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Overview of Soft-switching DC-DC Converters

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Article Info	ABSTRACT
	Application of soft switching in DC-DC converter has achieved a remarkable success in power electronics technology in terms of reduction in switching losses, improve in power density, minimization of electromagnetic interference (EMI) and reduction in the volume of DC-DC converters. Quite a number of soft switching techniques had been reported in the past four decades. This paper aims at providing a review of various soft switching techniques, based on topology, the location of the resonant network, performance characteristics, and principles of operation. In addition, converters area of application, advantages as well as limitations are also highlighted.

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1. INTRODUCTION

Load requirements of most electrical equipment are not always compatible with that of sources of electrical energy like photovoltaic cells, utility supply, batteries etc. For electrical equipment to effectively utilize these energy sources, there is a need for an interface between these sources and the receiving end. Generally, the (DC-AC or DC-DC) converter is a popular and commonly used interface for this purpose.

Computers un-interrupted power supplies (UPS), renewable energy systems, vehicle auxiliary power supplies all require a high step-up voltage gain from a DC-DC converter. However, due to the narrow duty cycle of a conventional boost converter, such requirement cannot be met [1], [2]. Achieving a high voltage gain by a pulse width modulated (PWM) DC-DC converter becomes a major problem due to a simple fact that; during turning ON and OFF of the power switches very fast transition of voltage $\left(\frac{\delta v}{\delta t}\right)$ and current $\left(\frac{\delta i}{\delta t}\right)$ occurs on the power switches. These changes may lead to the generation of electromagnetic interferences (EMI) noise which may exceed the permitted level in the power lines. On the other hand, power dissipation will rise during the transition of states resulting from the existence of current through and the voltage across the switches. This happens due to the fact that, in the cause of closing a switch, maximum current through it is established and the voltage across the switch is the same as when it was open. Due to demand for small converter size and high power density, a severe effect can be observed since these converters are required to operate at a high switching frequency [3]-[5]. Furthermore, since losses in these converters increase as a results of increase power dissipation, reducing switching losses significantly increases power density and efficiency of the converters [6]-[11]. To overcome the problems of EMI, switching losses and low efficiency, soft switching techniques is a worthy solution [3], [12]-[14]. High power density, high reliability, reduced

volume and lower ratings of components can be achieved with a high-switching frequency and soft-switching converters [3], [15]-[20].

In soft switching techniques, higher frequency resonant network is added to hard switching topology to shape the switching waveform with the intent of minimizing the switching losses, EMI and switching stress [16], [21]. Two commonly soft-switching methods are; zero-voltage-switching (ZVS) and zero-current-switching (ZCS) [14] respectively. A number of soft-switching using either ZVS or ZCS to reduce switching losses in power converters operating at high switching frequency are reported [12], [22]-[34]. One of the widely used methods of achieving soft-switching is using a resonant tank.

This paper aims to provide a review of various soft-switching techniques, with reference to families, the location of the resonant circuit, mode of connection of the resonant elements and voltage-current waveforms behavior. Three major families' classifications are considered i.e. quasi-resonant converters (QRC), multi-resonant converters (MRC) and resonant transition converters (RTC). The three families are later classified into several categories as discussed in the following topics:

Discussion on the family classification of resonant converters including their different subcategories is given in the second section of this paper. The third section concludes and summarizes the paper.

2.   CLASSIFICATION

Resonant converters are obtained by adding a resonant active snubber to conventional PWM converters for the achievement of suitable combine features of resonant converters and PWM converters [16], [17], [35]. These converters classification are categorized on the basis of the number of reactive elements in the resonant network, location of the elements in the converter, (i.e. load side, or switch side), mode of connection of resonant network (series, parallel or series-parallel), and the behaviour of the switching (ZVS, ZCS). Figure 1; shows the classification of resonant converters and topologies.
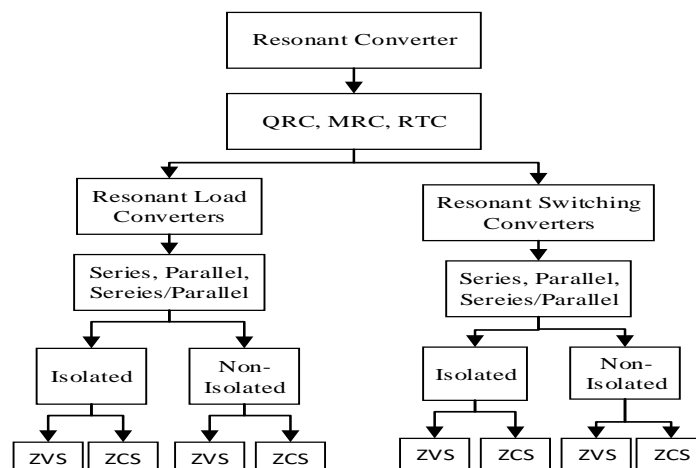

Figure 1. Classification of resonant converters

2.1. Quasi-Resonant Converters (QRC)

These converters are reported in [14], [21], [36], [37]. In principle, QRC consists of only two auxiliary components made up of one inductor and one capacitor(L_r, and C_r). Depending on configuration or converter application, the auxiliary element can be connected in series or parallel or both (series-parallel). In addition, the series-parallel connection can be either with respect to the switch or load of a particular converter. All this is targeted at obtaining ZVS, ZCS, zero voltage transition (ZVT) or zero current transition (ZCT) on either the switch or the diode. This is with respect to how the reactive elements are connected with the switch and diode [38]. However, this configuration, in spite of its simple design and low current stress for the switches, simultaneous soft-switching for both the diode and the switch is not feasible [39]. Furthermore, in ZVS-QRC (single ended), the active switch is subjected to excessive voltage stress [39], [40] which is proportional to the load range. This makes them suitable for low power applications [14] In addition, resonant peak voltage demands highly rated device [41]. Although, the active switch and the diode operates at ZVS & ZCS, the parasitic junction capacitance of the rectifier diode interact with the large resonant inductor, resulting in large noise from switching oscillation. Figure 2 (a) shows ZVS-QRC with a resonant

capacitor (C_r) shunted across the main switch to achieve ZVS while Figure 2 (b) shows ZCS-QRC with resonant inductors (L_1, L_2) connected in series with the switches (S_1 and S_2) to facilitates in ZCS turn-on of the switches.

(a)   (b)
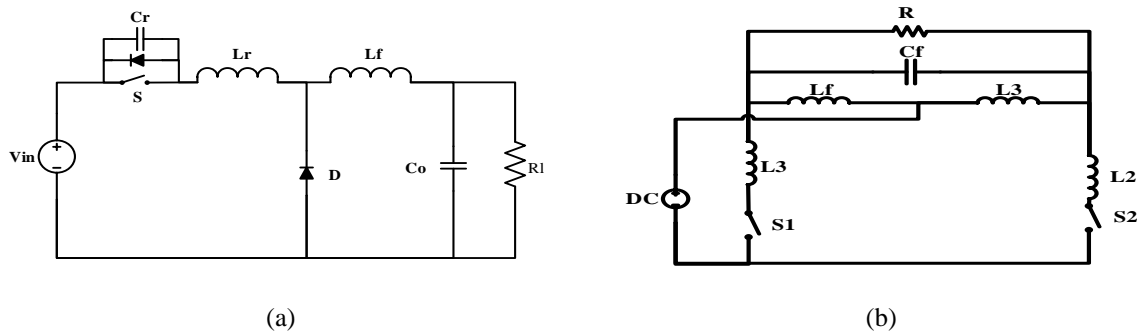
Figure 2. QRC (a) ZVS-QRC [37] and (b) ZCS- QRC [21]

2.2. Multi-Resonant Converters (MRC)

MRCs are modified version of QRC consisting of multiple reactive components as reported in [42]-[46]. The reactive elements composing of two resonating inductors and one resonance capacitor (L_s, L_m and C_s) as depicted in Figure 3. The two modes of connection for achieving ZVS and ZCS is reported in [38]. Depending on the mode of operation, ZVS or ZCS can be simultaneously provided for both the diode and the switch respectively. Hence, MRC are known as double-ZVS or double-ZCS converters. In ZVS-MRC all semiconductor devices operates at zero-voltage switching, thereby, significantly reducing noise and switching losses, at the expense of increased conduction losses, as a result of high circulating current. Consequently, both active and passive switches suffers from voltage and current stresses. These converters are suitable for high frequency operation and in comparison with QRC their voltage and current stress are moderate.
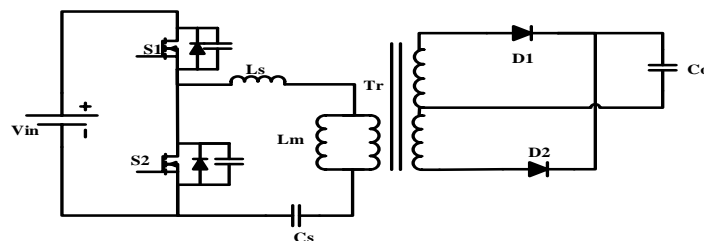

Figure 3. LLC series resonant MRC(45)

2.3. Resonant Transition Converter (RTC) or Zero Transition Converters (ZTC)

RTC utilizes four auxiliary elements consisting of two auxiliary resonant tanks (L, C), and two auxiliary switches. Detailed analysis of these converters can be found in [47]-[50]. RTC is designed to provide zero-current transition (ZCT) [10], [13], [51], [52] or zero-voltage transition (ZVT) as reported in [8], [12], [53]-[55]. ZCT is designed to make the main switch turn-off when the current flow through it is zero. However, ZVT technique is intended to make the main switch turn-on from turn-off state as the voltage across the switch becomes zero. Figure 4 (a) and (b) shows the ZCT and ZVT converters respectively. ZTC are mostly affected by hard switching of the auxiliary switch, limitation in voltage conversion range, high circulating current, high peak current/voltage stress, and additional conduction losses. In addition, resonant transition (RT) PWM converters operate near boundary conduction mode, allowing an additional resonant transition phase to bring the switch voltage to zero [20], [41]. Achievements of true zero voltage switching (ZVS) by the majority of these converters is only possible across limited voltage range. Table 1 summarises some of the advantages and disadvantages of QRC, MRC, and RTC as well as their associated losses and stresses. Furthermore, Table 2 is a summary of three major families of soft-switching converters, with respect to the number of count of the auxiliary components (L, C) in each family as well as their corresponding

auxiliary switch. It can be confirmed from Table 1 that RTC has a higher number of auxiliary components in comparison with QRC and MRC respectively. Consequently, Table 3 gives general remarks on the soft-switching condition of the three families of the converter.
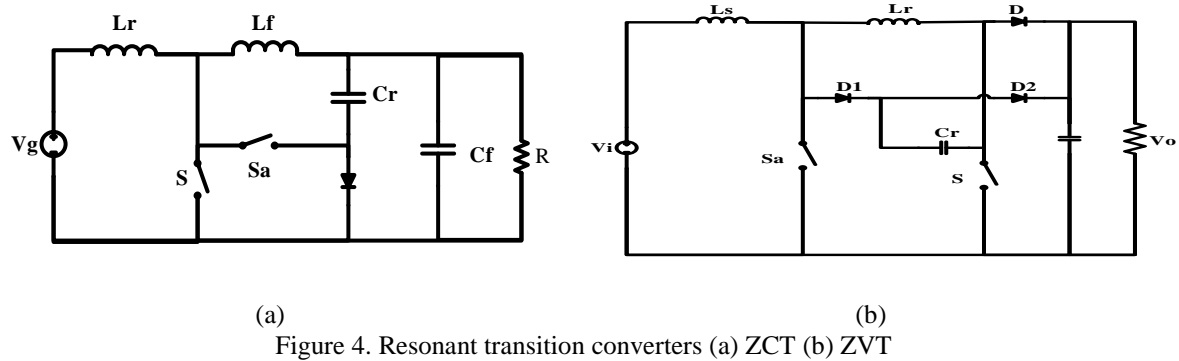

(a)   (b)

Figure 4. Resonant transition converters (a) ZCT (b) ZVT

Table 1. Comparison of the Main Properties of QRC, MRC, and RTC

Converter Family	Switching losses	Conduction losses	Voltage stress	Current stress	Application	Merit	Demerits
QRC	Severe switching noise due to the interaction of rectifier diodes, parasitic capacitance with the large resonant inductor	Losses due to high circulating current which leads to low power density and efficiency	Excessive voltage stress proportional to the load range	Low current stress for the active switch	Suitable for low power application	Low components count compared to MRC and RTC converters	Rely heavily on frequency control; additional resonant peak voltage necessitates more highly rated device.
MRC	Reduced switching losses and noise	Increase in conduction losses owing to smaller filter and reactive components	moderate voltage stress for the active and passive switches compared to QRC	Moderate current stress for both active and passive switch	Suitable for high-frequency operation, such as LCD/LED drivers, power supply chip for Microprocessor unit etc.	Wider control dynamics, All power switches operate with ZVS	High circulating current, excessive voltage stress due to the resonant effect of leakage inductance and device parasitic capacitance
RTC	Lower switching losses than PWM converters	Increase in conduction losses due to additional components	Low voltage stress	Low current stress	Suitable for high power application	High power density & efficiency	Complex control system. The auxiliary switch does not commutate softly. Limited range of ZVS

Table 2. Number of Resonant Elements base on the Family of Resonant Converters

S/N	Family	Number of Auxiliary elements	Number of Resonant Capacitor	Number of Resonant Inductor	Auxiliary Switch
1.	QRC	2	1	1	0
2.	MRC	3	1 or 2	1 or 2	0
3.	RTC	4	1	1	2

Table 3. General Remarks on the Family Classification of Resonant Converters

N	FAMILY	REMARKS
1.	QRC	Does not Produce simultaneous soft switching for the switch and the diode. Both switch and diode produce soft switching simultaneously.
2.	MRC	LLC & LCC topology have a desirable relationship between frequency and gain as a smaller change in frequency results into significant change in gain, as against the regular resonant converters.
3.	RTC	Hard switching for all switches, provide soft switching only during switching commutation, provides additional voltage/current stresses on the main switch and the diode

Resonant converters can be classified on the basis of the location of the resonant network in the converter circuit. The details are explained in the proceeding topics.

a.   Resonant switch converters:

These converters consists of a resonant tank network, which is connected in series or parallel or hybrid (series-parallel) with the switch. Figure 2(a) and 2(b) are an example of such converters, where a resonant capacitor is connected in parallel with the switch and a resonant inductor connected in series with the switch respectively. The series, parallel or hybrid connection can be in the form of isolated series resonant switching converters [14], [56], [57], [42] or non-isolated series resonant switching converters [58], isolated parallel resonant switching converters [25]. An isolated parallel resonant switch converter consists of a parallel capacitor connected with the power switches to provides ZVS and non-isolated parallel resonant switching converters consisting of one or more element in parallel with the switch.

Due to the fact that, in series resonant converters, resonant elements are connected in the main power path, subjecting the resonant inductor to bidirectional voltage, and consequently, generating additional voltage stress on the semiconductor devices. In addition, conduction losses are significantly increased due to substantial circulating energy as a result of all power flowing through the resonant inductor.

However, in parallel resonant switch converter, the shunt resonant circuit is activated for partial resonance to attain ZVS or ZCS during switching transition. Consequently, the circuit reverts back to PWM operating mode after switching transition.

b.   *Resonant load converters*:

In this configuration, the load appears in series, parallel or series-parallel with the resonant tank. In a series-parallel resonant load converter, the resonant capacitor (oscillatory) is divided into two sections, by connecting one in parallel with the load and the other one in series with the coil. Thereby, forming a series-parallel network between the load and the oscillatory circuit. Such converters can have a galvanic isolation between the source and the load (isolated) [59] or non-isolated type, as reported in [25], [56] to provide ZVS & ZCS respectively. Due to the series connection of the resonant element in power flow path, the components suffer from voltage and current stress, this limited their application in high power levels. Resonant load converters are therefore suitable in constant load application. however, turning the load of this converter close to resonant frequency provides good voltage regulation.

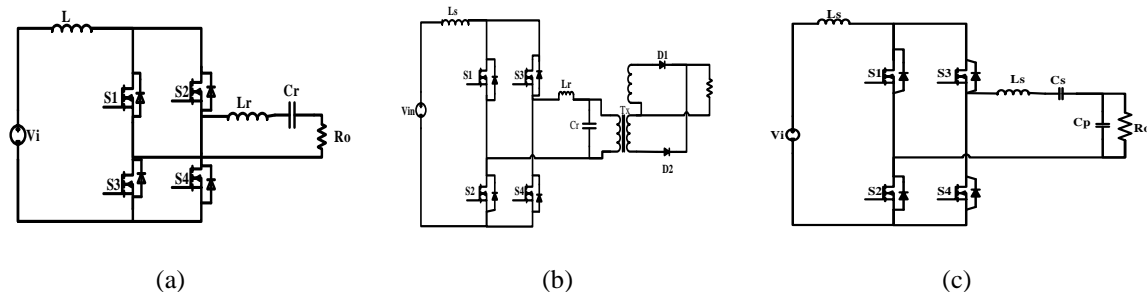| (a) | (b) | (c) |

Figure 5. Resonant load converters (a) series resonant. (b) Parallel Resonant. (c) series-parallel Resonant

Due to the parallel resonant capacitor at the transformer secondary as shown in Figure 5b the diodes are soft-switched, and the diode capacitance formed part of parallel resonant capacitance. This facilitates high switching frequency operation of the load resonant circuit, and easily operated in ZCS mode by operating below the resonant frequency. Perhaps, this requires snubber diodes, very high voltage transformer as well as high-speed diodes. Consequently, series loaded resonant converters are most suitable for high voltage, low current applications. While parallel-load resonant converters are mostly used in low-voltage, high-current applications. The series-parallel resonant converters can run over a wider input voltage and load [60]. In addition, load resonant converters allow size and weight reduction as a result of their high-frequency operation without sacrificing conversion efficiency. This aspect makes them suitable for high-frequency applications. [61] Operation of these converters depends on operating point and resonance frequency making them unsuitable for a wide range of operating conditions.

c.   Series, Parallel and Series-Parallel Resonant Converters:

A load of these converters is connected in series, parallel or series-parallel with the oscillatory (auxiliary) circuit as indicated in Figure 6 (a), (b) and (c) respectively. Series resonant converter (SRC) are

reported in [42], [34], [62]. Compared to hard switched converters SRC has lower EMI, reduced the size and lower losses due to switching. They provide much high power supplies and improved in conversion efficiency [63], [64]. Perhaps, SRC is associated with much more nonlinear dynamics hence, much more complex to control [63], [65]. However, at no load condition, the output voltage of SRC cannot be regulated. In parallel resonant converters (PRC), the resonant capacitor is connected in parallel with the load through transformer coupling which is not mandatory.
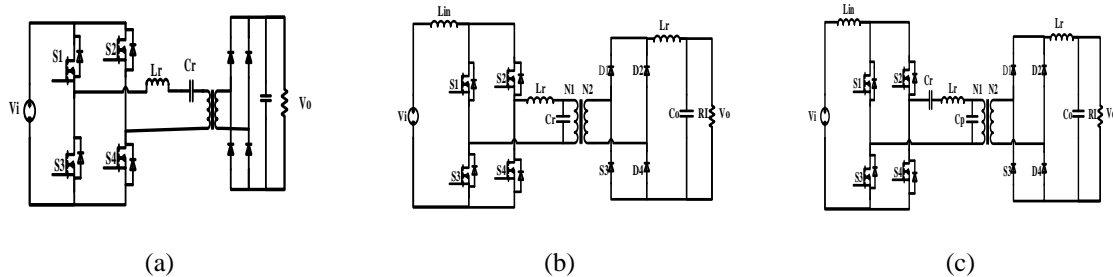

Figure 6. Resonant converter (a) series resonant converter [62] (b) Parallel resonant converters **(c)** Series-Parallel resonant converters

Unlike SRC, PRC can operate at no-load. ZVS can be achieved with the converter operating above resonance frequency. These converters have a high circulating current and they are inherently short-circuit protected. Series-parallel converters as reported by a number of authors as "LLC type parallel resonant converters" or converter using LCC- type commutation or hybrid converters [66]-[69], posses a combine attractive features of both series and parallel resonant converters.

Hence, the above-discussed converters can further be categorized on the basis of their voltage-current waveforms behavior. Soft-switching PWM can be classified into four main groups as ZVS, ZCS, ZVT, and ZCT respectively. Soft-Switching is provided by ZVS & ZCS; thus, ZVT & ZCT are advanced, so switching power loss can be completely destroyed or diverted to entry or exit [18], [50].

d. Zero Voltage Switching (ZVS):

Basically, in ZVS, switching occurs at the zero-voltage condition of the turn-on device, by making the switch voltage zero and slowing down the voltage rise creating a time delay for the current so that current transition occurs when the voltage is zero [16], [41] ZVS eliminates capacitive turn-on loss, and grossly reduced switching losses [16]. A number of converters using this switching technique are reported in [25], [70]-[81], the topologies of which can be either isolated type [56], [57], [70], [71], [74], [77], [80]-[82] to achieve galvanic isolation and voltage scaling or non-isolated type [72], [75], [76], [79], [83]. A ZVS for a bridgeless power factor correction (PFC) boost converter operating in continuous conduction mode (CCM) was reported in [84], this provides ZVS for the switches and reduces switching losses. Similarly, the heat management problem associated with traditional diode rectifier [85] has been eliminated due to the controlled transition in the output diode current at turn-off. These converters depend on soft switching for high-efficiency operation. Thus, at high frequency, these features cannot be guaranteed at variable operating conditions [41]. Figure 7, illustrates a basic single-ended type ZVS constant voltage (CV) converter.
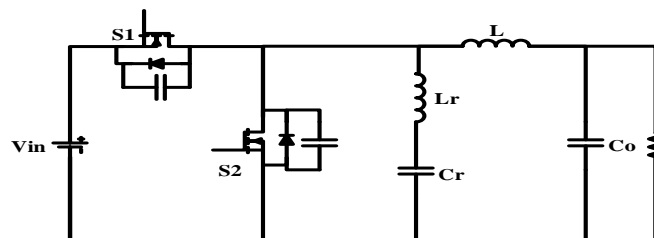

Figure 7. Basic single-ended type ZVS-CV converter

1) Zero Current Switching (ZCS):

These converters are reported in [44], [86]-[98]. ZCS reduce switching losses at turn-off by forcing the switch current to zero, before its drain-source voltage increase from zero to turn-off static value. ZCS at turn-off facilitates in removing the stored charges which might cause a long current tail. This feature makes ZCS highly desirable [97]. Figure 8(a) and 8(b) shows a full bridge resonant ZCS boost converter and a full bridge resonant ZCS boost converter with parallel auxiliary circuit respectively. However, the majority of the ZCS proposed in literature reduced switching losses at the expense of increase conduction losses. This is due to high circulating energy caused by the resonant inductor in series with the power switch. This action exposes the power switch to a high current stress and a rectifier diode to high voltage stress. Another limitation of ZCS is the severe parasitic ringing of the power switch. As a results of non-utilization of the output capacitance of the power switch, the capacitance oscillates with the resonant inductor when the switch turn-off causing parasitic ringing. The low frequency parasitic ringing causes significant switching loss, noise and increase in voltage stress of the power switch. In addition, ZCS operates with constant on-time control. ZCS are more effective in IGBT switching losses reduction than ZVS particularly at low frequency [44] and high power application where minority carrier devices are used as a power switch.
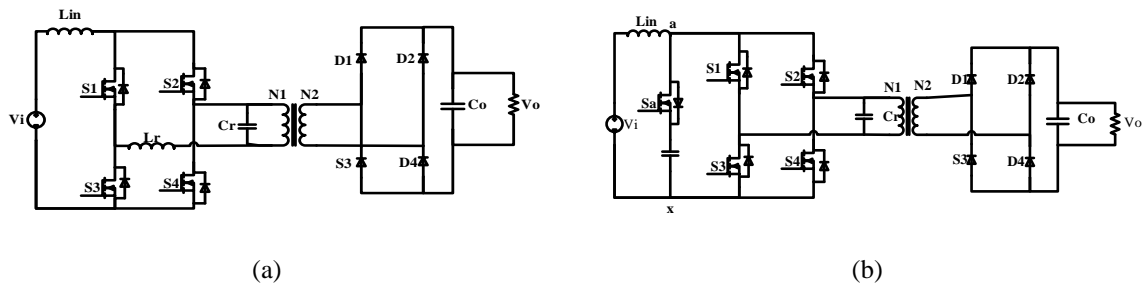

(a)   (b)

Figure 8. (a) Resonant ZCS full-bridge boost converter [89] **(b)** Resonant ZCS full-bridge boost converter with parallel auxiliary circuit

2) Zero-voltage zero-current switching (ZVZCS):

A number of converters are proposed by different authors to provide ZVZCS [98] for the main switch and diode simultaneously. Some of which are isolated [22], [43], [99]-[101] and non-isolated [4], [35], [58], [102]-104]. Figure 9 (a) and 9 (b) illustrates an isolated type ZVZCS converter and an interleaved ZCS-ZVS boost converters respectively.

ZVZCS for an interleaved boost converter had also been reported in [105]. The technique provides ZVS for all active and passive semiconductor device during turn-on and turn-off conditions, over a wide output load variation and the auxiliary switch operates at ZCS. Beside significant reduction in voltage and current stress in these converters, the converter does not support variable frequency operations.
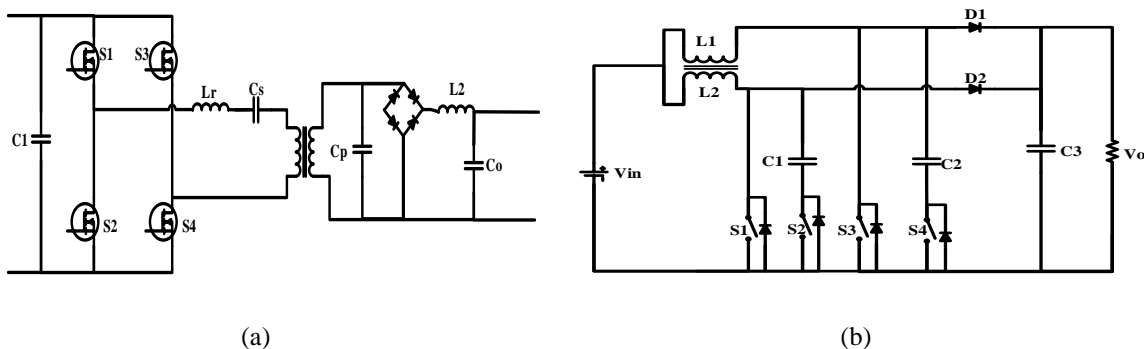

(a)   (b)

Figure 9. ZVZC Converters (a) Isolated type ZVZCS (b) Interleaved ZCS-ZVS boost Converter(58)

3) Zero current transition (ZCT):

Converter Figure 10 shows a basic ZCS converter with a couple of resonant elements (L_r & C_r), an auxiliary switch and diode (S_a & D_a) respectively. ZCT technique can significantly reduce turn-off switching

losses through forcing to zero the outgoing switch current prior to its turn-off [106]. Some of the attractive features of ZCT are: minimum circulating current, variable load operation, low voltage and current stresses on the main switch and diode. Perhaps, one of the major drawbacks of these converters is hard switching at turn-on for the main switch and main diode at turn-off, given rise to large reverse recovery losses. In addition, ZCT converters does not support variable switching frequency operation [107].

Similarly, ZCT converter has high voltage stress for the diodes which is twice as high as in the PWM converters. Another drawback is the voltage swing that appears across the main switch (S1) due to the interaction between its output capacitance and resonant inductor [38].
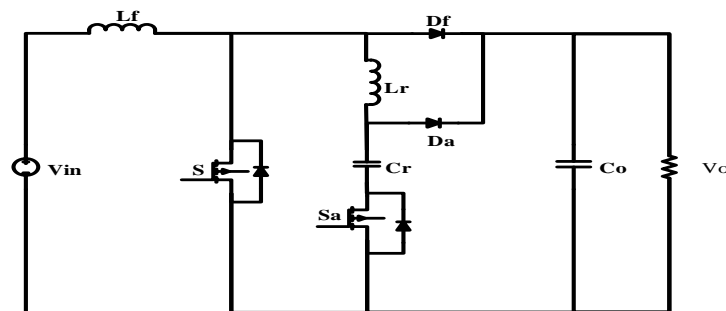

Figure 10. Basic ZCT converter

4)   Zero voltage transition (ZVT) Converters:

In these converters are set of diodes, an auxiliary switch, and a snubber cells (L_r & C_r) the snubber circuit can be passive snubber or an active snubber cell [17], shunted across the main switch [108]. The shunt resonant network is activated to create a partial resonant during the switching transition to achieve ZVS or ZCS. Figure 11 depicts a conventional boost type ZVT converter. After switching transition the shunt resonant network is disable and the operation of the converter during most of the switching cycle is similar to that of PWM converters. In ZVT auxiliary switch does not commutate softly. However, it has a lower switching losses when compared to PWM converters [38]. In addition, ZVT has a complicated control circuit as well as additional conduction losses due to addithe tional auxiliary circuit [108].
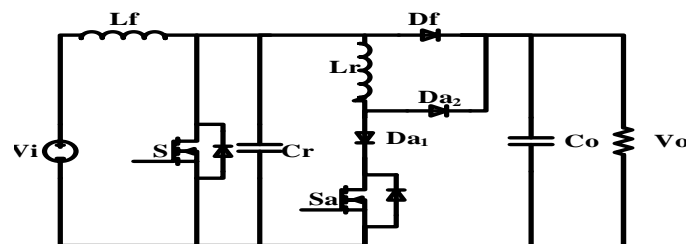

Figure 11. Conventional ZVT converter

Furthermore, ZVT PWM technique provides ZVS for the power switch and the rectifier diodes, it is, therefore, more attractive in higher voltage application (power factor correction circuit) where reverse recovery problem of the higher-voltage diode is of primary concern [16], [109], [110]. Table 4 gives highlights of features of resonant converters in terms of their current and voltage behaviors.

Table 4. Features of Resonant Converters Based Voltage Current Waveforms Behaviour

	ZVS	ZCS	ZVT	ZCT
Merits	• Grossly, reduced switching losses • Eliminates turn-on losses of the parasitic capacitance and Miller effect • Low current stress	• Eliminates switching losses during device turn-off & switching losses at turn-on	• Small Voltage/current rating and size of the auxiliary components • Provides soft-switching without increasing voltage or current stress on the switch • ZVT PWM have a combine advantage of Conventional PWM & resonant converters	• Minimum circulating current, minimum voltage/current stress • Variable load operation. • low voltage stresses on the diode and low voltage/current the main switch • reduced turn-on & turn-off losses of the main switch
Demerits	• The switches if without voltage clamping, will be subjected to excessive voltage stress, proportional to the load	• High capacitive turn-on losses proportional to the switching frequency. • High circulating energy, exposing the power switch to a high current stress and rectifier diode to high voltage stress • Significant power loss at high voltage and high frequency due to energy discharge through the switches by the capacitor at turned on	• Lower power density • Harder control than normal PWM converters • Circuit operation depends on line and load conditions. • Limited voltage conversion range. • For ZVT-PWM the auxiliary switch does not operate with soft-switching • The auxiliary switch is used for providing ZVT or ZCT for the main switch but does not contribute to power processing.	• Hard switching at turn-on for the main switch and main diode at turn-off, given rise to large reverse recovery losses. • Does not support variable switching frequency operation • ZCT converter has high voltage stress for the diodes which are twice as high as in the PWM converters.
Application	• Suitable for high-frequency operation	• Effective for IGBTs in reducing switching losses than ZVS at low frequency	• Applicable in high voltage high-frequency switched-mode power conversion application. • Deemed most suitable for MOSFET based power converters	Reduced switching losses for the main switch with auxiliary switch achieving ZCS, while keeping the corresponding device voltage and current minimum, which are very suitable for IGBT applications.

3.   CONCLUSION

Soft-switching techniques made possible the increasing demand of higher frequency converters with higher power density, high efficiency, compact size, and low EMI and losses. This article focus on various soft-switching techniques.

Emphasis had been given to general family classification soft-switching techniques which have been further classified. Quasi-resonant converters (QRC) active switch are subjected to low current stress, thus, the operation of these converters relay heavily on frequency control. Similarly, peak voltage resulting from resonant tank necessitates more highly rated device. MRC have moderate voltage stress on the switches and their conduction losses when compared to QRC is on the higher side. MRC is suitable for high-frequency operation. RTC has a .\complex control system, due to additional switch which also increases conduction losses, however, voltage and current stress of these converters are low. Furthermore, ZVS/ZCS reduces switching losses at turn-on and turn-off at the expense of high voltage/current stress. ZVT & ZCT provides soft-switching with minimum voltage/current stress on the main switch, perhaps these converters are faced with problems of limited voltage conversion range and variable frequency operation.

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