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A Passive Lossless Soft-Switching Snubber for Telecom Power Supplies

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Abstract—At present the majority of power supplies or power converters use switch-mode technology. Higher switching frequencies allow reduction of the magnetic component sizes with PWM switching converters but cause higher switching losses and greater electro-magnetic interference. To reduce these switching losses active or passive soft-switching methods are used in various applications.This paper presents a passive lossless soft-switching snubber for telecom power supplies. Simulation results are given to demonstrate the validity and features of the snubber.

Index Terms—coupling inductor, electrolytic capacitors, Pulse Width Modulation (PWM), soft-switching, zero-current turn ON,zero-voltage turn OFF.

1. INTRODUCTION

Recently, a number of soft-switching PWM techniques were proposed aimed at combining desirable features of both the conventional PWM and resonant techniques. Among them, the zero-voltage-transition (ZVT) PWM technique is deemed desirable since it implements zero-voltage switching (ZVS) for all semiconductor devices without increasing voltage current stresses. This technique minimizes both the switching losses and conduction losses and is particularly attractive for high-frequency operation where power MOSFET's are used as power switches.

The main contributions of the paper include the following.

(a) A passive lossless soft-switching snubber for PWMinverters. Compared with the passive snubbers in [2],[3],[4],[5],[6][7],[8],[11],[12],[13] and [14], it can reliably achieve both zero-current turn ON and zero-voltage turn OFF without extra active, special timing and control so that the reliability of the inverters is higher and the control is simpler.(b)Inductors coupled closely on a single core in the proposed snubber are used to recover snubber energy losslessly to the input and reduce di/dt of power switches during turn-ON transient effectively, which realizes zero-current turn ON. However, in the existing literatures concerning passive snubber for inverters,coupling inductors were only used to recover snubber energy.(c)Superior to passive snubbers for PWM inverters in existing literatures, a novel freewheeling circuit included in the proposedsnubber is used to realize freewheeling of output phase current of inverters in the dead time[1]. Therefore, dead time has less negative impact on output phase current of PWM inverters, which incorporates the proposed passive snubber, compared to hard-switching inverters, especially in low output frequency. In addition, deadtime has no negative impact on soft-switching, which overcomes the drawback of passive snubber in [9] and [10].

2. PROPOSED LOSSLESS SOFT-SWITCHING SNUBBER

A passive lossless soft-switching snubber, which includes two resonant capacitors C_{r1} and C_{r2} , two resonant inductors L_{r1} and L_{r2} , and two center-tapped coupling inductors L_1 and L_4 to reduce the voltage regulation during turn-OFF transient and the current rate of change during turn-ON transient to obtain both zero-voltage turn OFF and zero current turn ON are shown in Fig.1. The feedback diode D_f and a coupling inductor L_f are placed to recover the energy stored in L_1,L_4during commutation of main switches (S_1 , S_4). L_1, L_4 , and L_f are coupled closely on a single core. C_{d0}, C_{d1} , and C_{d2} are the same capacity electrolytic capacitors, each of which bears approximately $1/3$ of dc source voltage V_d. Diode D_1 and D_2 connected across the transformer. It is then connected to a filter circuit in order to reduce the ripple content of the dc output. The ac output from the transformer of the proposed circuit is converted to dc using a rectifier and used in telecom field.

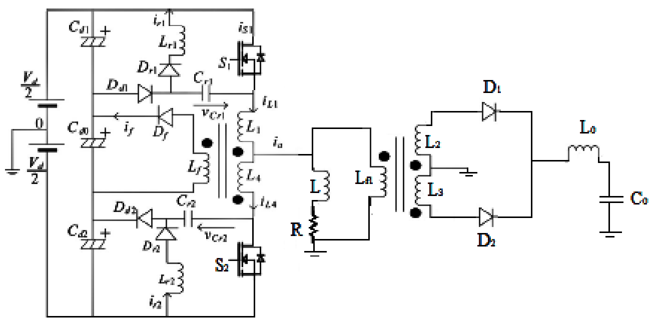

Fig. 1.Proposed passive lossless snubber

3. OPERATING PRINCIPLE

A detailed analysis of circuit can be performed based on operation stage given in Fig. 3. S_1 forward carrying the load current is set as initial condition. The initial value of C_{r1} and C_{r2} are V_{Cd1} and V_{Cd2}. The key theoretical waveform is shown in Fig.2.

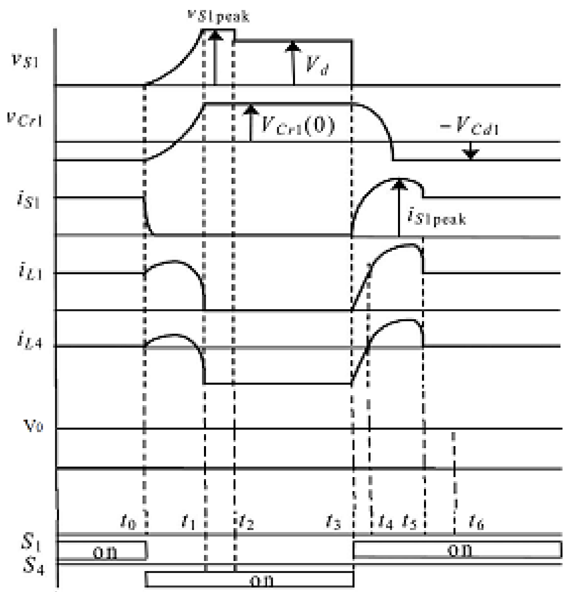

Fig. 2. key theoretical waveform

Stage 1: t < t_0 : S_1 carries load current. That is, $i_{s1} = i_{L1} = i_a$, $V_{cr1} = -V_{cd1}$, $V_0 = \frac{V_d}{2}$. The diode D_1 is forward biased.

Stage 2: t_0 < t < t_1 : S_4 turns on as soon as S_1 turns off at t_0 when $V_{s1} = V_{cr1} + V_{cd1} = 0$. The voltage across S_1 will rise from zero at relatively low rate of change to prevent the voltage jump during turn-OFF transient. The current flowing through S_4 will also rise from zero at relatively low rate of change to prevent the inrush current during turn-ON transient. The current formerly carried by S_1 is shunted by the capacitor path consisting of D_{d1}, C_{r1} , L_1 and the current thus charges C_{r1} .When the voltage across C_{r1} reaches $V_{cr1(0)}$, the operation of the circuit proceeds to stage 3. In stage 2, as soon as S_4 turns on, C_{r2} and L_{r2} begin to take part in resonance and when the voltage across C_{r2} reaches $-V_{cd2}$, the operation of the circuit proceeds to stage 2'.

Stage 2':The diode D_{d2} starts conducting, clamping V_{cr2} to $-V_{cd2}$ in stage 2'. The residual energy in L_{r2} is transferred to C_{d2} and the current flowing through the inductor L_{r2} decrease linearly. When the current decreases to zero, stage 2' ends. Stage 2' is an energy transfer process, which is independent of other stages.

Stage 3: t_1 < t < t_2 : The diode D_f starts conducting, clamping - V_{Lf} to V_{cd0} and C_{r1} to $V_{cr1(0)}$. The energy stored in L_1 and L_4 is recovered to C_{d0} through D_f and L_f . The current I_f flowing in the inductor L_f is decreasing linearly to zero, the operation of the circuit proceeds to stage 4. The diode D_2 is forward biased.

After each stage of operations the diodes D_1 and D_2 is alternatively forward and reversed biased on the polarity appeared at the end of coupled inductors. This is an uncontrolled rectifier and we get a steady DC output. The current flow is represented in each state of operation as shown in Fig. 3

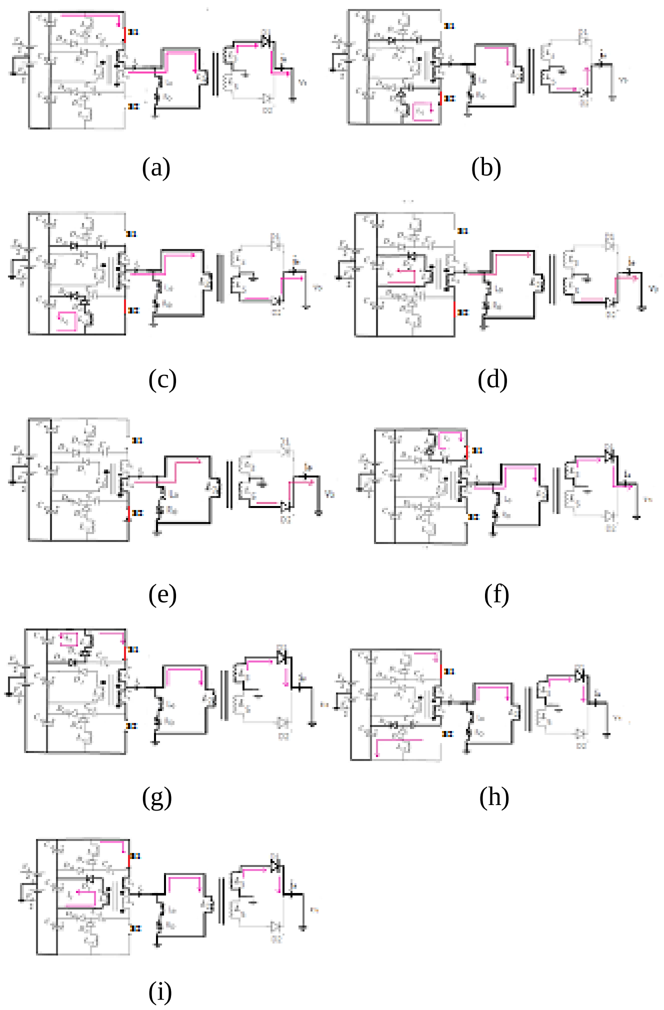

Fig .3. Commutation process. (a) Stage 1, (b) stage 2, (c) stage 2', (d) stage 3,(e) stage 4, (f) stage 5, (g) stage 5', (h) stage 6, (i) stage 7.

Stage 4: t_2 < t < t_3 : The commutation process from S_1 to D_4 ends and the steady stage of D_4 carrying the load current starts, inwhich the voltage across S_1 is V_d.

Stage 5: t_3 < t < t_4 : S_1 turns on as soon as S_4 turns off at t_3. Then the circuit enters commutation process. Because the current is flowing through D_4 , S_4 is zero-voltage switched off. The current flowing through S1 will also rise from zero at relatively low rate of change to prevent the inrush current because of the existence of L_1. L_1 and L_4 undertake voltage $\frac{V_d}{2}$, respectively, so that the current of L_1 increases linearly and the current of L_4 decreases linearly accordingly, which ensures the soft turn ON of S_1 and reduces $\frac{d_i}{d_t}$ in D_4 turn OFF. This stage ends when the current of D_4 is equal to zero. In stage 5, as soon as S_1 turns on, C_{r1} and L_{r1} begin to take part in resonance. The duration of the resonance is equal to the duration of the resonance between C_{r2} and L_{r2} . When the voltage across C_{r1} reaches $-V_{cd1}$, the operation of the circuit proceeds to stage 5'.

Stage 5':The diode D_{d1} starts conducting, clamping V_{cr1} to $-V_{cd1}$. The current flowing in the inductor L_{r1} is also decreasing linearly.

Stage 6: t_4 < t < t_5: The current of L_1 goes on increasing, larger than the load current. Then the current of L_4 starts to rise from zero. C_{r2} is charged until the voltage across C_{r2} reaches $V_{cr2(0)}$. When V_{cr2} is equal to $V_{cr2(0)}$, the operation of the circuit proceeds to stage 7.

Stage 7: $t_5 < t < t_6$:The diode D_f starts conducting, clamping V_{Lf} to $V_{cd(0)}$. At the same time, the voltage across C_{r2} is clamped to $V_{cr2(0)}$.The energy stored inL_1 andL_4 is recovered to C_{d0} through the path composed of $D_f$and L_f. The current I_f flowing in the inductor L_f is decreasing linearly. When $I_f$decreases to zero, the operation of the circuit returns to stage 1 and waits for the next switching period.

4. CONTROL METHOD

Sinusoidal PWM is used to generate PWM signal as shown in Fig.4. For realizing Sinusoidal PWM, a high frequency triangular carrier wave is compared with a sinusoidal reference wave of the desired frequency. The carrier & reference waves are mixed in the comparator. When sinusoidal wave has magnitude higher than the triangular wave, the comparator output is high, otherwise it is low.

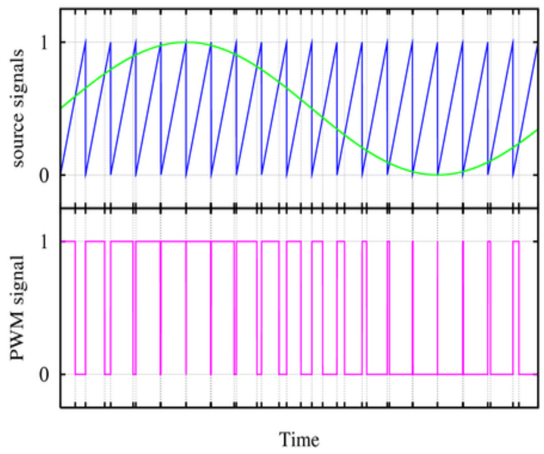

Fig.4. Sinusoidal PWM waveform

5. ANALYSIS AND DESIGN

5.1 Parameter design is based on the following conditions:

1)The rated current and voltage must be higher than maximum current and voltage of main power switches.
2) $L_f$is equal to L_1or L_4 in inductance for analysis simplification andL_1 , L_4 ,$L_f$are coupled closely without leakage inductance.
3)C_{d0}, C_{d1} , and $C_{d2}$are large enough to keep the voltage stable within one period.
4)When power switches are turned off, the $\frac{d_v}{d_t}$must be less than or equal to device critical andwhen power switches are turned on, the $\frac{d_i}{d_t}$must be less than or equal to device critical to achieve zero-voltage turn OFF and zero-current turn ON.

5.2 Calculating Air-Core Inductors:

The approximate inductance of a single-layer air-core coil may be calculated from the simplified formula:

$$L(\mu H) = \frac{d^2 n^2}{18d+40l} \quad (1)$$

Where:
L = inductance in micro henry,
d = coil diameter in inches (from wire center to wire center),
l = coil length in inches, and
n = number of turns.

Example: What is the inductance of a coil if the coil has 48 turns wound at 32 turns per inch and a diameter of 3/4 inch? In this case, d = 0.75, l = 48/32 = 1.5 and n = 48.

$$L = \frac{0.75^2 \times 48^2}{(18 \times 0.75 + 40 \times 1.5)} = 18\mu H$$

To calculate the number of turns of a single-layer coil for a required value of inductance, the formula becomes

$$n = \frac{\sqrt{L(18d \times 40l)}}{d} \quad (2)$$

Example: Suppose an inductance of 10 µH is required. The form on which the coil is to be wound has a diameter of one inch and is long enough to accommodate a coil of 11/4 inches. Then d = 1 inch, l = 1.25 inches and L = 10.0. Substituting:

$$n = \frac{\sqrt{10(18 \times 100) \times (40 \times 1.25)}}{1} = 26.1\text{turns}$$

6. SIMULATION RESULTS

The performance of the topology is evaluated by simulating the circuit in matlab. A Simulink model is developed for a proposed lossless snubber for an inverter phase leg is shown in Fig.5. The output voltage and current waveform are analyzed in detail. Table. 1 shows the parameter used for simulation.

TABLE.1
SIMULATION PARAMETERS

Vd(input voltage)	600V
Cd0,Cd1 and Cd2	500µF
Cr1 and Cr2	500µF
L1,L4 and Lf	100µH
Lr1 and Lr2	200µH
R(load)	10Ω
L(load)	47 µH
Vo(output)	300 V

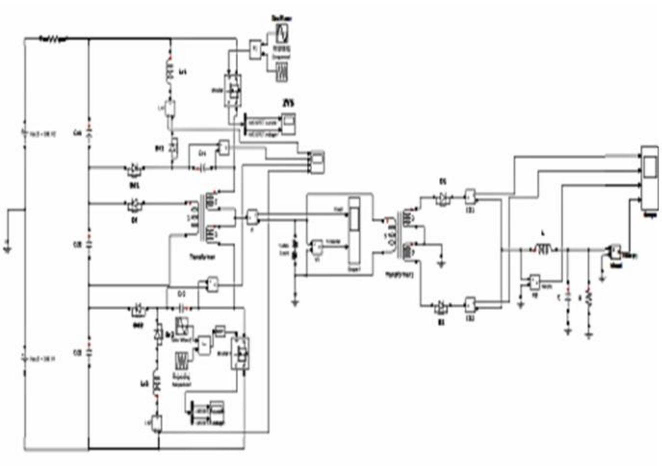

Fig.5. Simulation diagram of a proposed lossless snubber

Since MOSFET is a majority-carrier devices, it exhibits a current tail at turn-off which causes considerably high turn-off switching losses. To operate MOSFET's at relatively high switching frequencies, either the ZVS or the zero-current switching (ZCS) technique can be employed to reduce switching losses. Basically, ZVS eliminates the capacitive turn-on loss, and reduces the turn-off switching loss by slowing down the voltage rise and reducing the overlap between the switch voltage and switch current. This technique can be effective when applied to a fast MOSFET with a relatively small current tail. Fig.6. shows the ZVS of $S_1$and S_2. The output of passive lossless soft-switching snubber produce a 48V DC which is shown in Fig.7

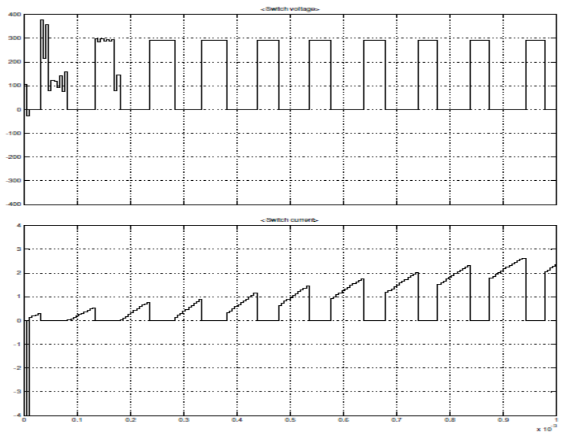

Fig.6. ZVS of $S_1$and S_2.

The transistors (MOSFETs or IGBTs) in leading or lagging leg are turned–on while their respective anti-parallel diodes conduct. Since the transistor voltage is zero during the entire turn-on transition, switching loss does not occur at turn–on.

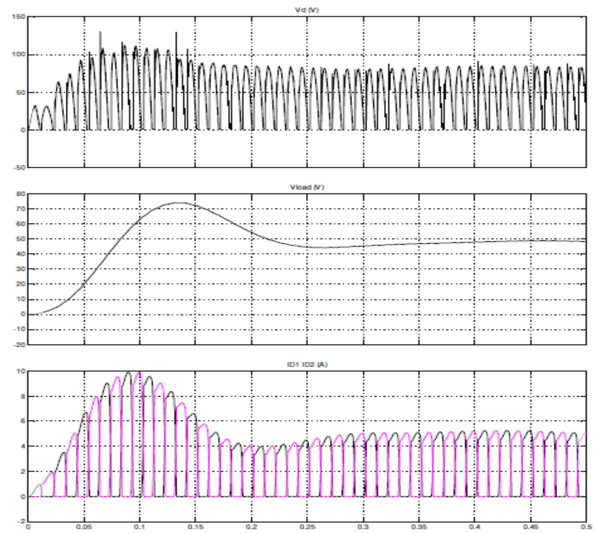

Fig.7. Output waveform

By analyzing the output waveform it is clear that the output voltage and current produced by the circuit is less than the rated voltage and current. The maximum current actually flowing through the resonant inductor and coupling inductor is less than the maximum current allowed to flow through them.

7. CONCLUSION

The passive lossless soft-switching snubber for PWM inverters employs only passive component and they requires no additional control. It realizes both zero-current turn on and zero-voltage turn off and produces lows EMI and improves efficiency because of soft switching. They improves the quality of the output and reduces distortion ratio of output line voltage and phase current, compared with hard-switching inverter and overcomes the negative influence caused by dead time on output phase current of the inverter, especially inlowoutput frequency. Passive soft-switching improves reliability and simplicity of control circuit, compared with the active soft-switching snubber, and makes the total inverter cost lower than the active soft-switching snubber, in view of the total price of components in the inverter. A passive turn-on and turn-off snubber not only should slow the $\frac{d_i}{d_t}$ and $\frac{d_v}{d_t}$ of an active switch but also losslessly recover the zero-current inductor and zero-voltage capacitor energy and maintain a manageable voltage stress across the switches and diodes. All these functions are executed during the switch transition interval. The length of the switch transition interval is dependent on the switch speed, converter characteristics and size of the soft-switching components. The rest of the time, the converter is operating in the normal PWM converter mode. The simulation results have indicated that the soft-switching of power switches can be realized by using the proposed snubber to improve efficiency. Besides, the distortion ratio of output phase current and line voltage can also be reduced. This circuit can be extent to application level like telecom power supplies.

8. FUTURE ENHANCEMENT

The passive lossless soft-switching snubber provides a viable alternative to the existing soft-switching inverters. The passive lossless soft-switching snubber is especially suited for silicon carbide (SiC) device inverters because SiC diodes have no or minimal reverse recovery current, which reduces $\frac{d_v}{d_t}$ uniformly at both turn-on and turn-off to further soften the switching.The passive lossless soft-switching snubber circuits can be widely implemented in power electronics where in no additional active source is requiring for the development of snubbers and it provides a wider scope in $\frac{d_v}{d_t}$ protection and loss free switching of semiconductor switching in inverters which is a major fact when high frequency and high power applications like improving the autonomous underwater vehicle's activity and expand the scope of its navigation. Contactless power transmission technology has been widely spread in recent years. The contactless power transmission system is loosely coupled coupler connection, making the transmission efficiency of the system is greatly reduced.

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