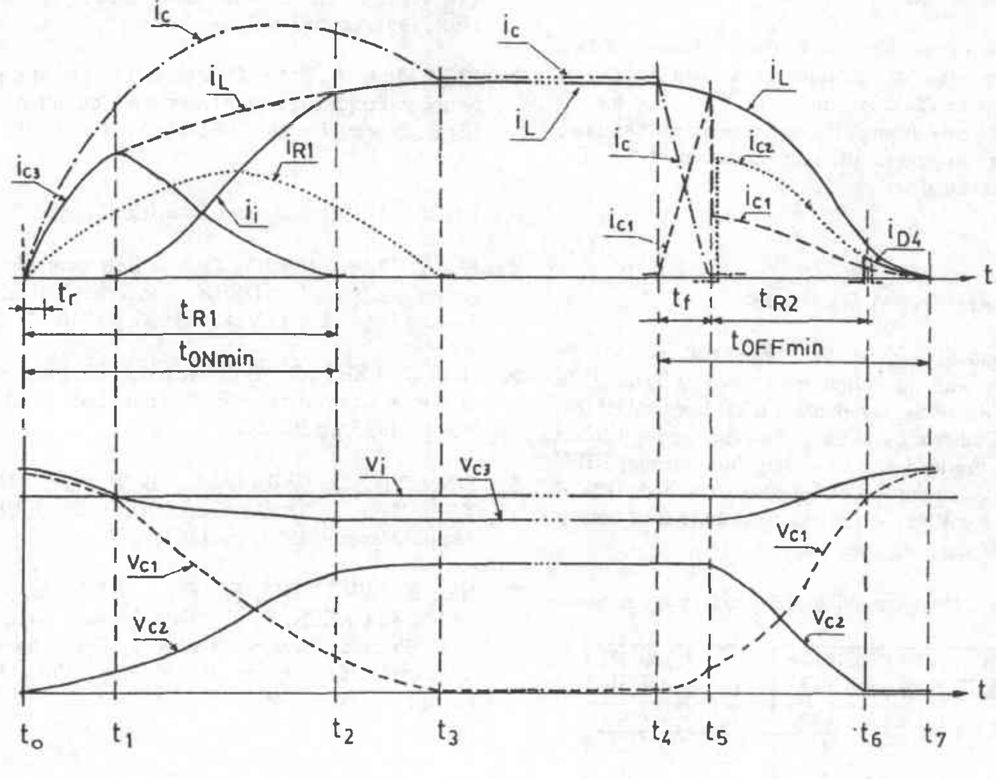

Fig.3. Operation waveforms for the DC chopper in Fig.1.

Here, for $v_{C2} = 0$ can be

$$\alpha_{R2} = \text{inv}\tan\frac{2.\omega_2.L_{S1}.C_{e2}.V_{C23}}{2.L_{S1}.I_L - R_L.C_{e2}.V_{C23}} \tag{20}$$

and this interval of time, if $\alpha_{R2} > 0$,

$$t_{R2} = \frac{1}{\omega_2}\alpha_{R2} \tag{21}$$

if $\alpha_{R2} < 0$,

$$t_{R2} = \frac{1}{\omega_2}(\pi + \alpha_{R2}). \tag{22}$$

In these expressions,

$$\omega_2 = \sqrt{\frac{1}{L_{S1}.C_{e2}} - \frac{R_L^2}{4.L_{S1}^2}} \tag{23}$$

$$C_{e2} = C_{S1} + C_{S2} \tag{24}$$

$$\delta_2 = R_L / (2.L_{S1}) \tag{25}$$

$$Q_2 = \omega_2.L_{S1} / R_L. \tag{26}$$

$t_6 < t < t_7$ Interval

At the end of resonance, with the conduction of D_{S4}, the energy that is possible to remain in L_{S1} is transferred to C_{S3} capacitor until $V_{C3} \geq V_i$., then it circulates freely through D_{S3} and is dissipated on load. Therefore, minimum off-state duration of the DC chopper is calculated as

$$t_{OFFmin} \cong t_f + t_{R2}. \tag{27}$$

3. EXPERIMENTAL RESULTS

The proposed circuit has been realized in the laboratory with the components given in Table 1. In the selection of the components it has been aimed that the IGBT current I_{Ctr} at the end of rise time t_r reached 10 % of the load current during turn-on, and IGBT voltage V_{C15} at the end of fall time t_f reached 10 % of the source voltage, and minimum durations of time at on and off-state becomes 7 µs.

Tablo 1. Component list of experimental circuit.

IGBT	IXSX35N120A	L_{S2}	200 µH
D_i	DSEI20-12A	C_i	470 nF
D_{S1}-D_{S5}	DSEI12-12A	C_{S1}	47 nF
L_i	200 µH	C_{S2}	68 nF
L_{S1}	200 µH	C_{S3}	2,2 µF

The circuit has operated at 500 V and 10 A and various frequencies until 30 kHz succesfully. It has been observed that one switching energy loss was 0,25 mj in the proposed circuit and was 10 mj in the circuit with resistor and capacitor and diode (RCD) snubber. And minimum durations of time of on and off-state were 7,5 µs approximately.

5. CONCLUSION

In this work, a passive lossless snubber cell has been designed for an ohmic loaded PWM IGBT DC chopper fed by a diode bridge from ac mains. Detailed analysis of the DC chopper equipped with the designed snubber has been presented. ZCS turn-on and ZVS turn-off have been achieved by designed snubber cell for IGBT and snubber diodes in PWM DC chopper. di/dt during turn-on and dv/dt during turn-off have been restricted largely by designed snubber cell. Switching energy has been transferred to input with passive components only. A 500 V and 10 A and 20 kHz prototype of DC chopper with designed snubber cell has been implemented in the laboratory and analyses above have been verified.

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