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Resonant switched capacitor voltage multiplier with interleaving capability

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ABSTRACT

This paper presents a switched capacitor voltage multiplier with resonant-type current between capacitors; these current waveforms are achieved by designing a resonant topology combined with a safe switching strategy. Moreover, the proposed converter provides interleaving capability, soft switching, modular structure and a reduced number of components. These features yield a low cost converter with high voltage gain scalability, reduced input current ripple and limited peak currents between capacitors. Experimental results that corroborate the advantages of the proposed topology are presented.

1. Introduction

Nowadays plenty of applications require a power source with high DC output voltage, e.g. insulation testing, X-ray generation, high-voltage DC (HVDC) transmission, and renewable energy source conditioning (e.g. for PV panels, fuel cell stacks, etc.). Consequently, step-up topologies with high output voltage gains are required to satisfy the demands of a high DC voltage bus. Well-known step-up topologies such as the boost converter can theoretically achieve infinite voltage gain when the duty cycle tends to one; however, in practice the leakage resistance of the input inductor limits the efficiency of the converter, hence the practical voltage gain limit is usually specified around four [1,2]. Moreover, the use of extreme duty cycles for high voltage gain purposes undermines the use of high PWM frequencies, due to the inherent switching delays in semiconductor devices [2]. Unfortunately, a limited switching frequency is followed by larger size inductors and capacitors that are used to preserve current and voltage ripple specifications.

In order to overcome the above limitations, several step-up converter topologies that achieve high voltage gains have been proposed. For instance, in [3] an interleaved converter with input-parallel and output series connection characteristics is presented. This converter features a high voltage gain at relatively low duty cycle values; however, its main disadvantages are the large amount of components inherent in the topology and high stress in the semiconductor devices. In [4] a transformer-based high gain interleaved converter that combines a fly-back topology with a traditional boost converter is presented. This converter achieves low switch voltage stress by balancing the output voltage among several devices using switched capacitors; however, the use of a transformer results in a bulky and heavy converter. Other plausible high voltage gain topologies whose advantages/disadvantages can be weighted according to particular applications have been recently proposed in [5–8].

Among the topologies that have been proposed in the literature to achieve high output voltage gains, switched capacitor structures have been considered as a convenient alternative, since they permit high voltage gain configurations, exhibiting other conceivable features such as high power density. Moreover, they are suitable for several applications, see e.g. [8–10].

Switched capacitor converters (SCC) are characterized by its small volume and weight, providing a good integrating capability, since they bypass the requirement of magnetic components such

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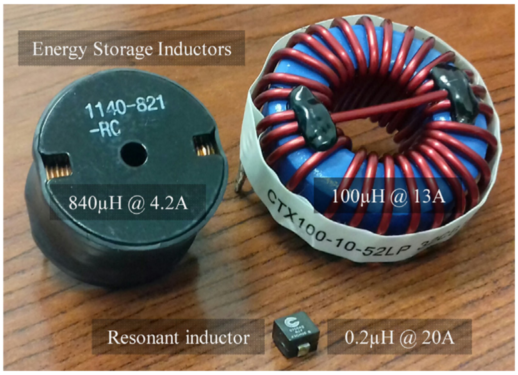

Fig. 1. Size comparison among energy storage and resonant inductors.

inductors and transformers [9,11,12]. As mentioned before, one of the main advantages of switched capacitor circuits is their absence of energy-storage inductors. However, one of the main challenges of pure SC structures is the current peak resulting from the sudden parallel connection of capacitors; for instance, when complete charge interchange is implemented such a current spike may be considerably high and may increase the RMS value of such current and consequently the converter losses.

In order to circumvent this issue, switched capacitor structures are combined with tiny resonant inductors [13–16]. In Fig. 1, we show a comparison between traditional energy storage inductors and resonant inductors. This resonant feature also enables a soft-switching operation with a low switching loss, since they replace the traditional impulsive currents by sinusoidal-like ones [17,18].

In this paper, we propose a voltage multiplier circuit based on the resonant switched capacitor (RSC) principle. The proposed circuit does not contain energy storage inductors, but tiny-size resonant series inductors. This feature enhances the specific power and power density of the converter. The topology can be used as an alternative to transformer-based converters such as fly-back, half-bridge or push-pull, in applications where a high voltage ratio is required but isolation is not mandatory (see e.g. those mentioned in [19,20]). Moreover, the proposed converter has interleaving capability, which implies that it may be modularly constituted by several small converters whose input can be connected in parallel. This property allows scalability to higher power and enables input current ripple reduction.

Our proposed topology is also parsimonious, due to its reduced number of components and low voltage stress in semiconductor devices, which is in sharp contrast with respect to other similar solutions (see e.g. [3]). Furthermore, it is also transformer-free, which represents a significant improvement for practical implementations with respect to other plausible topologies, see e.g. [4]. Finally, current stress is also reduced due to the integration of resonant inductors, pushing forward a technological progression with respect to other early approaches (see e.g. [8–10]). Analytical expressions and experimental results are presented to demonstrate the operation principle of the proposed converter.

The paper is organized as follows. Section 2 introduces the proposed resonant switched capacitor circuit and its operation principle along with important analytical expressions. Section 3 presents several extensions of the proposed circuit. Section 4 presents the experimental validation. Finally, in Section 5 we draw some conclusions of the presented work.

2. Proposed topology

The basic cell of the proposed topology is shown in Fig. 2(a). It contains two transistors (s_1, s_2), two diodes (d_1, d_2), two capacitors (C_1, C_2), and a small resonant inductor (L_r). In practical implementations, L_r is very small compared to energy storage inductors.

The operation of the converter is explained considering four switching states, resulting from the switching action and the inductor current. Transistors switch complementary, i.e., when s_1 is closed, s_2 is open and vice-versa. The circuit operation is introduced by using simulation traces of the resonant inductor current and the input current, see Fig. 2.

State I: Transistor S_1 closes and S_2 is open, see Fig. 2(c). The resonant current i_{L_r} charges capacitor C_1 through d_1 as shown in Fig. 2(b). The current i_{L_r} has ideally a sinusoidal shape, which is traditional in resonant LC circuits, the current must cross zero after a period of time expressed as:

$$t_1 = \pi\sqrt{L_r C_1} \tag{1}$$

After this period the diode d_1 forbids the current to be negative, then the inductor is charged and discharged completely in this state. The diode d_2 remains reverse biased with respect to the voltage across C_2. The output voltage is provided by the series connection of C_2 and the input source; consequently, during this state the voltage in C_2 decreases with a slope equal to I_o/C_2. After this state, C_1 is now charged, if C_1 is big enough its voltage ripple would be small and V_{C_1} is basically equal to V_g.

Fig. 3 shows the typical current waveform during a step transient on a series RLC under-damped circuit obtained by a standard theoretical analysis of dynamical systems. In real circuits small parasitic resistance is present in the loop causing a damping factor ξ to appear, leading to a small deviation from the expected ideal sinusoidal current shape, the diode prevents the current to become negative and then the switching state changes when the current reach zero.

State II: This is a transition state in which S_1 remains closed in a safety delay, as will be explained in Section 2.5, the period of the current may be larger because of the natural deviation of passive components from their nominal value, and because of the parasitic resistance, and then S_1 is left closed during this delay to prevent s_1 to open before the current in the loop is equal zero, see Fig. 2(d).

State III: In this switching state S_2 is closed, which produces a current in the loop shown in Fig. 2(e). In this stage C_1 transfers charge to C_2. At the end of this stage, the voltage across C_2 is equal to $V_{C_1} = V_g$, whereas the voltage across C_1 is equal to $V_C = V_g - ((I_o/C_2)\,\mathrm{D}T_s)$. In this case, there is a current through the resonant inductor during a time:

$$t_3 = \pi\sqrt{L_r \frac{C_1 C_2}{C_1 + C_2}} \tag{2}$$

Note that diode d_2 and switch S_2 form a unidirectional path for the energy transference, this make not possible the transference of energy from C_2 to C_1 and stops the current when it reaches zero.

State IV: This state operates similarly as state II, and acts as a safety delay to prevent opening the loop when the inductor drains some current.

2.1. Differential equations

In this section, we study the dynamics of the proposed converter. We show that safe commutation implies imposing a zero initial condition for differential equation of the current through the inductor at switching instants. Such zero initial condition reveals the operational principle of transfer of charge between capacitors of the converter. We consider the two main dynamic regimes