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An Enhanced Voltage Gain Techniques in Quadratic Boost Converters - A Systematic Review

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Abstract: High voltage gain non-isolated boost DC-DC converters are widely employed in applications such as hybrid electric vehicles, aircraft power supplies, photovoltaic (PV) systems and fuel cells (FC) applications. The use of conventional boost converters in high-gain applications is affected by their practical limitation on their voltage gain. Several boost converter topologies based on different voltage lift techniques have been studied and reported; them is quadratic boost converter (QBC). These converters have recently emerged as an interesting topology because of the quadratic nature of their voltage gain, simple among structure and simple control scheme. Recently modified topologies of QBC employing different voltage lift techniques aimed at further enhancing their performance are reported. This paper is aimed at presenting a review on the advances in quadratic boost converters topologies. In this article, QBC are categorized into five groups: magnetically coupled based on coupled-inductor (CI), switch-inductor (SI), switch-inductor switch-capacitor (SC-SI), switch-capacitor (SC), and soft-switching QBC. Furthermore, the paper makes a comprehensive comparison of various QBC in terms of voltage conversion ratio, total component count, input current ripples and voltage stress across switching devices.

Keywords Quadratic boost converter, high voltage gain, voltage gain enhancement, Voltage multiplier cell

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1. INTRODUCTION

Due to the increasing climate change concerns, renewable energies have been considered as the primary alternative to conventional (fossil fuel-based) energies. Photovoltaic (PV) energy is one of the various renewable energy sources fast gaining popularity, which is attributed to its zero pollution, availability and sustainability [1]. However, one major drawbacks affecting the use of PV is their relatively low output voltage from 10 to 50 V [1], [2]. Consequently, to enjoy the maximum benefits of renewable energy sources, use of high voltage gain converter as an interface becomes necessary [3]. Conventional boost converter despite having simple structure and control scheme, the converter is affected by practical limitation on its voltage conversion ratio as well as increase power loss at high duty cycle [4]–[8]. Consequently, high voltage gain DC-DC converter is desirable in many applications, such as renewable energy [9], telecommunication system, electric vehicle (EV) [10], DC-based microgrids [11], drones power supply, unmanned area vehicle (UAV) and fuel cells [10].

To overcome the limitations of extreme duty cycle and large voltage gain, several topologies of boost DC-DC converters have been studied and reported. A magnetic coupling technique using high frequency transformers [12]–[15] and coupled inductor [16]–[19] are widely reported. These converters step-up the voltage gain by increasing the turns ratio of the magnetic device. However, increasing the turns ratio further increases the converter loss, volume and weight thus, reducing the converter efficiency [20], [21]. In addition to that, the leakage energy induces high voltage stress across the power switches [5], [9], [17]. Combining multiple converters in series/parallel or series-parallel [22]–[24], have been reported to enhance voltage gain, thus, this approach increases the number of component count. Furthermore, connecting two stage of boost converter to increase the converter voltage gain is reported [25]–[27]. Unfortunately, this concept complicates the design of the compensator involving multiple active switches. Other methods are based on switch-capacitors (SC) multiplier cell [28]–[31], diode switch-capacitor voltage multiplier cell [32] and switch-inductor (SI) cells [6]. Thus, indiscriminate used of capacitor and inductor cells at the input side of the converter makes the input current exhibits a pulsating behaviour. Other voltage boosting method reported is using a quadratic boost converters (QBC) [33]–[38]. This converter produces a voltage gain as a quadratic form of that of a conventional boost converter at a limited duty cycle. The converter possesses the attributes of low components count and simple structure. Furthermore, interleave converters using a combination of the above methods to further increase the voltage gain are reported [18], [39]–[41].

This paper presents a review of various topologies of QBC. Furthermore, the paper make a comprehensive review of different voltage gain lift techniques, in addition a comparison of various QBC topologies from different aspects such as, voltage conversion ratio, total component count, input current ripples and voltage stress across switching devices will be carried out. The paper is breakdown as follows: Section 2 presents the classification of QBC based on type of voltage lift method, Section 3 a comparison of various QBC topologies based on different voltage lift method and section 4 presents the conclusion.

2. CLASSIFICATIONS OF QBC

Single switch QBC have been reported in the literature [42], [43], these converters have simple control architecture due to their single active control switch. Similarly, the quadratic nature of their voltage gain at limited duty cycle and the current source characteristics makes them suitable for application such as in fuel cell energy conversion. However, a classical single switch QBC presents high EMI level because the switch do not present auxiliary commutation [44]. Furthermore, for application requiring very high voltage gain, the voltage gain of these converter needs to be enhanced. Several methods aimed at increasing the gain of QBC are proposed and reported in the literature. The classification can be done based on different criteria: – the most common ones are based on switch capacitor cells (SC), switch inductor cells (SI), coupled inductor (CI), voltage multiplier cell (VMC) and a hybrid method which can be based combination of the aforementioned methods as shown in Figure 1.

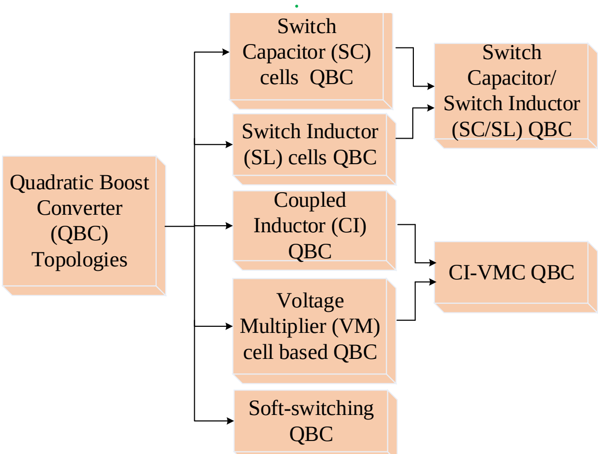

Figure 1. Classification of quadratic boot converter

3. SWITCH-CAPACTTOR-BASED QBC

Switched capacitor (SC) voltage gain boosting method uses a combination of multiple units of switch capacitor which reduces the voltage stress on each cell [45]. This method uses the ability of high energy density of the capacitor to increase the voltage step-up ratio. SC converters require small voltage and current ratings of device and their configuration without inductor make them lighter in weight and smaller in size which increase their power density [46]. High voltage gain QBC based on switch capacitor cell structure are reported in [31], [47], [48]. The converters reduce the voltage stress on the semiconductor devices with increased voltage gain at low duty cycle. Subhani *et al* [47] introduced an ultra-high gain improved QBC based on switch-capacitor cell. The proposed converter is suitable for renewable energy application due to its continuous input current feature and common ground between source and load as depicted in Figure 2.

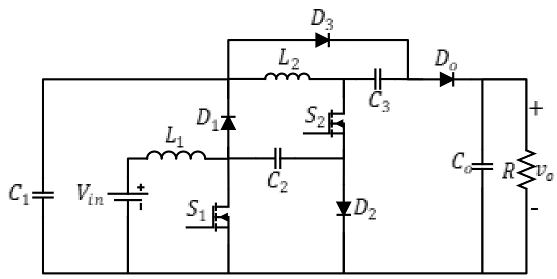

Figure 2. An ultra-high gain improved QBC based on switch-capacitor cell [47].

A high gain QBC for fuel cell EV application based on the concept of asymmetric inductor magnetization is reported in [48] and shown in Figure 3. The converter employed a switched-capacitor cell at the output which reduce the voltage stress. However, high current stress across the power switch is evident.

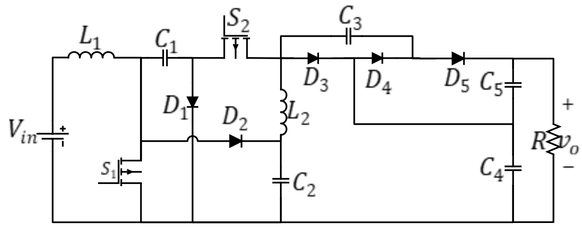

Figure 3. A high gain QBC for fuel cell electric vehicle application [48]

To improve the voltage gain of a conventional converter, a capacitor-diode cell is used to aid the input voltage during on-state as reported in [49]. The converter employs the concept of asymmetric inductor input voltage and capacitor-diode cell to boost the converter gain as shown in Figure 4. In addition, the proposed converter has the following positive attributes low power rated switching device, minimum components count, continuous input current, and high-power density. Consequently, the voltage stress across the power switches is high.

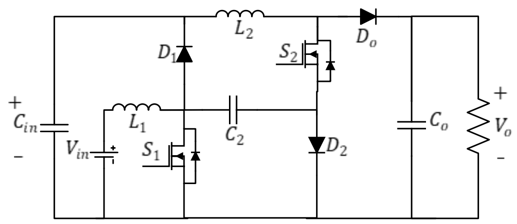

Figure 4. Converter reported [49]

Generally, in SC technique the capacitors are operated in switching state and therefore, large current spike (transient current) is evident at switching transient. This feature negatively affect the useful life of an equipment [50]. In addition, due to the pulsating nature of the input current of SC, large current ripple and EMI issues are some of its drawbacks. This aspect limits their use in low power applications [51]. To mitigate the turn-off spikes of the power switches and the voltage stress caused during switching turn off transient a double resonant SC converter is proposed in [52]. The converter employs a passive regenerative snubber circuit to suppress the turn off voltage spikes and voltage stress across the semiconductor devices. In addition, power switches and diodes are turn off with ZVS and ZCS respectively. However, at heavy load the converter has a limited regulation range. Furthermore, resonant network increases the circuit component count.

4. SWITCH-INDUCTOR QBC

Switched inductor (SI) approach is another method used to enhance the voltage conversion ratio of converters. This techniques improve the converter voltage gain by using the principles of parallel charging of the reactive components [53]. A classical switch inductor boost converter has a voltage stress equal to the output voltage across the power switch. This necessitates the use of a high current rated power switch which in turn increase the cost of the converter. In addition, increase in voltage gain requires a high number of passive components which reduces the converter power density. To reduce the number of passive components, a switch inductor dual switch DC-DC converter is proposed [54]. The converter has a high voltage gain and a limited duty cycle. This aspect reduces the possibility of the converter entering inductor current saturation at a duty cycle of greater than 50%. In consequence, all the power switches are operated under hard switching.

Samiullah *et, al;* [55] proposed boost converter based on SI-SC integration to lift the voltage gain. The proposed converter provides high voltage gain at limited duty cycle and low peak inverse voltage for the output diode. These features make it attractive for various applications, such as DC microgrid, FC and PV. The concept of switch inductor is adopted on a quadratic boost converter derived by cascading an inverting boost converter with a restructures ZETA converter [56] as shown in Figure 5. This converter, when compared to conventional buck-boost converter, exhibits lower input and output current ripples. Furthermore, the converter has better voltage gain characteristics and its common ground feature simplify the design of controller. However, the cascaded structure increases the components count, cost and the converter volume. Similarly, the converter exhibits high voltage stress across the active switches.

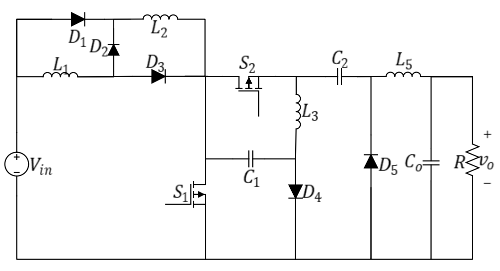

Figure 5. Switch inductor based QBC [56]

A conventional switch inductor boost converter employs a switch inductor to increase the voltage gain, however, it is important to note that increasing the voltage gain causes a corresponding increase in the voltage stress across the active switch. To reduce the voltage stress across the active switch a modified switch inductor boost converter is proposed [53]. The converter is a modified version of the classical switch inductor boost obtained by replacing one of the diode with switch inductor as illustrated in Figure 6.

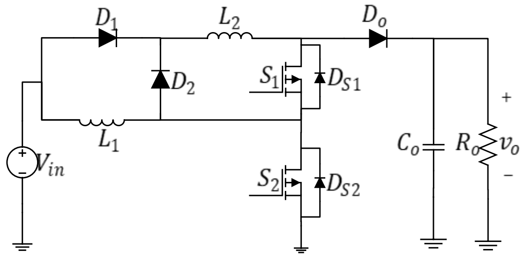

Figure 6**.** Modified switch inductor boost converter [53]

This converter uses the inherent parallel charging and discharging property of inductor to achieve high voltage conversion ratio. Similarly, the total output voltage of this converter is distributed among the two power switches thereby reducing their respective voltage stresses.

5. SWITCH-CAPACITOR/INDCTOR QBC

Converters combining a traditional switched-boost converter and switched-capacitor/switched-inductor cells are presented [6], [57], [58] Some of the attractive attributes of this combination includes high voltage conversion ratio, low number of passive components, low voltage stress across semiconductor devices and possible expandability by employing additional cells. The QBC reported in [58] achieved a high voltage gain QBC with the help of additional voltage multiplier cell (VMC). The voltage multiplier is based on inductor-capacitor-diode circuit as depicted in Figure 7. In comparison with conventional single switch QBC, this converter has a voltage conversion ratio of 40. However, for an application requiring much high voltage gain, the number of VMC needs to be increased. This increases the converter volume, cost, components count and reduction in the power density.

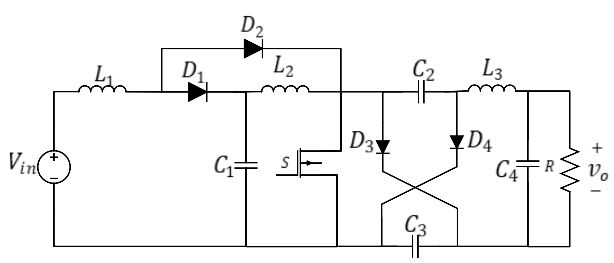

Figure 7. QBC based on inductor-capacitor-diode multiplier cell [58]

The application of SC-SI has been reported to reduced input current ripple in high gain DC-DC converter [59]. This converter employs a parallel operation of switch-capacitor and switch-inductor cells. Some of the benefits derived from the topology include simple control, high voltage gain and power density, as well as reduced values of magnetic components. However, transient response of this topology can be affected requiring special design consideration of the dynamic behaviour.

6. COUPLED-INDUCTOR BASED QBC

Predominantly, voltage boost techniques of non-isolated converters are grouped as coupled inductor type and non-coupled inductor type. Converters based on coupled inductor (CI) encounter a significant voltage boost by adjusting the tuns ratio of the coupled inductor. These converters reduce the number of magnetic cores by accommodating multiple winding on a single core thus, simplifying the converter structure and cost. These converters are similar to isolated converters with common ground between the source and the load. Several research involving coupled inductor-based converters are investigated and reported [17], [50], [60]–[63]. However, the majority of the coupled inductor-based converters are negatively affected by excessive voltage stress on the power switch due to leakage inductance of the couple inductor.

Integration of coupled inductors into QBC is an interesting topic due to its impressive impact on the step-up factor. Izadi, *et al.* [64] presented an improved gain non isolated QBC employing an integrated three winding coupled inductor to form a conventional quadratic impedance network as illustrated in Figure 8. This topology increases the boosting factor and efficiency by 12 and 94% respectively. Although the boosting factor is high, the three-winding coupled inductor reduced the power density. The converter reported in [20] achieve an experimental voltage gain of 20 with the help of couple indcutor and a multiplier cell. Similarly, the controller design is simplified due to common ground between source and load. However, this converter is not suitable for renewable application involving PV due to excessive input current ripple which affects the life span of the PV.

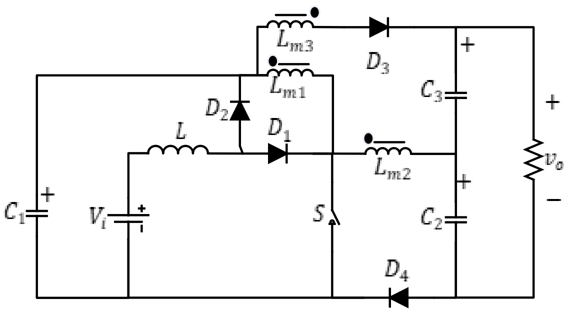

Figure 8. A non-isolated high gain, high efficiency QBC [64]

It is important to note that to achieve ultrahigh voltage gain, couple inductor-based converters rely heavily on increasing the turn ratio of the coupled inductor. Consequently, high turns ratio of the couple inductor leads to large leakage inductance, increase in voltage stress across switches, EMI problems and high current ripple which affect the system performance [50], [65]. To reduce the current stress across the power switch, a reduced current stress coupled inductor based high step-up boost converter is studied and reported by [61][66].

Santa *et, al.* [61] proposed a generalized current stress reduction method by modifying the topology of the coupled-inductor. The current stress is reduced by using the inductance of the coupled-inductor during the resonating half cycle. This topology is depicted in Figure 9. it can be seen that no extra circuit is required for the modification, however, the power switches are operated under hard switching.

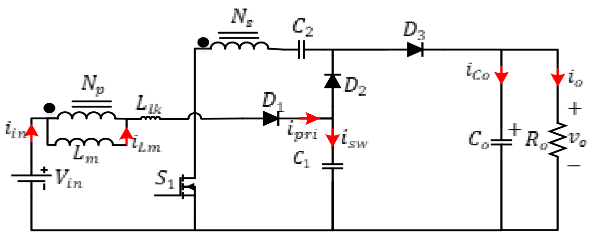

Figure 9. A generalized switch current stress reduction method [61]

In [66] an improved coupled inductor-based QBC is reported. This converter reduced the voltage stress on the power switch by employing an active clamp circuit as shown in Figure 10. In addition, the clamp circuit operates under zero voltage switching (ZVS) condition. Due to reduced voltage stress, a low voltage rating, low on-resistance power switch can be used to reduce conduction loss. However, due to additional active clamp circuit, the cost, volume and power density of the converter is affected.

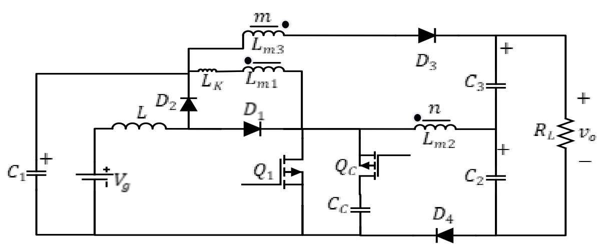

Figure 10. An improved coupled inductor based QBC with reduced voltage stress [66]

7. VOLTAGE MULTIPLIER CELL BASED QBC

One possible solution of integrating multiple energy sources and obtain high voltage conversion efficiency is by using a voltage multiplier cell (VMC) approach on a conventional converter. A VMC approach employs a network of capacitors and diodes to increase the magnitude of electrical power. Switch diode capacitor cells when integrated in a boost converter retain the attractive features of SC such as high voltage gain. Several converter using this technique are studied and reported in the literature

[65], [67], [68]. Hwa-Dong *et al* [69] report an improved high gain QBC with a voltage gain of three times higher than that of the classical QBC. In the improved QBC the second inductor of the conventional QBC is replaced by a VMC and a SC network to further boost the gain as illustrated in Figure 11. Moreover, the voltage stress across the power switches is further reduced. However, the additional circuit increases the component count and reduce the power density.

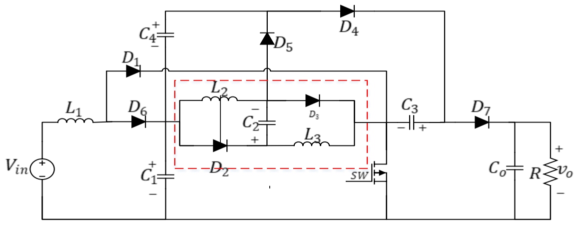

Figure 11. Modified QBC [69]

Javed *et al;* [70] proposed a VMC-QBC used in energy storage application as shown in Figure 12. The converter produces a voltage gain two times higher than the convention QBC with a voltage stress less than the output voltage across the power switch. The output voltage is increased with the help of VMC. However, the VMC increase the number of components making the converter bulky and costly.

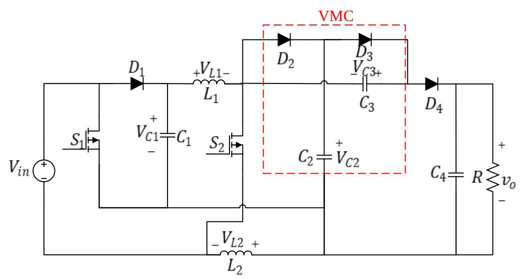

Figure 12. A VMC based QBC for energy storage application [70]

Introducing a VMC has proven to be successful in improving the voltage gain of power converters as reported by many authors. However, this technique is done at the expense of increasing the number of components count, cost and an increase in the power density. In order to reduce the converter components count, one of the input inductor of a QBC is shared by the VMC as reported in Figure 13 [32]. This converter poses some advantages which includes reduced number of components, higher voltage gain and reduced voltage stress on the diodes. However, the voltage stress across the power switch is high. This requires the use of high voltage rated switch, which increase the cost of the converter.

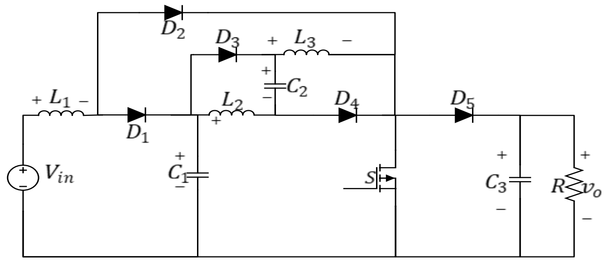

Figure 13. Effective combination of QBC with VMC [32]

Navamani *et al;* [71] proposed a high gain QBC in which the switch voltage stress if a function of the VMC as shown in Figure 14. The voltage stress on the semiconductor device of this convert is reduced by increasing the voltage multiplier cells. Similarly, this converter has high switch utilization factor. However, increasing the VMC suffer from similar disadvantage with other VMC technique of increased component count and reduction in the power density.

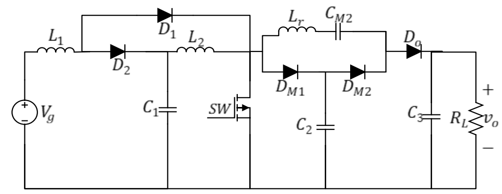

Figure 14. high gain non isolated QBC with VMC [71]

8. COUPLED INDUCTOR AND VMC BASED QBC

Combining a conventional QBC with coupled inductor (CI) and a voltage multiplier cell (VMC) has led to new topologies. This concept has been adopted by many authors to improve the voltage conversion ratio [1], [2], [72]–[75]. The converter proposed in [2] uses dual coupled inductor and a voltage multiplier cell to boost the voltage gain of a QBC as shown in Figure 15. This converter has low voltage stress on the power switch as well as continuous input current which make it an ideal choice for renewable energy application.

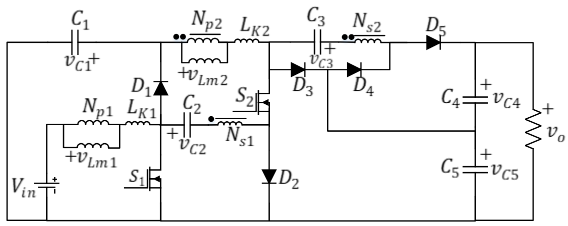

Figure 15. Converter reported in [2]

The converter reported in [72] uses a couple inductor and a voltage doubler rectifier to further increase the voltage gain. Moreover, due to resonance operation, low turn-off current of the power switches is reduced. Furthermore, the voltage rectifier diodes are turned-off under ZCS mitigating the diode reverse recovery issue. However, the presence of multi winding couple-inductor increase the volume and cost of the converter. The converter proposed in [73] exhibits a common ground between the source and the load which simplify the control scheme. The voltage spike due to leakage inductance is alleviated by the clamp circuit. Furthermore, as shown in Figure 16 the component of the VM cell is shared with the clamp circuit while improving the voltage conversion ratio at low component count. Perhaps, the clamp circuit reduced the power density.

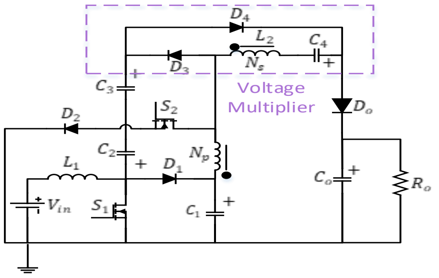

Figure 16. Synchronous dual switch-converter based on CI and VMC [73]

The QBC reported in [75] employ a three winding coupled-inductor and a voltage lift cell as illustrated in Figure 17. The output voltage of the voltage lift cells generates energy supplied to the output of the QBC.

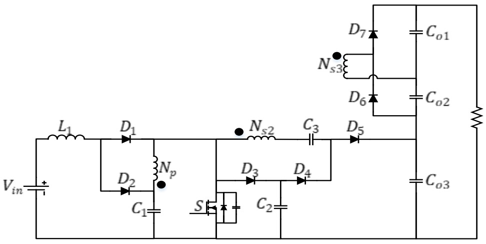
Figure 17. Single switch QBC based on three winding coupled-inductor [75]

Although, the leakage inductance can be recycled to increase efficiency, the converter has low power density due to high number of component count. Similarly, the resonant effects of the leakage inductance and the parasitic capacitance of the semiconductor devices impose a stress across the devices.

9. SOFT-SWITCHING QBC

To further reduce the losses of a QBC which increase the converter overall efficiency, soft switching techniques is adopted as reported by so many authors. Korada *et al.* [76] propose an adaptive soft-switching QBC with no additional auxiliary circuit. In this topology one of the input diodes is replaced with low rated switch as shown in Figure 18. All switches and the input diode are operated under soft-switching condition. However, this topology has an increased number of active switches which complicated the control scheme.

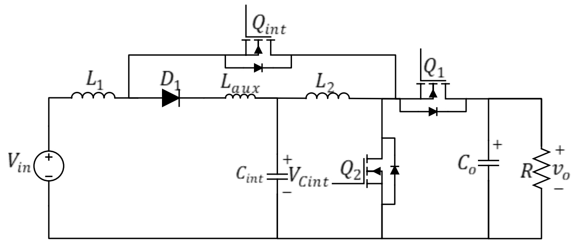
Figure 18. Adaptive soft-switching QBC [76]

Conventional single switch QBC presents a high level of EMI due to non-auxiliary commutation of the power switches. To address this limitation a QBC employing two auxiliary resonant commutation cells shown in Figure 19 is reported in [44]. This converter provides large voltage step-up. Moreover, the additional resonant network facilitates soft-switching operation of the power switches in addition to its ability to operate at high frequency. Although soft-switching is achieved, the resonant network reduces the power density of the converter by increasing the number of component count.

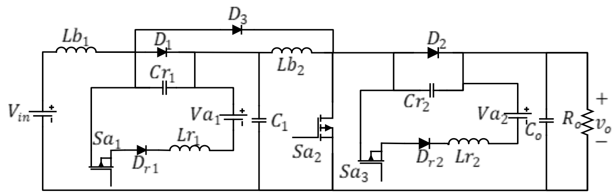
Figure 19. Soft switching QPWMBC [44]

An ultrahigh step-up QBC based on coupled inductor shown in Figure 20 is proposed and reported in [50]. The voltage gain of this converter is enhanced using a coupled-inductor and a voltage doubler cell with reduced voltage stress. In addition, the leakage inductance of the coupled inductor is used to achieve zero current switching (ZCS) across the output diode, this increases the efficiency of the converter.

A soft switching QBC based critical conduction mode is proposed in [77]. The converter employs a small auxiliary inductor in series with one of the input diodes as illustrated in Figure 21. The proposed converter achieves ZVS of

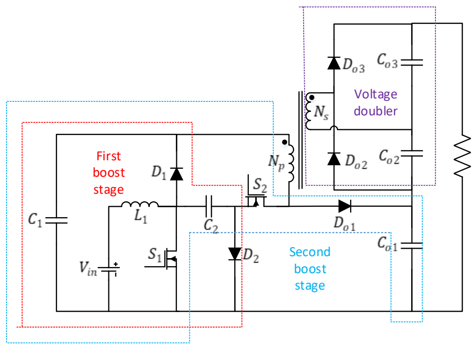

Figure 20. An ultrahigh step-up QBC [50]

the all the power switches, furthermore, the input diode operates under ZCS condition and free from reverse recovery issue. However, due to resonance effect between the output inductor and the parasitic capacitances of the power switches, high current ripple at the output is evident.

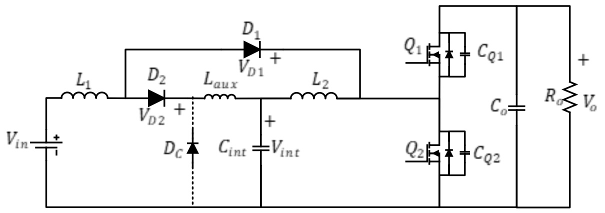

Figure 21. New CRM topology for ZVS in QBC [77]

A summary of the merits and drawbacks of the various voltage lift methods discussed is presented in Table 1.

10. COMPARATIVE ANALYSIS

Comparison among different converters reported in the literature are presented in Table 2. The criterion for the comparison is based on the type of input current, input current ripple, total number of components, voltage conversion ratio, common ground feature, soft switching and peak efficiency. Moreover, for high step-up converters, voltage gain is the main parameter of consideration. For this reason, voltage gains capability of some selected converters reported are plotted as shown in Figure 22. For all the selected converters, it is seen a larger boosting factor can be obtained by increasing the duty cycle. Among the selected converter, the SC configuration employing asymmetric inductor magnetization reported in [48] has the highest voltage conversion ratio.

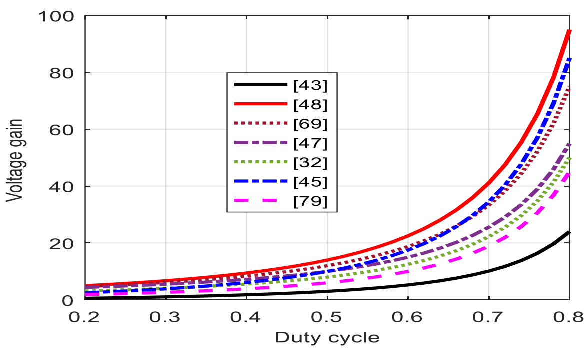

Figure 22. Comparison of voltage gain of the proposed converter with other convertes

11. CONCLUSION

This article presents a review of different methods of increasing the voltage conversion ratio in quadratic boost converter for high voltage gain application. Different topologies reported in the literature are considered in the review and the merits and drawbacks of each method is highlighted. Some selected QBC reported are considered for comparison. The comparison is based on the type of input, number of component, voltage conversion ratio softswitching and efficiency among others. It is envisage that this review will serve as a guide for selecting a QBC for a particular application.

Table 1. Features of QBC topologies

Topology	Merit	Drawback
SI QBC	• Improve voltage gain due to principles of parallel charging of the reactive components. • Leakage inductance energy can be recycled. • The output voltage can be increased by using additional switched cells. • Limit the input current ripple.	• High component count. • Pulsating input current. • Not suitable for application with low input current ripple requirement. • High voltage stress across power semiconductor. • Severe voltage spikes across switch due to energy stored in the leakage inductance. • Require a resonant or clamp circuit to suppress spike.
SC QBC	• Good voltage boost when compared to SI • Small voltage and current rated devices. • Lighter weight due to inductor free configuration. • High power density. • Suitable for high power application due to low EMI related issues. • Minimal magnetic component. • Modularity, simple structure and probability for monolithic integration. • Low resistance to EMI compared to SI.	• Draws high peak pulsating current from renewable energy source (RES). • Poor regulation. • Require capacitor diode cells to enhance voltage regulation performance. • Capacitor are operated in switching state; therefore, large current spikes is evident. • High voltage gain application requires multistage arrangement of SC. • Increase complexity due multiple stage SC for high gain application. • Vulnerable to instability under varying load. • High inrush current through capacitor during charging. • Increase voltage stress across power switches.
SI-SC QBC	• Improved voltage gain • Continuous input current. • The output voltage can be increased by cascading additional switched cells. • Low voltage stress across the output diode. • Lesser ripple content in output voltage and current.	• High input current ripples due to direct connection of capacitor to the input • High ripple current which is vulnerable to RES. • Discontinuous input current.
CI-QBC	• Flexibility in turns ratio adjustment to achieve the desired gain. • Reduced duty cycle and conduction loss. • Improved performance due to energy flow through both magnetic and electric paths. • Reduced core size. • Reduced cross regulation and cross coupling. • Leakage inductance energy can be recycled. • Easy to increase the voltage gain. • Can be effectively coupled in large number to provide high voltage.	• Challenge due to complex magnetic design • Presence of voltage spikes across switches due to leakage inductance. • Require external clamp and snubber circuits to mitigate energy due to leakage inductances. • Increase in voltage stress across switches. • High current spikes. • Lower power density with increased in turns ratio. • Large core and copper loss. • EMI issues. • Circulating current.

VMC	• Low voltage stress on power switches • Low commutation loss. • Veery simple and effective in increasing the voltage gain of a converter. • Wide operating range of duty cycle.	• Require additional power stage to achieve high gain at moderate duty cycle. • Utilizes many diodes and capacitors, • Use of many multiplier cells increasing the converter cost and volume.
CI-VMC	• Simultaneous improve voltage gain and device stresses. • Low voltage stress across the power switch • Possible ZVS ability • Increase in loss and reduction in efficiency due to requirement of large number of diodes and capacitors.	• High voltage spike due to stored energy in the leakage inductance. • Require snubber circuit to absorb leakage inductance. • Increased complexity • Reduced efficiency • Increase in number of components.
Soft-switching QBC	• Reduced losses • Increase efficiency I am running a few minutes late; my previous meeting is running over. • High switching frequency ability. • High power density.	• Require an active auxiliary network for soft-switching operation. • Increase in component count.

Table 2. Comparison of various QBC reported in the literature.

Ref	Input Current type		Input current ripple	Voltage conversion ratio	Number of components						Common ground	Soft switching	Max efficiency
	Continuous	Pulsating			L	CI	C	S	D	TC			
[43]	-	√	Moderate	$\frac{2D-D^2}{(1-D)^2}$	2	-	2	1	3	8	yes	No	85 %
[48]	√	-	Low	$\frac{3+D}{(1-D)^2}$	2	-	5	2	5	14	yes	No	93.6 %
[69]	√	-	Low	$\frac{3}{(1-D)^2}$	3	-	4	1	7	15	Yes	No	94 %
[47]	√	-	Low	$\frac{3-D}{(1-D)^2}$	2	-	4	2	4	12	Yes	No	90 %
[32]	√	-	Low	$\frac{2}{(1-D)^2}$	3	-	3	1	5	12	Yes	No	97.1 %
[72]	√	-	Low	$\frac{2N+1+D+n(1-D)}{(1-D)^2}$	1	2	6	2	5	16	Yes	ZCS	96.28 %
[66]	√	-	Low	$\frac{(1+n)(2-D)}{(1-D)^2}$	1	1	3	1	4	10	Yes	No	94 %
[78]	√	-	Low	$\frac{(n^2+(1+n)(3+))}{(1-D)^2}$	-	2	5	2	5	14	Yes	No	95.2 %
[45]	√	-	Low	$\frac{1+3D}{(1-D)^2}$	3	-	5	2	4	14	Yes	No	-
[79]	√	-	Low	$\frac{1+D}{(1-D)^2}$	-	2	3	2	3	10	Yes	No	-

L is the number of inductors, CI is the number of coupled inductors, C is the number of capacitors, S is the number of switches, D is the number of diodes and TC is the total number of components.

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