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Brief review on snubber circuits

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Abstract.- This paper presents a summary of the main types of snubber circuits; generally classified as dissipative and non-dissipative or active and passive snubbers. This type of circuits are commonly used because of they can suppress electrical spikes, allowing a better performance on the main electrical circuit. This article intent to describe the currently snubber circuits and its applications without getting into their design.

I. INTRODUCTION

Snubber circuits are reduced component networks applied on switching circuits whose function is to control the effects of circuit reactances. Snubbers enhance the performance on the switching, resulting on higher efficiency, higher switching frequency, smaller size, lower weight and lower electromagnetic interference (EMI). When a snubber is properly implemented, the switch will have lower average power dissipation, lower peak power dissipation, and lower peak operation voltage and current, resulting on less stress on the switch and increasing the reliability and operating life [1].

Power switches need to cut off the load current at turn-on and turn-off times under the hard switching conditions. Hard switching refers to the stressful switching behavior of the power electronic devices. The switching trajectory of a hard-switched power device is shown in Fig.1. During the turn-on and turn-off time, the power device has to withstand high voltage and current simultaneously, resulting in high switching losses and stresses. Dissipative passive snubbers are usually added to the power circuits so that the dv/dt and di/dt of the power devices could be reduced, and the switching loss and stress are diverted to the passive snubber circuits. However, the switching loss is proportional to the switching frequency, thus limiting the maximum switching frequency of the power converters.

In the 1980's, research efforts were diverted towards the use of resonant converters. The concept was to incorporate resonant tanks in the converters to create oscillatory (usually sinusoidal) voltage and/or current waveforms so that zero voltage switching (ZVS) or zero current switching (ZCS) conditions can be created for the power switches. The reduction of switching loss and the continual improvement of power switches allow the switching frequency of the resonant converters to reach hundreds of kilo-Hertz (typically 100kHz to 500kHz) [2].

The most general classification of snubbers may be either passive or active networks. Passive snubbers are limited to resistors, capacitors, inductors and diodes. Active snubbers include transistors and other active switches that often imply extra circuitry. Even though, the classification of snubbers might be related to the way in which the energy is transferred to and from the snubber. If the energy stored in the snubber is dissipated in a resistor the snubber is classified as dissipative but if the energy is moved back to the input or to the output the snubber is classified as non-dissipative. Also; a snubber can be classified as polarized or non-polarized depending on the direction of the energy moves, in or out the snubber and on one or both edges of the switching-control waveform. Other classification of these circuits is the rate of rise of voltage (dv/dt) or voltage clamping; and for current snubbers are all rate of rise control (di/dt) types as there is no passive current limiting device available yet [3]. Finally, other way to classify the snubber circuits is the type of operation, so through the operation type we could shape the load line to keep it within a safe operating area (SOA) for the overload snubbers, and reducing or eliminating voltage or current spikes [4]. On the following sections of this work, a brief explanation of main types of snubbers circuits is described.

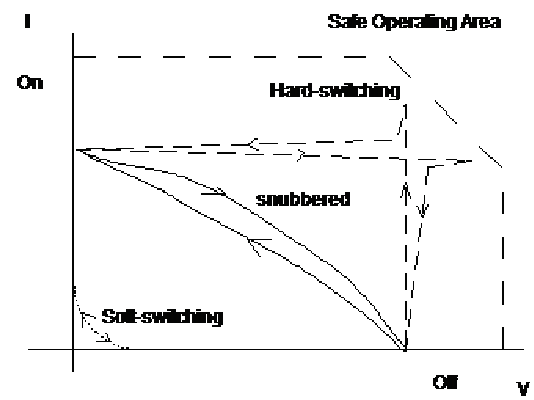

Fig. 1. Hard-switching, snubbered and soft-switching trajectories [2].

II. DISSIPATIVE PASSIVE SNUBBERS

Dissipative snubbers are considered the simplest ones and they can be classified as voltage snubbers (turn-off) and current snubbers (turn-on). The main snubber circuits are the following ones.

Dissipative Voltage Snubbers

RC Voltage Snubber: RC snubber provides a reduction of the parasitic resonance in the power stage. If R and C values

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are correctly chosen, the switching losses reduce up to 40%. Fig. 2a shows the basic RC voltage snubber where the resistor value must be close to the impedance of the parasitic resonance which is intended to damp. The snubber capacitance must be larger than the circuit capacitance where the snubber is applied but be small enough so the power dissipation of the resistor is kept to the minimum [5].

RCD Voltage snubber: A typical application of the resistor-capacitor-diode snubber is to control the dv/dt on the drain or collector of a switching transistor. When the switch turns off, the current flows by the snubber diode to the snubber capacitor until it is charged to the circuit voltage. When the switch turns on, energy stored on the capacitor is dissipated on the snubber resistor, Fig. 2b. The RC time constant needs to be smaller than switching frequency, because the capacitor needs to charge and discharge on each switching cycle.

This snubber is widely applied because of its simplicity and the use of only passive components, but as reviewed on [5], a circuit modification of this configuration is adding a ferrite step-up transformer into the discharge path like in Fig. 2c, it is then possible to return a 70% of the stored energy back to the dc supply.

Dissipative Current Snubbers

The purpose of a current snubber is to control the di/dt and it is often used to control the rate of decrease of current in the turn-on of the main switch. A series inductance allows the switch to fully turn-on by the time the current reaches its operating value.

Simple RL Current Snubber: This circuit is not often used because of its practical point of view. The resistor tends to be really small for good damping of the circuit, which makes the power dissipation high. This circuit is often used on input/output filters where the AC component of the current is relatively small and the resistor provides the necessary damping. The diagram of a RL snubber is shown on Fig. 3a. An example of these snubbers is a ferrite bead which is a RL circuit than can be effective on low power applications [3].

RLD Current Snubber: When a diode is added on series

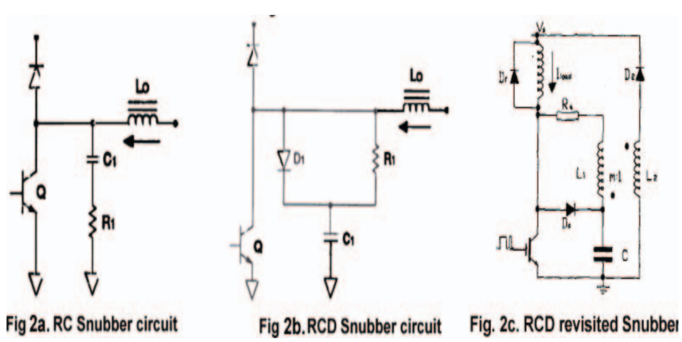

Fig. 2. Main voltage dissipative snubbers [5].

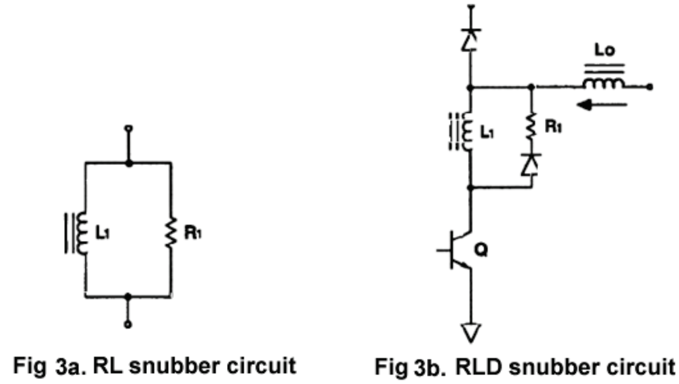

Fig. 3. Main current dissipative snubbers [3].

with the snubber circuit, the resistor reduces its dissipation as it will work on the rising edge of the current waveform. The inductor works normally when the switch turns on and the current flows through the resistor when it is needed to dissipate the energy stored in the inductor. In this scheme is important to take care of the diode reverse recovery current as well as the load current. Figure 3b shows the basic RLD current snubber, but normally this kind of snubber is used with the RCD snubber to have a turn-on and turn-off circuit [3].

III. NON-DISSIPATIVE PASIVE SNUBBERS

Non-dissipative snubbers reuse the energy stored on the snubber elements to the input, the output or just recirculating this energy for the next cycle. All of the non-dissipative snubbers are polarized and they do not provide damping which is by definition a dissipative function in this kind of circuits.

Non-dissipative snubbers are often called resonant circuits, which were studied prior to the availability of fully controllable power switches, due to that thyristors were the major power devices used in power electronic circuits. Each thyristor requires a commutation circuit, which usually consists of a LC resonant circuit, for forcing the current to zero in the turn-off process. With the recent advances in semiconductor technology, the voltage and current handling capability, and the switching speed of fully controllable switches have significantly been improved. However, the use of resonant circuit for achieving zero-current-switching (ZCS) and/or zero-voltage-switching (ZVS) has also emerged as a new technology for power converters. This article will not explain each of the resonant circuits but a main classification of these circuits is shown in Fig. 4 [2].

Non-dissipative Voltage Snubbers

There are only a few non-dissipative voltage snubbers. All of them are polarized and they operate only in one edge of the switching waveform and are reset on the other edge. This kind of snubbers can be really complex by themselves and specially if combined with non-dissipative current snubbers [3].

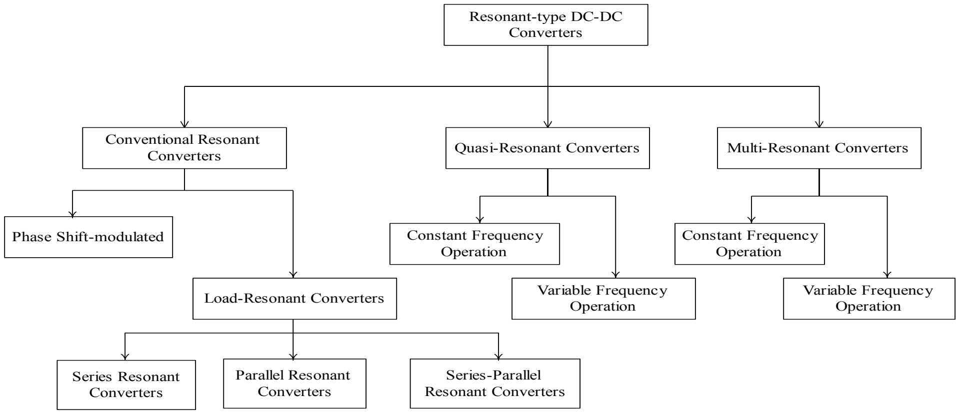

Fig. 4. Resonant circuits classification [2].

Three diode, two capacitors and one inductor configuration

One of the basic voltage snubber is the three diodes, two capacitors and one inductor configuration which can be designed as a two terminal or three terminal circuits. On the two terminal circuits, as shown in Fig 5a [3], which is applicable to the buck, boost and buck-boost converters, generally the two capacitors have the same value. Capacitors and inductor produce a higher resonant frequency than the switching frequency of the circuit.

A brief explanation of the circuit is as follows: at the beginning, the switch Q is off and the capacitors C1 and C2 are discharged. Then the switch Q is turned on and the snubber must rest on in this part of the cycle, here diodes D1 and D2 will turn off and the capacitor will apply Vcc to the inductor L1 because capacitors are discharged. Current will flow through L1 until this current reaches zero and the diode D3 turns off. At this point, both capacitors are charged to Vcc and the snubber is ready to turn off part of the cycle. When the switch turns off, the inductance current from L1 flows to the capacitors and the diodes in series with the capacitors are effectively in parallel controlling the rate of change of voltage across the switch.

Another configuration of the three diodes, two capacitors and one inductor circuit is a three terminal configuration as shown on Fig 5b. This circuit has three terminals and only can be used on the buck, boost and flyback configurations [3]. The operation begins when the switch turns off and C1 is discharged and C2 is charged at Vcc. At this point, D0 is conducting the current of L0. When the switch turns on, the diodes in series with the capacitors stop conducting and Vcc is applied to L1, because C2 is charged to Vcc, the current flows from C2 to C1 through L1 and D3 until C2 is completely discharged. When the switch turns off again the current flows through L0 into the snubber, discharging C1 and charging C2, controlling the dv/dt even if one of the capacitors charges and the other discharges.

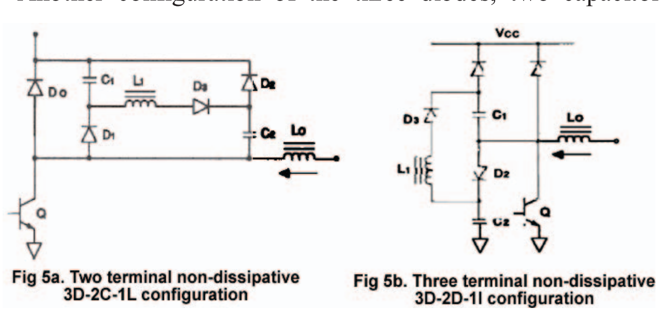

Fig. 5. Three diode, two capacitor and one inductor non-dissipative configurations [3].

Voltage snubber with intermediate voltage: The voltage snubber from Fig. 6 [3], is a three terminals non-dissipative snubber which requires an intermediate voltage, making this converter specially adequate for forward and flyback converters. Also, this circuit is usually used in association with a current snubber for a resonant circuit. The operation mode begins when the switch turns off and C1 is charged to the difference of voltage between V1 and V2 which for example can be the input and output voltages of a boost converter. When the switch turns on again, the capacitor will force the voltage on the inductor snubber be negative, which will ring with the capacitor until the current through the snubber reaches

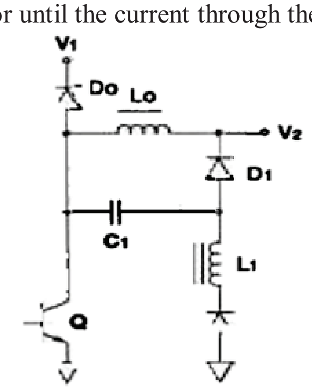

Fig. 6. Voltage snubber with intermediate voltage. [3]

zero. This voltage will be reversed but not be larger thanV2. When the switch turns off once again the current from the inductor will flow into the capacitor through the diode D1 and back to V2 controlling the dv/dt of the circuit. When the voltage is enough to turn on, the main diode and capacitor will charge to the initial state.

Non-dissipative Current Snubbers

Non-dissipative current snubbers are similar to dissipative snubbers but the energy stored on the inductor is transferred back to the source or directed to the output instead of being dissipated. The most common non-dissipative current snubbers are now described.

Flyback reset current snubber: One of the most obvious way to dissipate the stored energy on an inductor is to put an extra winding on it so the energy can be directed anywhere and provides a controlled overvoltage condition. As shown in Fig. 7 [10], the two possible configurations for this circuit are: a buck or flyback circuit (Fig. 7a) or a boost circuit (Fig 7b), where the value of the primary inductance is the same as it would be for a dissipative snubber. The biggest problem with this kind of snubber is that the leakage inductance between the primary and secondary winding of the inductor can cause a large voltage spike on the switch.

Resonant recovery current snubber: The purpose of this kind of snubber is to provide a voltage to reset the snubber inductor to zero current on each cycle. This network is designed to reduce the inductor current as quick as possible to zero and certainly a single diode will clamp the switch voltage but then there would be no voltage across the snubber inductor so it will continue conducting until the switch is turned on again and there would be working as a simple current snubber. The snubber capacitor need to be small so it has a significant voltage change due to energy of the snubber inductor and this capacitor is calculated by the relation between the energy stored of these two elements (1) [6]. Resonant recovery current snubber is shown in Fig 8.

$$\tfrac{1}{2}\mathrm{LI}^2 = \tfrac{1}{2}\mathrm{CV}^2 \therefore \mathrm{C} = \frac{\mathrm{LI}^2}{\mathrm{V}^2} \qquad (1)$$

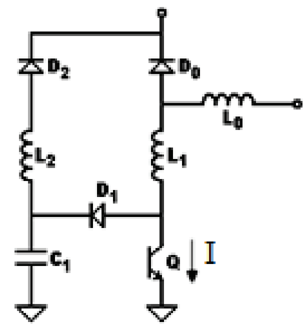

Fig. 8. Resonant recovery current snubber [6]

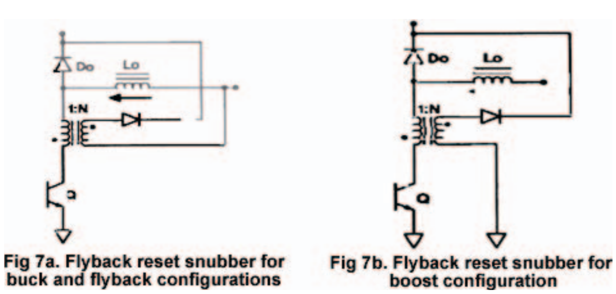

Fig. 7. Flyback reset snubbers [10]

Where I is the current switch when it turns off and V is the voltage change in the capacitor. L is the snubber inductance and C is the snubber capacitance. To have a fast reset, the capacitor should be small. The inductor can have two different values to discharge the capacitor, either large or small. If the inductor value is small, then the resonant frequency will be smaller than the switching frequency and the diode is necessary to limit the resonance. But if the inductor value is large, the resonance frequency will be much greater than the switching frequency and the diode it is not necessary due to the inductor is in continuous conduction and the discharge will be a straight line [6].

IV. Active Snubbers

Active snubbers are those which include switches on their configurations. This makes the design more complex but this kind of topologies are recently being studied to achieve reduction of switching losses. For example, Tantisukarom et al. [8] designed, for low power applications, an inductive snubber to control the di/dt during the ZCS condition and the capacitor discharge over the semiconductor switch to achieve the ZVS condition. Fig 9 shows the ZCS – ZVS active snubber boost converter proposed in [8]. This circuit applies a soft switching and a non-dissipative snubber. As described by the reference, the output voltage can be calculated by (2) and the inductor current ripple by (3), concluding an improvement due to the soft turn off condition of the snubber diode.

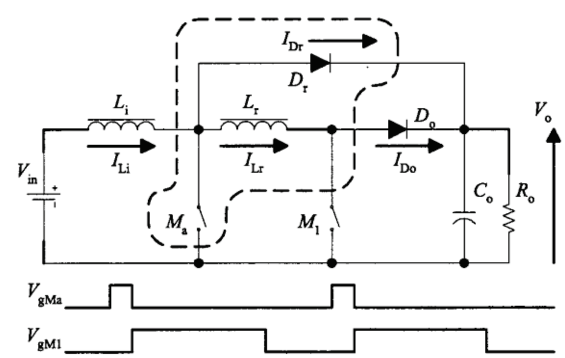

Fig. 9. ZVS and ZCS active snubber with few components on a boost converter [8]

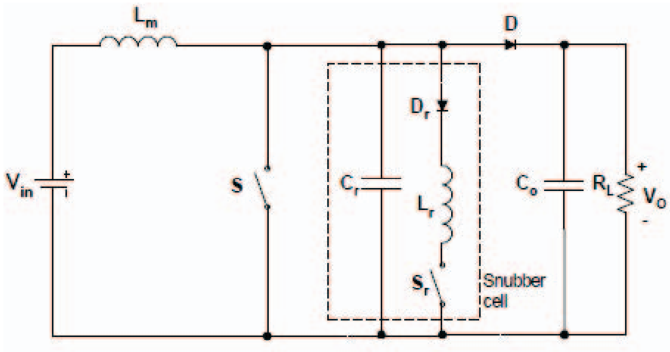

Fig. 10. Active resonant cell circuit [7].

$$V_o = V_{in}\frac{1}{(1-D_{S'})}\frac{1}{1+\frac{L_r}{D_{S'}R_o t_{off'}}} \quad (2)$$

$$\Delta I_{L_i} = \frac{VoTs}{Li}Ds(1-Ds)+\frac{Lr}{Ro} \quad (3)$$

Where $D_S = 1 - t_{off}/t_s$, and R_o is the resistive load.

Jovanovic and Jang research shows that the same design can be used for high-power applications [9]. Where a soft-switching scheme applied to an active snubber helps employing a minimum component count by reducing the reverse recovery losses on the high-power (1kW) boost converter diode. This active snubber employs a snubber inductor, rectifier, and ground-referenced direct drive for the snubber switch, and operates with overlapping gate-drive signals of the boost and snubber switches, which enhances the robustness of the circuit.

Other important active circuit is proposed in [7], see Fig. 10. The general active cell is applied to a boost converter. This circuit applies an active snubber which uses an auxiliary switch to recover the stored energy in the snubber capacitor during turn off of the main switch; also it applies soft switching commutation consequently reducing switching losses and EMI.

V. CONCLUSIONS

After reviewing this article, it is understandable that the snubber circuits can be mainly classified on two big categories: active and passive snubbers. Active snubbers can importantly reduce switching losses but they need extra circuitry to control the active switch making more complex circuits which are not appropriate to all applications due to the added power consumption of the control and active elements, and the increase in complexity of controlling these elements. Passive snubbers are relatively simple to design and they can reduce switching losses so the design needs to be chosen between dissipative or non-dissipative snubbers.

Dissipative Snubbers have fewer components and are relatively less complex but are less efficient, than non-dissipative snubbers because non-dissipative snubbers reuse the energy stored on snubber elements to turn it back to the source, sending it to the load or using this energy to prepare to the next transition of the waveform. The decision on selecting a dissipative snubber and a non-dissipative snubber will come on deciding the cost of elements and power reduction needed, all this to decide between a voltage dissipative snubber (RC and RCD snubbers), current dissipative (RL and RLD snubbers), voltage non-dissipative (3D-2C-1L or intermediate voltage snubber) and current non-dissipative (Flyback reset current or resonant recovery snubber) or a combination of a turn-off and turn-on snubber.

A properly designed snubber circuit will enhance the circuit operation, reducing switching losses, electromagnetic interference, and temperature on elements achieving higher frequency switching, less total components and less weight of the final circuit.

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