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Review of High-Frequency High-Voltage-Conversion-Ratio dc-dc Converters

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Abstract—The development of high-frequency power converters is continuously improving their power density, efficiency and fast dynamic response. Among them, high-voltage-conversion-ratio dc-dc converters are widely used in high gain, i.e. step-up/-down or bidirectional applications, such as power supply for data center, dc micro-grids, electrical vehicle charging systems and so on. In this article, the current main high-frequency high-voltage-conversion-ratio dc-dc converters are classified into inductive-based and capacitive-based approaches, which can then be described further by four kinds in detail, namely transformer-based, coupled-inductor-based, and switched-capacitor-based, as well as combination of coupled inductor and switched capacitor. A comprehensive analysis and comparison is given, which can provide guidance for proper topology selection and further topology optimization.

Index Terms—High-frequency dc-dc converters, high-voltage-conversion-ratio dc-dc converters, inductive, capacitive.

List of acronyms

- HVCR: high voltage conversion ratio
- VRM: voltage regulation module
- HF: high frequency
- SR: synchronous rectifier
- ZCS: zero current switching
- ZVS: zero voltage switching
- DCX: dc non-regulated transformer
- PPDAB: partial parallel dual active bridge
- DSAB: double-stacked active bridge
- TSC: tapped-series-capacitor
- ITSC: interleaved tapped series capacitor
- ACCIB: active clamp coupled-inductor-based

- SCC: switched capacitor converter
- RMS: root mean square
- ReSC: resonant switched capacitor
- CCM: continuous conduction mode
- DCM: discontinuous conduction mode
- SCL: switched capacitor inductor
- PWM: pulse width modulation
- EMI: electromagnetic interference
- STC: switched tank converters
- CLSC: coupled inductor switched capacitor
- VM: voltage multiplier
- HVM: hybrid voltage multiplier

I. INTRODUCTION

High-frequency power conversion technology has become critical for high power density, high efficiency, fast response and low cost power electronics. In particular, high-frequency dc-dc converters with high-voltage-conversion-ratio (HVCR) including high step-up/down and bidirectional capabilities, have more and more significance to data-center power supplies, renewable energy systems, electric vehicles, and many other applications [1]–[4]. As the curve in Fig.1 shows, in the recent decades, the operating frequencies keep increasing up to several hundreds of kHz and MHz range. In comparison of low frequency systems, the main diversity is that value and volume of passive components decreases, which improve power density, but the switching losses greatly increase in high frequency (HF) converters, and therefore, HF converters are greatly expected to achieve soft switching. Another difference is that the parasitic parameters will affect converter operation significantly, so that they need well controlled and can even be used in the corresponding circuit, such as leakage inductance and magnetizing inductance in resonance tanks.

Fig. 1. Power density curve under different operating frequency situations.

For obtaining HVCR, the traditional multi-stage architectures have some inevitable shortcomings, such as the large volume of converters and high number of passive components. Besides, after the energy is transmitted through

multiple stages, the efficiency gradually reduces [5]-[7]. Given that, the current main high frequency HVCR dc/dc converters can be classified into inductive-based and capacitive-based approaches. The first category can be further divided into transformer-based and coupled-inductor-based converters. Capacitive-based approaches, instead, can be divided into switched-capacitor-based and switched capacitor with coupled-inductors-based converter. The specific classification of HVCR converters is shown in Fig. 2.

Topologies using inductive-based approach can be adopted in step-up or step-down applications [8]-[11], however, their limited duty cycle prevents them from achieving high

conversion ratio, which also causes high voltage and current stress over components employed. In order to overcome these drawbacks, and matrix transformer structures [17]-[28] and interleaved structures [30]-[31] have been proposed. When isolation is not necessary, converters based on coupled inductors can provide a simple and effective solution. The wide voltage conversion ratio can be achieved with the aid of coupled inductors and other passive devices. Therefore, they have been extensively used in voltage regulator modules (VRM) [32]-[33], buck-boost converters with lower dc bus voltage and others [34]-[35].

Fig. 2. Classification of high-frequency high-voltage-conversion-ratio dc/dc converters.

Owing to favorable trade-offs between device utilization and conversion ratio, switched capacitor converters (SCC) have emerged as prime candidates for high-power-density and HVCR converters because of their inherently higher energy density [68]-[78]. Compared to conventional Buck or Boost topologies, SCCs offer lower conduction losses for a given voltage-current rating of the power devices, moreover they are small size and lightweight circuits, which makes them easy to be integrated. However, they have the shortage of discrete output voltage, and significant inrush current at start-up. By introducing small magnetic components or utilizing parasitic inductances, the typical SCCs can achieve resonant or phase-shift operations, thus regulating voltage conversion ratio and reducing both switching losses and electromagnetic interferences (EMI) [68]-[82]. On the other hand, a combination of coupled inductors and switched capacitors is also broadly adopted in high voltage gain situations [59]-[92], [89]-[97]. Their common feature is using coupled inductors to lift the voltage of capacitors and perform the discharging of the switched capacitors in series. The voltage conversion ratio can be regulated by pulse width modulation (PWM).

In this paper, the structure characteristics, advantages and

disadvantages of HF HVCR dc-dc converters are discussed and reviewed in detail in Sections II-V, then, comparative analysis is given in Section VI and conclusion is drawn in Section VII.

II. TRANSFORMER-BASED TOPOLOGIES

HF transformers can provide galvanic isolation and large voltage/current gain, as well as match impedance between primary and secondary sides. In the following, LLC and DAB converters, either full-bridge or half-bridge configurations for inverter or rectifier circuits, are taken as typical examples, for other resonant topologies, the similar topology construction principle can also be used.

A. Transformer-based LLC converters

The HVCR LLC converter with conventional transformer is shown in Fig. 3(a) [14]. The transformer needs a large turns ratio and it suffers the total voltage conversion pressure. Besides, due to package and thermal constraints, it is necessary to connect synchronous rectifiers (SRs) in parallel, which is difficult to arrange close to the terminal, and causes large leakage inductance and winding losses as well [15]-[16]. To deal with this issue, the transformer can be split into several

smaller ones. The LLC converter with an integrated planar matrix transformer is shown in Fig. 3(b) [17]. The matrix transformer is composed of basic transformer arrays connected to each other to form a single transformer. The traditional single-core structure is divided into several cells with primary windings in series and secondary windings in parallel. The primary currents of the transformer subunits are the same, so the secondary currents are balanced. This structure is very suitable for distributing a large secondary current evenly to every SR, which reduces the secondary current stress and improves the system efficiency. Detailed optimal design and tradeoff analysis of this kind of converters are reported in [18]-[19].

To further reduce the voltage stress, the Sigma converter is proposed in [20] as a 12V VRM to power a microprocessor. In [21] a single-stage converter based on the Sigma converter structure is proposed as a 48V VRM. The structure of the proposed converter is shown in Fig. 4. The Sigma converter is a quasi-parallel converter, in which the input side of two converters are connected in series while the output side is connected in parallel. One is LLC-DCX, which is for transmitting most of the energy to the load. The other is a buck converter, which is for regulating the output voltage. The power shared between the two converters depends on their input voltages because of the equal input current. This power sharing can significantly improve the efficiency of the entire system, thus providing a valid solution for high voltage conversion applications [22]-[23].

Fig. 3. LLC converter. (a) with conventional transformer. (b) with matrix transformer presented in [17].

Fig. 4. Sigma converter for 48V VRM presented in [21].

B. Transformer-based DAB converters

Similar method can be used in other circuits, such as the DAB converter. A partial parallel dual active bridge (PPDAB) converter is shown in Fig. 5 [24]. With several parallel output cells, this topology has current balancing capability and flexible controllability. In order to reduce the number of magnetic components, integrated magnetic component structure is expected and adopted. Compared with discrete magnetic core, integrated solutions reduce core and copper losses, thus improving both efficiency and power density of the system [25]-[27].

A soft-switching high-step-down dc/dc converter based on the active bridge technique is presented in [28], which is called double-stacked active bridge (DSAB) converter. This topology achieves high efficiency high-voltage conversion by using a “double stacking” structure of two stacked full-bridge as shown in Fig. 6. The DSAB converter has several advantages: i) it reduces the rated voltage and improves the overall performance of the converter; ii) it can achieve ZVS easily, thus reducing switching losses; and iii) two stacked converters can realize additional switching modes, overcoming the shortage of losing ZVS operation under light loads, which is a common drawback of conventional DABs [29].

Fig. 5. PPDAB converter introduced in [24].

Fig. 6. Double-stacked active bridge (DSAB) converter presented in [28].

In summary, for the transformer-based topologies, the basic topologies are the LLC converter and the DAB converter. To achieve high voltage conversion ratio, the transformer turns ratio must be very high, which is very challenging. A very effective method to solve this problem is to use a matrix transformer. In this solution, the conventional transformer is divided into several sub-transformer cells. In step-down applications, the primary side (high voltage side) windings are in series and the secondary side (high current side) windings are in parallel. With this method, the turns ratio of the sub-transformer cells can be greatly reduced.

From another perspective, to reduce the transformer conversion stress, the input series output parallel (ISOP) structure can also be used in step-down applications. Usually, two circuits are stacked at the input side and the output of the two circuits are in parallel. With this structure, the transformer turns ratio can be reduced and the output side current can be handled. For step-up applications, the structure should be reversed.

In the future, more sophisticated integration method for matrix transformer should be developed, which can help to reduce both the number and the losses of the magnetic core. Also, for the ISOP structure, the series structure with more stacked parts at the input side should be investigated, in order to further reduce the both voltage and current stress. Also, the derivation criteria and operating methods should be further studied.

III. COUPLED-INDUCTOR-BASED TOPOLOGIES

With similar structure as transformer, coupled inductors based on different windings with electrical connections are also widely used to improve the voltage conversion ratio.

A. Basic coupled-inductor converters

To achieve high conversion ratio, a coupled inductor can be added into a Buck circuit. A tapped-inductor buck converter is shown in Fig. 7(a) [36]-[37], which can enhance the voltage conversion ability. To further extend the voltage conversion ratio and achieve soft switching, a tapped-series-capacitor (TSC) buck converter is proposed in [38]-[39], as shown in Fig. 7(b). The extra series capacitor C_r can store energy and form a resonant tank with the leakage inductance of the coupled inductor. It can help to withstand part of the voltage difference

and realize soft-switching characteristics. If the source of S_3 is connected to the output instead to ground, another structure of the TSC Buck circuit is achieved, as illustrated in Fig. 7(c) [40].

Fig. 7. (a) Conventional tapped-inductor buck converter [36]-[37]. (b) Tapped-series-capacitor (TSC) Buck converter in [38]-[39]. (c) TSC Buck converter with S_3 source connected to output [40].

Some topologies are derived from the TSC Buck converter [41]-[43]. The converter in [41], as shown in Fig. 8(a), has a high step-down ratio. The magnetizing inductor current and the voltage stress of S_2 are very small, but additional diodes and extra energy transfer capacitors are needed. The high step-down converter in [42], as shown in Fig. 8(b), adds an additional output inductance L_o and an energy transfer capacitor C_2 . It is characterized by zero average dc magnetizing inductance current, non-pulsating output current ripple and higher efficiency than the TSC Buck converter [38]-[39]. Reference [43] proposes the modified step-down converter in Fig. 8(c), which adds an extra auxiliary circuit composed of a small capacitor C_3 and a MOSFET S_4 to the circuit in Fig. 8(b), reducing the size of the coupled inductor and the magnetic flux. Also, the voltage spike of S_3 is further restricted and the voltage conversion ratio is much higher than [42].

Fig. 8. Topologies derived from the TSC Buck converter. (a) Step-down converter with wide voltage conversion ratio [41]. (b) High step-down converter with zero dc magnetizing inductance current characteristics and non-pulsating output current ripple [42] (c) modified high step-down converter [43]

B. Interleaved coupled-inductor converters

Parallel and interleaving structures can effectively reduce the current ripple of the input source and allow for an increased power level by sharing a high input current of step-up dc/dc converters. Hence, the current stress of the semiconductor devices and the magnetic component size of the input side can be reduced [44].

Based on above circuits, with interleaving method, a two-phase configuration of TSC Buck is shown in Fig. 9(a). To further reduce voltage stress and increase the conversion ratio, an interleaved tapped series capacitor (ITSC) Buck converter topology [45]-[46] is proposed by inserting the capacitor C_1 , as shown in Fig. 8(b), which combines the advantages of both Buck and TSC Buck converters. Compared to TSC Buck converter in Fig. 7(b), the voltage-conversion-ratio is doubled. Also, it achieves automatic current balancing.

Fig. 9. (a) Two-phase TSC Buck converter. (b) ITSC Buck converter proposed in [45]-[46].

Some converters use the dual coupled inductors concept that comprises of series secondary side coupled inductors for high step-up applications with high power density. As shown in Fig. 10, [47] proposes two coupled inductor based DC/DC converters in the way that it shares the primary sides of coupled inductors and integrates the secondary sides of coupled inductors in a dual coupled structure. All active components are

implemented at the low voltage side with ZVS of all switches and ZCS of all diodes, leading to a high efficiency.

Fig. 10. Topology proposed in [47].

The topology proposed in [48] and shown in Fig. 11 is composed of an interleaved structure, an asymmetric voltage multiplier (VM) cell and a passive lossless clamped circuit. The input current ripple is kept at low value with the help of the interleaving structure.

Besides, [49] introduces an asymmetrical interleaving high step-up converter with a voltage multiplier module. This structure integrates a flyback-boost converter and an interleaving boost converter with dual coupled inductors. [50] introduces an input parallel output series dc/dc converter, which employs an improved interleaving boost converter and VM module. The converter in [51] employs active clamp to achieve ZVS, and hence the switching loss can be reduced significantly.

Fig. 11. Topology proposed in [48].

C. Coupled-inductor converters with basic modules

Couple-inductor converters combine different modules to realize soft-switching, high voltage conversion and high efficiency [52]-[57]. Clamp circuit cells and voltage multipliers are two typical modules, which can be added in coupled-inductor topologies. Here, the concept is simply introduced, together with some typical topologies. More details on voltage-boosting techniques and topologies can be found in [58].

a) Coupled-inductor converters with clamp circuit cell

To reduce the effect of leakage inductance, clamp circuit is a widely used way to absorb the leakage energy and even further improve the conversion ratio.

A high step-up converter with a passive clamp circuit consisting of a diode and a capacitor is shown in Fig. 12 [54]. The leakage energy is also released to the output through the clamping capacitor C_c during the off period. The switching voltage spikes are effectively suppressed, and the structure of this converter is simpler than the active clamp scheme. The active clamp coupled-inductor-based converter (ACCIB converter) is shown in Fig. 13 [55].

Fig. 12. Clamp-mode coupled-inductor buck-boost converter [54].

Fig. 13. Active clamp coupled-inductor-based converter [55].

b) Coupled-inductor converters with voltage multipliers

A half-wave voltage multiplier is inserted in the converter proposed in [56] and shown in Fig. 14. It has the same advantages as Fig. 13. Besides, its coupled inductor acts as a forward transformer to charge C_m during the turn-on interval, and as a filter inductor to provide energy to the output during the turn-off interval, utilizing the magnetic component fully.

To further improve the voltage gain and reduce the turn ratio, voltage multiplier cells are adopted in many topologies. For instance, [59]-[61] employ diode-capacitor VMs in coupled-inductor converters, [60]-[62] propose converters with an asymmetric VM integrated with its secondary winding, and [63]-[66] propose converters with two diode-capacitor cells connected in parallel with secondary winding.

Fig. 14. Single-phase improved ACCIB converter with voltage multipliers[56].

Fig. 15 shows an example of combination of VM and coupled-inductor converter as introduced in [92]. When additional VMs are employed, a higher dc gain is obtained, but at the price of high cost and large volume. That is also why in many of the above references, either voltage stress on the output diode is high or the ratio of voltage gain to component count is relatively low [67].

Fig. 15. Topology proposed in [92].

In summary, for the coupled-inductor-based topologies, the basic structure is tapped-inductor Buck circuit. The voltage conversion ratio is still limited by turns ratio and duty cycle. To

further extend the step-down ability with proper turns ratio and duty cycle, the tapped-series-capacitor (TSC) Buck converter is proposed. The intuitive explanation is to add a capacitor between the input side and the output side, which can withstand a certain dc voltage; this also helps to extend voltage step-down ability. On the other hand, the capacitor can be used to resonate with leakage inductance, which helps to achieve soft-switching.

Based on the TSC Buck circuit, more HVRC are proposed. One derivative method is to use the interleaved structure, which can reduce voltage stress and current ripple. Another modifying method is to adjust the coupled inductor structure, which can further enhance the voltage conversion ability. With the similar idea, the step-up converter can be built by adding a voltage multiplier cells.

In the future, advanced non-isolated topologies based on coupled-inductor need be further developed by using multi-winding structures. Meanwhile, voltage step-down cells or voltage step-up cells can be added between the input and output side. Also, without using a clamp circuit, the leakage inductance is expected to be absorbed or resonate with capacitors to achieve soft-switching.

IV. SWITCHED-CAPACITOR-BASED TOPOLOGIES

Switched capacitor circuits and its derivative topologies are gradually adopted in power electronic systems, especially high voltage conversion ratio applications. One of the classic switched capacitor converter structures is the Dickson topology, as shown in Fig. 16(a). The voltage on C_1 equals to the input voltage V_{in} , the voltage on C_2 is twice of the input voltage, and the voltages on C_3 and C_4 are $3V_{in}$ and $4V_{in}$ respectively. The conversion ratio of the Dickson converter under no-load conditions is 1:5. If the input and output voltage positions are swapped, the output voltage is one-fifth of the input voltage.

The shortcoming of Dickson topology is that the switch voltage stress is high. In order to reduce the voltage stress on the switched capacitors, switched-capacitor converters with a ladder structure are proposed, as shown in Fig. 16(b). Compared to the Dickson structure, the voltage on each capacitor in the ladder structure is V_{in} , and does not increase with the increase of the voltage gain. which improves conversion capacity.

Fig. 16. Classic topologies. (a) Dickson structure. (b) Ladder structure.

The voltage conversion ratio can be increased with the addition of capacitors. A drawback of SCCs is their fixed conversion ratio, in fact, the magnitude of the output voltage can only be a fraction or a multiple of the source voltage. The switching capacitor is exposed to a voltage difference between the source/load and the switching capacitor, thus resulting energy transferring losses (charging losses) and high current spikes.

For high-voltage-conversion-ratio and high-frequency operations, many topologies are proposed based on the two basic architectures to solve above issues, which can be classified in two distinct categories: Dickson-based and ladder-based switched-capacitor converters.

A. Ladder-based switched-capacitor converters

a) Ladder structure with small resonant inductor

A small resonant inductor can be added in the capacitor charging loop in order to reduce charging losses and spikes, thus, a SCC can be transformed into a resonant switched capacitor (ReSC) converter, as shown in Fig. 17 [68]. Because of high frequency and small inductance, the derived topologies still own similar advantages as high energy-density and small volume, meanwhile, resonant energy conversion enables zero current switching which can significantly reduce both peak and RMS current value.

Fig. 17. Topology proposed in [68].

The manuscript [68] presents an optimization model for 2:1 switched capacitor and resonant switched capacitor converters. This can provide favorable trade-off among switching and conduction losses, enabling higher efficiency at a given power-density. Comparisons show that ReSC topology achieves better efficiency and higher power density up to the point in which the

additional conduction losses from adding the magnetic component are higher than the best case for the SCC.

Resonant switched capacitor converters are designed for different operation for soft switching, ZCS in DCM mode and ZVS in CCM mode. In [69], a stray inductance helps to achieve ZCS operation when the switching frequency is up to 500 kHz; [70] adopts zero current detection method to compensate for both the processing delays (from detection to switching action) and the large variations of the resonant characteristics (due to transition between subcircuits), and for any other component variations.

Manuscripts [71]–[75] have demonstrated that the voltage regulation issue of the ReSC converters can be overcome by designing the converters to operate under CCM operation, which reduces both components current stresses and conduction losses, thus, obtaining higher output power values. Also, operating at a fixed switching frequency slightly higher than the resonant frequency results in smaller components, higher power density, and lower EMI noise level. Besides, it realizes PWM-controllable voltage conversion. The voltage-gain range is improved significantly, so that it can tolerate large input-voltage-variation while providing output voltage regulation.

b) Ladder structure with switched-capacitor-inductor cell

As mentioned before, to achieve high-voltage-conversion rates, the required numbers of capacitors tend to soar, increasing the volume and complexity of the converter. To solve this problem, [76] introduces a switched-capacitor-inductor (SCL) cell that comprises inductors, capacitors, and diodes to realize higher voltage conversion and PWM controllability, as shown in Fig. 18. The structures of the SCC and SCL cell can be generalized. The voltage conversion ratios are not only PWM controllable but also adjustable with different structures of SCC and SCL cells, allowing for a flexible design using two design freedom degrees—structures of SCCs and SCL cells.

Fig. 18. Topology proposed in [76].

B. Dickson-based switched-capacitor converters

Based on similar method, small resonant inductors can also be adopted in Dickson structure to create soft-switching and soft-charging. There are two ways to adopt resonant inductors into Dickson structure, using lumped inductors or distributed inductors.

One example of Dickson structure using an aggregated inductor is given in [77], as shown in Fig. 19, where L_r is a small

inductor, which resonates with the capacitors available in the various loops when the switches turn on sequentially. The circuit performs good resonant behavior when the deviation of capacitors causes different resonant frequencies. ZCS condition during both turn-on and turn-off is obtained, thus allowing low switching loss and EMI. Device current is limited by the small resonant inductor and the current spike problem of the switched-capacitor can be solved. However, single inductor needs to occupy a relatively large space.

Fig. 19. Topology proposed in [77].

The distributed inductors can help the converter to reduce overall volume. In certain circumstances, stray inductors can be used. Compared to SCCs with lumped inductors, SCCs with distributed inductors can achieve full soft charging and offer better scalability. One example of SCCs with distributed inductors is proposed in [78], as shown in Fig. 20. In order to achieve regulated output and ZVS, a closed-loop phase-shift control is needed. However, the operating modes are very sensitive to parameter variations.

Fig. 20. Topology proposed in [78]

C. Switched tank converter

To solve above problem, a new class of resonant switched capacitor converters defined as Switched Tank Converters (STC) is proposed [79]. The transformation of SCC into STC topology is based on composition of elementary cells. Each cell can be defined a building block that has two different basic structures as shown in Fig. 21(a) and Fig. 21(b). The STC architecture is obtained by connecting the input and/or the output port of the building blocks in serial or/and in parallel. The resonant block of Fig. 21(a) pairs with the block of Fig. 21(b) and a resonant current flows across the circuit switching approximately at the resonant frequency. The non-resonant building block stabilizes

the voltage of the input and output terminals by connecting C_F to ground or to another stable voltage.

Fig. 21. Two fundamental building blocks in [80].

STC uniquely employs LC resonant tanks to partially replace the dc flying capacitors available in traditional switched capacitor converters, thus providing complete soft charging, soft-switching and low device voltage stress under all operating conditions. A typical step-down converter is shown in Fig. 22. In a step-down STC, all the switches are normally blocking either V_{out} or $2V_{out}$ in their OFF state. Compared to resonant switched capacitor converters, they have better characteristics, such as immunity of component deviation, low voltage stress and scalability. Table I presents comparison of SCC and STC topologies. The converters proposed in [84]-[88] combine STC topologies with Buck-boost or Buck topologies to realize partial voltage regulation.

In summary, for switched-capacitor-based topologies, the ladder circuit and Dickson circuit are two basic structures. However, their main shortcomings are their large charging/discharging and switching losses, also, the voltage conversion ratio is not continuous. Thus, based on these two basic topologies, small resonant inductors are added in series with the flying capacitor, which can help to achieve soft switching and soft charging/discharging.

Fig. 22. Topology proposed in [80].

TABLE I COMPARISON BETWEEN SCC AND STC TOPOLOGIES

	SCC	SCC with aggregated inductors [80] [82]	SCC with distributed inductors [78] and [83]	STC
Soft charging	No	Partial	Full	Full
Soft switching	No	Yes	Yes	Yes
Immunity to component non-idealities	Poor	Medium	Very poor	Very good
Device voltage clamp	Clamped, low stress	Case by case	No clamp, high stress	Clamped, low stress
Scalability	Poor	Medium	Very good	Very good

Also, the resonant switched capacitors can be divided into two fundamental building blocks, the non-resonant one and the resonant one. By combining the two fundamental building blocks, the switched tank converter (STC) has been proposed in recent years, which can achieve soft switching and soft charging. In addition, the circuit is insensitive to component deviations.

In the future, the switched-capacitor-based topologies, especially the resonant switched-capacitor circuit, should be focused on high current applications. In this case, how to achieve a compromise between the conduction loss and switching losses is a major concern. Also, the auxiliary module to extend the voltage conversion ratio should be further investigated.

V. SWITCHED CAPACITOR WITH COUPLED INDUCTOR BASED TOPOLOGIES

If a compromise between voltage gain and the numbers of switches and capacitors is expected, the coupled inductors can be adopted to increase the voltage gain of switched capacitor converters, which does not depend on the number of capacitors as described before. By adopting the coupled inductor and adjusting the turn ratio, the voltage gain can be dramatically increased.

Besides the typical switched capacitor topology structure, the basic concept of switched capacitor converter is also be used in other topologies, which means in high voltage side the capacitors are in series; in low voltage side the capacitors are in parallel. Based on the basic concept, many different topologies are also proposed.

A. Ladder structure with coupled inductor

[89] adopts the technique of both coupled inductor and ladder structure as shown in Fig. 23. When the switch is on, both magnetizing inductance and leakage inductance are charged by the dc source. The energy stored in odd capacitors is then transferred to even capacitors through the coupled inductor.

Fig. 23. Topology proposed in [89].

A part of the energy is transferred to odd capacitors by the input source through the coupled inductor. When the switch is off, the energy previously stored in leakage inductor and magnetizing inductor is released to capacitor C_1 . A part of magnetizing inductor energy is transferred to the secondary side through coupled inductor and charging odd capacitors. The

remaining energy and the energy stored in even capacitors is transferred to the load. The topology shows a relatively high conversion gain and can be easily extended without adding extra windings for high voltage conversion ratio.

The topology in [90] comprises a synchronous rectification boost unit and multiple coupled-inductor-switched-capacitor (CLSC) units, as shown in Fig. 24. Each CLSC unit includes two capacitors C_{2i-1} and C_{2i} , two diodes D_{2i-1} and D_{2i} ($1 \leq i \leq n$), as well as one winding having n_i turns of the coupled inductor.

Fig. 24. Topology proposed in [90].

The leakage inductance of the coupled inductor is utilized to achieve soft-switching of the diodes. The proposed converter can provide high voltage conversion ratio by employing multiple CLSC units or setting a larger turns ratio of the coupled inductor or increasing the duty ratio. For a specific converter, the turn ratio and the number of CLSC units are fixed, output voltage is controlled by changing the duty cycle in PWM mode with variable the load or input voltage. Compared to existing converters based on SCC and dual-winding coupled inductor, a higher voltage conversion gain is achieved as well as easy expansion ability.

B. Other SCCs with coupled inductor

a) Two-winding-based converters

Based on basic concept of switched capacitors, to obtain a high voltage gain, capacitors need to be connected in series in high voltage side and in parallel in low voltage side. Based on that, [91] proposed a high step-up dc/dc converter by replacing the inductor with a coupled inductor, as shown in Fig. 25. Switched capacitors C_1 , C_2 are used to transfer energy from the coupled inductor and lift the output voltage.

By introducing the coupled inductor, the voltage gain of the proposed converter is increased.

Fig. 25. Topology proposed in [91].

b) Three-winding-based converters

To further reduce the number of capacitors and diodes, a new hybrid voltage multiplier (HVM) cell is subsequently discussed, formed by a three-winding coupled inductor and only one VM, shown in Fig. 26. The new HVM is used for realizing a second proposed converter based on similar boost principles, but a higher voltage gain than the first proposed converter in Fig. 26 by using an extra VM. One of its advantages is the elimination of turn-off recovery problem of its output diode, which prevents undesired oscillations during its turn-off. The leakage inductance energy has been successfully recovered to the load.

Fig. 26. The second topology proposed in [92].

Fig. 27. Topology proposed in [97].

Other three-winding coupled-inductor based converters are proposed in [93]-[96]. One example of stacked three windings

coupled inductor SCC is shown in Fig. 27 [97]. It is based on the topology in [91], and it adds one more winding of the coupled inductor to further increase the voltage gain. It uses two output capacitors to relieve the high voltage stress of output diodes. It achieves zero voltage switching in both switches.

In summary, in switched capacitor converters with coupled inductors, the basic cell is the voltage multiplier (VM), which is typically composed by capacitors, inductor and diode. The basic topology can be obtained starting from a circuit composed by two windings coupled inductors. To further increase the voltage conversion capability and performance, a three-winding coupled inductor is gradually adopted in the circuit.

Also, for the ladder or Dickson circuit, the coupled inductor can be added to achieve soft switching. By changing the control variables, the voltage conversion ratio can be adjusted.

In the future, different voltage multipliers should be investigated to increase the voltage conversion ability, especially the topologies based on multiple winding coupled inductors. Also, for coupled inductors, the energy of the leakage inductance is expected to be used. For the ladder or Dickson circuit, the coupled inductor can also be added in the central part, which can further increase the voltage conversion ratio.

VI. COMPARISON AND SUMMARY OF INDUCTOR-BASED AND SWITCHED-CAPACITOR-BASED TOPOLOGIES

Based on the above analysis, a detailed quantitative summary of the topologies mentioned in this article in terms of number of components, voltage conversion ratio, switching voltage stress, soft-switching performance and peak efficiency is given in Table II. Another summary table, Table III, contains their characteristics, advantages, disadvantages and proper applications.

TABLE II. PROPERTIES COMPARISONS OF TYPICAL HIGH-FREQUENCY HIGH-VOLTAGE-CONVERSION-RATIO TOPOLOGIES.

Topology			(switch/ capacitor/ diode/ inductor/ transformer)	Voltage conversion ratio	Switch voltage stress	Switch current stress	Soft- switching	Isolated	Input/output voltage Switching frequency/ Power rating	Power density	Peak efficiency
Transformer- based converters	LLC	[17]	10/2/0/1/1	$1/2n$	$V_{in}/2$	8A	ZVS turn-on	Yes	380V/12V 1MHz/800W	900W/in ³	97.6%
		[21]	8/4/0/2/1	$1/n$	-	3A	ZVS turn-on (LLC)	Yes	48V/0.8~1V 1MHz (LLC), 600kHz (Buck)/ 80W	420W/in ³	93.4%
	DAB	[24]	16/2/0/1/1	$1/3n$	-	30A	ZVS	Yes	400V/50V 1MHz/1.2kW	30.8W/in ³	97.51%
		[28]	13/9/0/2/1	$1/n$	-	-	ZVS	Yes	380V/12V 175kHz/300W	60W/in ³	97.0%
Coupled inductor- based converter	Basic coupled- inductor converters	[38]	3/2/0/1/0	$\frac{DN_2}{N_1+N_2}$	$V_{ds1} = V_{ds3} = V_{in}$ $V_{ds2} = \frac{N_2 V_{in}}{N_1+N_2}$	3A	ZVS (S_1) ZVZCS (S_2, S_3)	No	48V/3.3V 100kHz/49.5W	170W/in ³	95.1%
		[41]	3/3/3/1/0	$\frac{DN_2}{N_1(1-D)+N_2}$	$V_{ds1} = V_{ds3} = V_{in}$ $V_{ds2} = \frac{N_2 V_{in}}{N_1(1-D)+N_2}$	6A	ZVS	No	48V/1.2V 100kHz/30W	-	90.2%
		[42]	3/2/0/2/0	$\frac{DN_2}{N_1+N_2}$	$V_{ds1} = V_{ds3} = V_{in}$ $V_{ds2} = \frac{N_2 V_{in}}{N_1+N_2}$	4A	ZVS	No	48V/3.3V 100kHz/33W	-	98.1%
		[43]	4/3/0/2/0	$\frac{DN_2}{N_1+2N_2}$	$V_{ds1} = V_{ds3} = \frac{N_1 V_{in}}{N_1+2N_2}$ $V_{ds2} = V_{ds4} = \frac{N_2 V_{in}}{N_1+2N_2}$	4A	ZVS	No	48V/3.3V 100kHz/33W	228W/in ³	94.8%

	Interleaved coupled-inductor topologies	[46]	6/4/0/2/0	$\frac{D}{2} \frac{N_2}{N_1+N_2}$	$V_{ds1} = V_{ds4} = V_{in}$ $V_{ds3} = V_{ds6} = \frac{V_m}{2}$ $V_{ds2} = V_{ds5} = \frac{N_2 V_{in}}{N_1+N_2}$	6A	ZVS	No	48V/3.3V 400kHz/66W	-	95.6%
		[47]	4/3/2/0/2	$\frac{3n+1}{1-D}$	$\frac{V_o}{3n+1}$	24A	ZVS	No	30-40V/400V 50kHz/1kW	30W/in ³	96.6%
		[48]	2/4/5/0/2	$\frac{3n+1}{1-D}$	$\frac{V_o}{3n+1}$	6A	ZCS	No	40V/400V 50 kHz/400W	13.1W/in ³	97.3%
	Topologies with basic modules	[54]	1/2/2/1/0	$\frac{N_1+DN_2}{(1-D)N_1}$	$\frac{V_o N_1}{N_1+DN_2}$	36A	-	No	48~75V/400V 100kHz/1kW	-	92.3%
		[56]	2/3/2/1/0	$\frac{N_1+N_2}{(1-D)N_1}$	$\frac{V_o N_1}{N_1+N_2}$	20A	ZVS	No	48V/380V 100kHz/500W	-	97%
		[92]a	1/6/6/0/1	$\frac{3+2n+nD}{1-D}$	$\frac{V_o}{3+2n+nD}$	10A	-	No	25V/400V 100kHz/200W	20W/in ³	95%
SC	Ladder based SCCs	[68]	4/3/0/1/0	$\frac{D_2}{3D_2+3D+1}$	$V_{in}/2$	-	ZVS	No	4.5V/2V 30MHz/3.35W	387W/in ²	85.7%
		[76]	4/5/4/2/0	$\frac{d}{md+(m-1)n}$	-	2.4A	-	No	48V/6V 200kHz/36W	21.5W/in ²	80%
	Dickson Based SCCs	[77]	2/4/4/1/0	3	-	8A	ZCS	No	40V/120V 200kHz/100W	-	90%
		[78]	9/4/0/5/0	1/6	2.6	4.2A	ZVS	No	60V/10V 500kHz/600W	-	N.A.
		[80]	10/4/0/2/0	1/4	2V _o	-	ZCS	No	54V/13.5V 320kHz/650W	54.2W/in ³	98.9%
SC+CL	Ladder structure with CL	[89]	1/4/4/0/1	$3+2n/1-D$	$V_o/3+2n$	20A	Hard switching	No	30V/380V 100kHz/300W	-	96.7%
		[90]	2/3/2/1/1	$\frac{1}{1-D} \sum_{k=1}^m \frac{n_k}{m+1-k}$	D/V_{in}	20A	ZCS	No	20-30V/200V 50kHz/120W	-	93.9%
	2 windings	[91]	1/2/3/0/1	$\frac{n+2}{1-D}$	$V_o/(2+n)$	8A	Hard switching	No	25-45V/380V 100kHz/100W	15W/in ³	96.4%
		[93]	1/2/3/1/0	$\frac{2}{1-D}$	$V_o/2$	4.4A	Hard switching	No	25-45V/380V 100kHz/100W	-	95.8%
	3 windings	[92]b	1/4/4/0/1	$\frac{2+ \langle N_1+N_2 \rangle + N_2 D}{1-D}$	$\frac{1}{2+ \langle N_1+N_2 \rangle + N_2 D}$	5A	-	No	25V/400V 100kHz/200W	24W/in ³	95%
		[97]	1/4/5/1/1	$\frac{n+2}{(1-D)^2}$	$V_o/(2+n)$	7.5A	-	No	16-36V/380V 40kHz/500W	44.3W/in ³	94%

TABLE III. SUMMARY OF HIGH-FREQUENCY HIGH-VOLTAGE-CONVERSION-RATIO TOPOLOGIES.

Topology			Characteristics	Advantages	Disadvantages	Appropriate Applications
Transformer-based Converters	LLC	[17]	The matrix transformer is used so the secondary current is balanced	<ul style="list-style-type: none">• Isolation• volume reduction by using leakage inductor to resonant	<ul style="list-style-type: none">• Large amount of switches	<ul style="list-style-type: none">• High voltage and high power situations• Isolation situations
		[21]				
	DAB	[24]	<ul style="list-style-type: none">• Good current balancing capability• Flexible controllability with several parallel output cells			
		[28]	<ul style="list-style-type: none">• High-voltage conversion can be achieved by using double stacked full-bridge structure			
Converters based on coupled inductor	Basic coupled-inductor topologies	[38][46]	<ul style="list-style-type: none">• Resonant cell around the switches and diodes can help to achieve soft-switching	<ul style="list-style-type: none">• High inrush current stress•Discrete output voltage	<ul style="list-style-type: none">• lower operating frequency than the transformer-based ones• Topologies are all non-isolated	<ul style="list-style-type: none">• Relatively low input voltage and low power situations• mostly high step-down situations
		[41]				
		[42]				
		[43]				
	Interleaved coupled-inductor topologies	[46]	<ul style="list-style-type: none">•Interleave two units of the basic coupled-inductor to boost output voltage	<ul style="list-style-type: none">• Low input current ripple•the current stress of the semiconductor devices• the power rating increases	<ul style="list-style-type: none">• Large amount of components• Relatively bulky	<ul style="list-style-type: none">• mostly high step-up situations• low current ripple situations
		[47]				
	[48]					
	Topologies with basic modules	[54]	<ul style="list-style-type: none">• Different clamp circuits are adopted to absorb the leakage inductance energy	<ul style="list-style-type: none">• lower high voltage spikes• higher voltage conversion ratio	<ul style="list-style-type: none">•Most topologies are non-isolated	<ul style="list-style-type: none">• mostly high step-up situations
		[56]				
[57]						
SC	Ladder based SCCs	[68]	<ul style="list-style-type: none">• Same voltage stress on capacitors, which is input voltage• Relatively large amount of	<ul style="list-style-type: none">• High power density• Able to be integrated•Fast dynamic response	<ul style="list-style-type: none">•High inrush current stress• Discrete output voltage	<ul style="list-style-type: none">• low power applications• modern power electronics
		[76]				

			capacitors	• Soft charging and switching to improve efficiency		applications
	Dickson based SCCs	[77]	• Large voltage stress on capacitors, which increases as capacitor amount • Small amount of capacitors			
		[78]				
		[80]				
SC+CL	Ladder structure with CL	[89]	The voltage conversion ratios are not only PWM controllable but also adjustable with different structures of SCC and SCL cells	• High design freedom • PWM controllability	• Voltage spike problem caused by leakage inductance • Complex coupled magnetic design	• large voltage conversion • Renewable energy system and distributed power microgrids.
		[90]				
	2 windings	[91]	• Use coupled inductor to increase capacitor voltages • Able to adopt voltage multiplier • Need clamping circuit to absorb leakage energy • Relatively high number of operation modes	• High boost ability • Need large amount of capacitor for voltage multipliers • Switches suffer low voltage stress and conduction loss reduced	• Diode recovery problems •large voltage spikes caused by leakage inductor	
		[93]				
	3 windings	[92]b				
		[97]				

As Table II and III show, the transformer-based ones are used in high voltage and high power situations, which provide the feature of isolation. However, usually the number of switches is large. The coupled-inductor-based ones are proper candidates for low voltage situations, which can reduce the number of switches. Usually, coupled-inductor-based circuits suffer from switching losses and the operating frequency is lower than the transformer-based ones. For HF HVCR, there are two main issues, one is how to achieve the desired conversion ratio with proper turns ratio of transformer or coupled inductor and duty cycle, the other is how to achieve the soft-switching to reduce switching losses.

For the first concern, it can be solved from the perspective of topology architecture. The basic concept can be described as “input series and output parallel”. In high voltage port, multiple stacked cells or series transformer winding can be adopted. In low voltage port (high current port), multiple cells or windings can be parallel or interleaving. With above methods, the voltage and current can be allocated. Another method is to add series capacitors or voltage multiplier between the input port and output port, which can help to carry part of voltage difference between input port and output port.

For the second concern, soft switching is greatly expected to improve efficiency. In the transformer-based converters, such as LLC, DAB, the soft switching characteristics, especially ZVS, can be easily realized based on inductive equivalent impedance of resonant tank. For high frequency situations, the leakage inductance of transformer is usually adopted to operate as the resonant inductor. For coupled inductor situations, resonant cell around the switches and diodes can help to achieve soft-switching. In hard switching converters, the clamp circuit is often used to absorb the leakage inductance energy in order to suppress high voltage spikes caused by the leakage inductance. Based on above analysis, the develop of new topologies should also follow the two principles.

Compared with the inductive-based approach, the capacitive-based approach is more suitable for low power applications. Classical SCCs do not rely on magnetic energy storage, which

can support a higher power density compared with traditional converters for a given conversion ratio. Thus, they are promising for high-power density and high-efficiency power supplies. For high frequency SCCs, two main concerns are the high switching loss and high charging loss. Thus, ReSC converter combining switched capacitor and resonant inductor is an emerging approach to achieve low switching loss and charging loss, such as STC, which can achieve soft switching, mitigate EMI and current spike issues.

To achieve a compromise between number of devices and voltage conversion ratio, SCC combined with coupled inductor is an effective method to increase the voltage gain. Because of its simple structure, high-voltage gain, low switching voltage stress, and mitigation of the reverse recovery problem of the output diode, the SCC based on coupled inductors is a promising candidate for renewable energy applications. Most of the capacitive-based converters are non-isolated, thus, switched capacitor combined with transformer to achieve isolation function should be further investigated in the future.

In summary, there are four categories of HVCR topologies addressed in the review. The transformer-based topology is suitable to be applied in isolated applications, and the other three topologies are suitable to be applied in non-isolated applications. From a power perspective, the transformer-based topologies are suitable to operate in high power applications. The coupled-inductor-based converters and switched-capacitor with coupled inductor-based topologies are suitable to operate in medium power situations. The switched capacitor circuit is suitable to operate in low power situations. From the power density perspective, the switched capacitor solution can achieve the highest power density. Based on the analysis above, the suitable topology for certain applications and specifications can be chosen among the four categories.

VII. CONCLUSION

High-frequency high-voltage-conversion-ratio converters represent an important research field in power electronic topologies and have high practical interest in many fields including renewable energy power systems, electric vehicle

power supply systems and many others, due to their wide input range, high conversion ratio, low stress, high efficiency, high power density and other excellent features. The working principle, and advantages and disadvantages of inductive-based and capacitive-based approach in the HF HVCR converters have been analyzed in detail in this paper. The performance of the corresponding topologies is briefly summarized and compared. This survey can provide guidance to select proper topologies and derive new topologies in HF HVCR dc/dc applications.

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