# Synthesis Of Lossless Passive Soft-Switching Converters With Defined Characteristics

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***Abstract: This paper derives general topological and electrical properties common to all lossless passive soft-switching converters with defined characteristics and proposes a procedure for the synthesis of new converters. The synthesis procedure uses the properties to determine all possible locations of the inductor and capacitor added to achieve soft switching. Then a set of circuit cells are used to easily add circuitry that recovers the energy stored in these elements. Typically the inductor and capacitor have been placed in series and parallel with the active switch respectively. But many other locations are possible and can lower the component count and reduce switch stress. Furthermore, additional circuitry accompanying the capacitor and inductor is used to recover their energy to either the load or the input. There are many different proposed circuits to accomplish this.***

**Keywords:** power converter, isolated topologies, controllable current, snubbers, Cuk converter.

## I. INTRODUCTION

Active or passive soft-switching methods have been used to reduce these switching losses. Recently, passive soft switching has received renewed inspection as a better alternative to active methods. Passive methods do not require an extra switch or additional control circuitry. They are less expensive, have higher reliability and have been reported to achieve higher performance/price ratios than active methods [1,2]. For PWM converters, passive soft switching reduces switching losses by lowering the active switch's di/dt and dv/dt to achieve zero-current turn on and zero-voltage turn off. Furthermore, by controlling the di/dt of the active switch, the reverse recovery current of the diodes are also controlled. Higher switching frequencies allow reduction of the magnetic component sizes with pulse width modulated (PWM) switching converters. Unfortunately, increased switching frequencies cause higher switching losses and greater electro-magnetic interference (EMI). The switching loss mechanisms include: the current and voltage overlap loss during the switching interval and the capacitance loss during turn-on. The diode reverse recovery also causes an additional conduction loss and further contributes to the current and voltage overlap loss

Typically the inductor and capacitor have been placed in series and parallel with the active switch respectively. But many other locations are possible and can lower the component count and reduce switch stress. Furthermore, additional circuitry accompanying the capacitor and inductor is used to recover their energy to either the load or the input. There are many different proposed circuits to accomplish this. It is the objective of this paper to find general topological and electrical properties that describe these recovery circuits and the placements of the resonant inductor and capacitor to facilitate the creation of new circuits. Furthermore, circuit cells can be constructed that simplify the creation of new soft switching circuits. The two necessary components that must be added to the circuit to achieve passive zero-current turn on and zero voltage turn off are a small inductor and capacitor. The inductor provides zero-current turn on of the active switch and limits the recovery current of the diodes while the capacitor provides zero-voltage turn off of the active switch. However, the topological rules that describe where these components must be place in the circuit have not been proposed in the literature.

## II. LOSSLESS PASSIVE SOFT-SWITCHING CONVERTERS

The switching frequency of this DC-DC power converter using IGBT power modules is selected to be 60 kHz. It is proved experimentally by the power loss analysis that the more the switching frequency increases, the more the proposed DC-DC converter can achieve high performance, lighter in weight, lower power losses and miniaturization in size as compared to the conventional hard switching one. The principle of operation, operation modes, practical and inherent effectiveness of this novel DC-DC power converter topology is proved for a low voltage and large current DC-DC power supplies of arc welder applications in industry. The definitions below first list the components that describe the hard switched PWM converter and then follow with additional components that are added to allow lossless passive soft switching. An essential element of isolated topologies, transformers, have been left out of the hard switched PWM components.

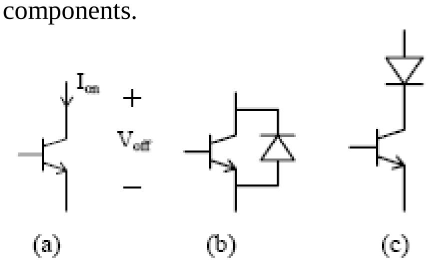


Fig. 1. Active switch implementation: (a) Transistor $I_{on}V_{off}>0$, (b) current bi-directional $V_{off}>0$, (c) voltage bi-directional $I_{on}>0$.

If S is in a loop satisfying the above condition then when S is turned on the switch current rises very rapidly while the switch voltage clamps to a nonzero value until the diodes complete their reverse recovery period. By inserting an inductor into this loop, the switch voltage can drop and the inductor sustains the voltage difference, which creates a controllable current slope. Additionally loops consisting only of S and D are assumed possible in PWM converters when implementing a current bi-directional switch. In this case both devices are represented as a single active switch S. As an example of property 1,

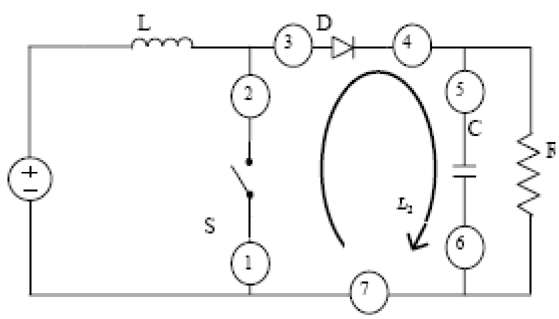


Fig. 2. ZCL locations for boost converter.

Fig. 2 shows the boost converter with loop $L_1$ comprised of elements S, D and C. As shown, there are 7 possible placements of the ZCL to achieve zero-current turn on of switch S. Until now only locations 2 and 3 have been proposed for lossless passive soft-switching boost converters [1,4,5,6,7,8]. However, locations 1 and 4 are viable new placements of the resonant inductor. Although locations 5, 6, and 7 are new and will also provide zero current turn on of S, they will adversely affect the load voltage and feedback control circuitry and so only locations 1-4 are proper.

## III. SYNTHESIS OF PASSIVE LOSSLESS SOFTSWITCHING CONVERTERS

Additional lossless passive components then need to be included to ensure the energy from the ZCL and ZVC is recovered. The number of additional components and their interconnections are virtually limitless. However, this paper proposes several circuit cells that can take each basic topology and realize a lossless soft-switching converter. The topological and electrical properties from Section II simplify the synthesis of lossless passive soft-switching PWM converters. The synthesis process is described for a group of single active switch DC-DC converters and may be extended to converters with more than one active switch. From property 3 and property 7 and the fact that there is only one active switch, only one ZCL and ZVC provide zero-current turn on and zero-voltage turn off of the active switch respectively. The locations of the turn-on inductor Lr and the turn-off capacitor Cr are described as the basic soft-switching topologies for a given hard switched converter. These basic topologies describe all passive soft-switching circuits originating from a given hard switched converter. The steps in the synthesis procedure are as follows:

**Step 1**: Take the element intersection of all loops satisfying property 1. From this set eliminate filter capacitors and the input power source Vs to obtain $L_{loc}$ elements where the inductor can be inserted in series. The number of possible zero-current inductor locations is then $2L_{loc}$, by inserting the inductor on either side so it makes a cut set with the element.

**Step 2**: For each inductor location of step 1, identify the locations of the zero-voltage capacitor sub circuit using the topological part of property 5. Using the sub graph defined in property 6, the number of locations can be found by defining the number of elements in the sub graph on either side of switch $S_i$ as $E_1$, and $E_2$, respectively. The number of capacitor sub circuit locations is a follows:

$$C_{loc} = (1 + E_1)(1 + E_2) \qquad (1)$$

These inductor and capacitor sub circuit locations make up the basic soft-switching topologies.

**Step 3**: For each basic topology match one or more of the given circuit cells to the ZCL and ZVC sub circuit locations to ensure the rest of the topological and electrical properties are satisfied.

Figs 3 shows two circuit cells that satisfy the pertinent turn-on and turn-off properties and also provides minimum voltage stress across the active switches. Among them, cell I has not been proposed in the literature. Cell II can be used to create a soft-switching boost converter shown in [5]. In the circuit cells, Lr and Cr are the ZCL and ZVC to satisfy properties 1 and 5. Ds1 and Cr make up the ZVC sub circuit. Lr also transfers the energy in Cr to Cs. Cs recovers the energy in Lr (property 4) and Cr Diodes Ds1, Ds2, Ds3 transfer the energy in Cs to the load or energy transfer capacitor each switching period and also satisfy property 8. Fig. 10 shows four circuit cells (i.e. cells III, IV, V, VI) that satisfy the pertinent turn-on and turn-off snubber properties but do not maintain the minimum voltage stress across the switch (property 8 not satisfied). For these cells Cs is a relatively large capacitor and stores the inductor Lr and capacitor Cr energy from cycle to cycle.

Elements Cr, Cs, and Ds2 comprise the ZVC sub circuit. Ls is relatively large and transfers the energy in Cs to a subset of (C ÈVs). Cells III and IV can be used to create converters similar to ones presented in [8], however cells V and VI are new.

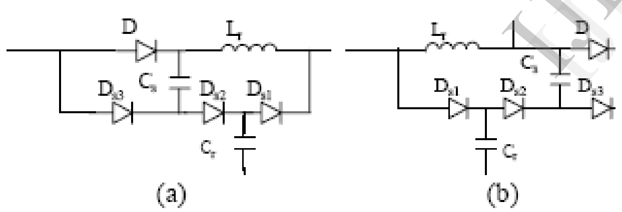


Fig.3. Circuit cells satisfying property 8. (a)Cell I; (b)Cell II

All cells in Figs. 9 and 10 become just turn-on snubbers by removing the capacitor Cr and a diode Ds1. Cells V and VI become just turn-off snubbers by not placing inductor Lr into a loop satisfying property 1. Most basic topologies require only one circuit to provide complete soft switching.

However, a few basic topologies must use two circuit cells, one for a turn-on snubber and one for a turn-off snubber. Cell V needs a slight modification to work as a turn-off snubber when realizing two basic topologies of the Cuk and Sepic converters and one basic topology of the buck quadratic converter. For these topologies the energy transfer capacitor, C, is inserted into the branch containing Cs so it make a cutest with Cs.

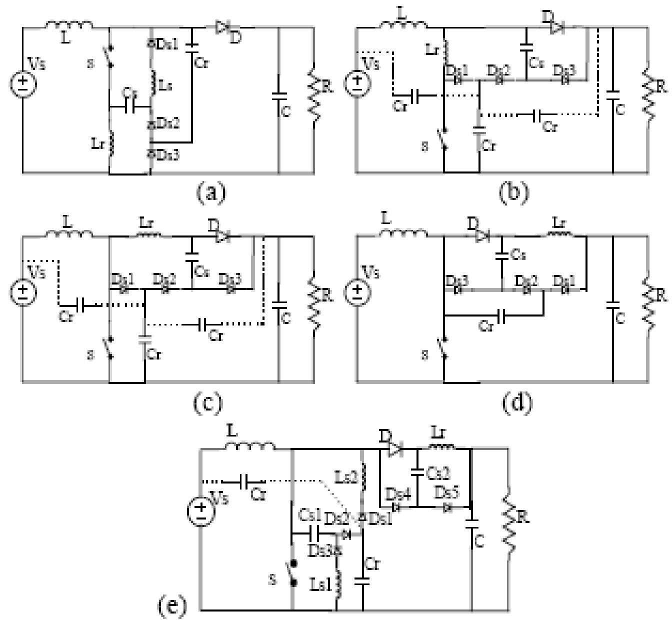


Fig.4. Synthesis results for the boost converter. (a) location L1-1
(b) locations L2-3 (c) locations L3-3 (d) location L4-1 (e) locations
L4-2.

Fig 4 shows the synthesis procedure results for the boost converter. It shows a set of soft-switching circuits, one for each *basic* topology. Each circuit provides both zero-current turn on and zero-voltage turn off of the active switch. Seven of the 10 circuits provide the active switch with the same voltage stress as the hard switched converter. Fig. 4a shows the circuit created using inductor location L1 and the circuit cell VI. Fig. 4b shows three circuits created using inductor location L2 and the circuit cell II. Each different capacitor *Cr* connection creates a different *ZVC sub circuit* location. Fig. 4c shows three circuits created using inductor location L3 and also uses circuit cell II. Here the circuit cell is inserted into the converter slightly differently to adjust for the different inductor location. Fig. 4d shows one circuit created using inductor location L4 and cell I. No other placements of the capacitor sub circuit are possible with this circuit cell. Therefore, Fig. 4e shows the additional two *ZVC sub circuit* locations for inductor location L4. These locations require two circuit cells. The turn-on snubber uses a modified version of Cell I (no Cr and Ds1) and the turn-off snubber uses Cell V.

## IV. A NEW SOFT-SWITCHING CUK CONVERTER.

Experiments with a new soft-switching Cuk Converter shown in Fig. 5 verified theoretical operations. The experimental circuit operated with the following parameters: Fs= 100kHz, $V_s$ = 50v, $V_o$ = 100v, $P_{out}$ = 100W, *Lr* = 4uH, *Cr* = 5nF.

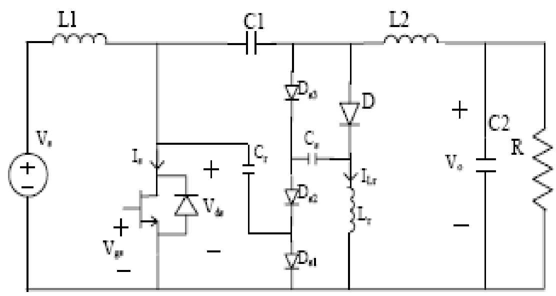


Fig.5. A new lossless passive soft-switching Cuk converter.

Fig. 6 shows the experimental waveforms. Fig. 6a shows the switch voltage and the $I_{Lr}$ current. Notice that the voltage stress across the switch is still 150 volts, the same as the hard switched converter. When the switch turns on the inductor *Lr* resets the *Cr* capacitor voltage to provide zero voltage turn off. Fig. 6(b) shows how *Lr* slows the switch current at turn on. The small current hump at the start is attributed to parasitic diode *Ds1* capacitance that must be charged. Fig 6(c) shows how *Cr* slows the switch voltage rise at turn off.

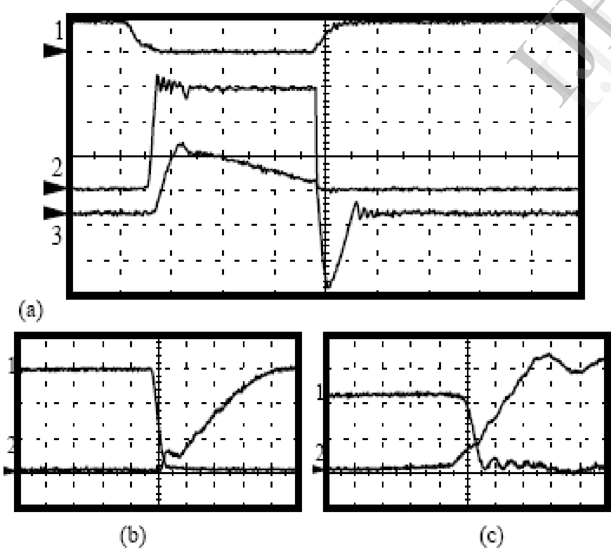


Fig. 6. waveforms for Cuk Converter. (a) Switching cycle. 1: $V_{gs}$ 20v/div; 2: $V_{ds}$ 50v/div; 3: $I_{Lr}$ 2amp/div; horizontal scale: 1us/div. (b) Switch turn on. 1: Vds 50v/div; 2: Is 2amp/div; horizontal scale: 50ns/div (c) Switch turn off. 1: Is 2amp/div; 2: Vds 50v/div; horizontal scale: 50ns/div

## V. CONCLUSION

This paper studies properties common to all lossless passive soft-switching converters that achieve the requirements cited in section IIb. Furthermore, property describes soft-switching converters that do not increase the voltage stress compared to the hard switched converter. These properties ease the development of a synthesis procedure for the creation of new converters. For a number of ZCL and *ZVC sub circuits* a complete set of *basic* soft switching topologies are defined for a given hard switched converter. This set of *basic* topologies describes all passive soft-switching converters for a given hard switched converter. Additional circuitry then needs to ensure the energy stored in these passive elements is recovered. The possible number of circuits to achieve this result is almost limitless, however, they also have many common properties. A set of circuit cells are then described that can be used to synthesis a family of soft-switching converters. As an example, 10 soft-switching boost converters are given and one soft-switching Cuk converter was shown with experimental results.



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