



Review of DC-DC Converter Topologies Based on Impedance Network with Wide Input Voltage Range and High Gain for Fuel Cell Vehicles

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Received: 7 May 2021 / Accepted: 31 August 2021 / Published online: 19 October 2021
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Abstract

The development of fuel cell vehicles (FCVs) has a major impact on improving air quality and reducing other fossil-fuel-related problems. DC-DC boost converters with wide input voltage ranges and high gains are essential to fuel cells and DC buses in the powertrains of FCVs, helping to improve the low voltage of fuel cells and “soft” output characteristics. To build DC-DC converters with the desired performance, their topologies have been widely investigated and optimized. Aiming to obtain the optimal design of wide input range and high-gain DC-DC boost converter topologies for FCVs, a review of the research status of DC-DC boost converters based on an impedance network is presented. Additionally, an evaluation system for DC-DC topologies for FCVs is constructed, providing a reference for designing wide input range and high-gain boost converters. The evaluation system uses eight indexes to comprehensively evaluate the performance of DC-DC boost converters for FCVs. On this basis, issues about DC-DC converters for FCVs are discussed, and future research directions are proposed. The main future research directions of DC-DC converter for FCVs include utilizing a DC-DC converter to realize online monitoring of the water content in FCs and designing buck-boost DC-DC converters suitable for high-power commercial FCVs.

Keywords Fuel cell vehicles · DC-DC boost converter · Evaluation systems and indexes · High gain topology

Abbreviations

CG	Common ground	TL	Three level
CIC	Continuous input current	VG	Voltage gain
EMI	Electromagnetic interference	VL	Voltage lifting
FC	Fuel cell	VM	Voltage multiplier
FCV	Fuel cell vehicle	VS	Voltage stress
ICR	Input current ripple		
IVR	Input voltage range		
PEMFC	Proton exchange membrane fuel cell		
PI	Proportional-integral		
PWM	Pulse-width modulated		
SC	Switched-capacitor		
SI	Switched-inductor		

1 Introduction

Fuel cell vehicles' (FCVs) only by-product is water, truly achieving zero emissions. In recent years, FCVs have developed rapidly in the field of new energy vehicles [1, 2]. However the voltages of fuel cell (FC) stacks cannot match the bus voltages of vehicles. Moreover, due to the shortcomings of FCs, such as slow dynamic responses and wide output voltage ranges, auxiliary power sources (such as batteries) are required to act as external energy storage systems [3, 4]. Therefore, DC-DC boost converters are utilized to achieve voltage decoupling and power distribution [5, 6].

The electrochemical reactions in FCs occur on the catalytic layers. At present, Pt is the catalyst typically used in FCVs [7]. Current ripples can induce the failure of Pt in the catalyst layer and even accelerate the degradation rate of

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the proton exchange membrane, reducing the lives of proton exchange membrane fuel cells (PEMFCs). In Ref. [8], an amplitude of low-frequency current ripple higher than 4% significantly reduced the durability and the life of the FC. In Ref. [9], the frequency of the current ripple in the FC system was required to be higher than 1.25 kHz. FCs can operate reliably for low-frequency current ripple contents lower than 5%. Therefore, to extend the lives of FCs, DC-DC boost converters require low input current ripples (ICRs).

The output characteristic of FCs are “soft”, namely, the terminal voltage of an FC decreases with increasing output current [10, 11]. The output characteristic curve of an FC is divided into polarization, ohmic, and concentration difference sections [12]. The polarization section corresponds to the initial stage of the reaction where the voltage drops rapidly. This reduction is caused by the movement of electrons between the electrodes and the destruction and reformation of chemical bonds during chemical reactions at the electrodes. The ohmic section corresponds to the deceleration of the voltage drop rate, and the decline curve becomes linear. This is caused by the resistance of the FC modules and the ionic resistance of electrolytes. The concentration difference section corresponds to an increased voltage dip under a large current, wherein the reactants reach the electrode surface by diffusion and convection. When the diffusion rate is lower than the rate of the electrode reactions, the reactant concentrates on the electrode surface and the electrolyte body differ significantly [13]. In conclusion, considering the V-A curve of FC, DC-DC boost converters require wide input voltage ranges (IVRs) to meet the current variations in FCs caused by different road conditions.

The voltage of a single FC is less than 1 V, and multiple FCs in series are used as an FC stack [14]. However, limited space in the vehicle, in turn, limits the number of single FCs, and the output voltage of the FC stack remains low. At present, the predominant DC bus voltage of an FCV is 400 V [15]. To achieve voltage matching, the voltage gain (VG) of the DC-DC boost converter should be as high as possible and no less than 10 [16].

Thus, to extend the lives of FCs, DC-DC boost converters should maintain continuous input currents (CICs) and ICRs [17–20]. Considering that the input voltage of an FC decreases with increasing input current, the step-up DC-DC topology should have a wide IVR [21, 22]. Owing to the limited space in FCVs, the converter should be miniaturized and also have high frequency, efficiency, and reliability [23].

A DC-DC converter constitutes a typical nonlinear system, and analyzing the dynamic operation characteristics of the circuit is complex. Based on accurate modeling, the static and dynamic characteristics of a DC-DC converter system can be easily analyzed and evaluated, and the controller parameters can be matched. Currently, the modeling methods of DC-DC converters primarily include a state-space

averaging method, pulse-width modulated (PWM) switch modeling, and an equivalent transformer method. Owing to the “soft” output voltage characteristics of FCs and the varying road conditions, DC-DC converters need to maintain a constant bus voltage and achieve dynamic regulation of output power. Realizing the control objective primarily includes following the given signal and suppressing the disturbance signal. Therefore, the rapidity, robustness, accuracy, and low complexity of the controller for the converter are important aspects in optimizing the performance of a DC-DC converter. Typical control methods for DC-DC converters include proportional-integral (PI) control, sliding mode control, adaptive control, robust control, fuzzy control, and novel integrated control strategies [24–27].

As part of FCVs, developing vehicle technology can promote research on DC-DC converters. For instance, the powertrain of FCVs can be divided based on the different powertrain structures into energy-type and power-type, requiring different types of DC-DC converters [28]. Permanent magnet synchronous motors, which have wide ranges of speed regulation, are commonly used in FCVs; therefore, DC-DC converters are required to regulate the output power quickly [29]. Vehicle velocities and driving conditions affect the output powers of FCs. Research on vehicle velocity estimation, motor torque, and stability control can provide guidelines for designing DC-DC converters [30, 31].

Most of the previous reviews focused on the classification of various DC-DC topologies, while ignoring the derivation of DC-DC topologies based on impedance network and the applicability of FCVs. The main contributions of this study are as follows. (1) Based on the different types of impedance networks, the non-isolated DC-DC converter topology was divided into four types: inductor + inductor, capacitor + capacitor, inductor + capacitor, and hybrid / cascaded. On the basis of the proposed principles of impedance transformation, 12 types of impedance network structures were derived and classified. (2) Based on this classification, the DC-DC topologies proposed in existing literature are reviewed, and the applicability of each DC-DC converter in the powertrain of FCVs is discussed. This provides the direction for designing DC-DC converters for FCVs. (3) An evaluation system of a DC-DC converter for FCV is established. The DC-DC converters proposed in mainstream literature are then compared and evaluated, and their applicabilities are discussed. (4) The issues faced while researching DC-DC converters for FCVs are summarized, and the future research directions for DC-DC converters are presented.

The main contents of this study are as follows: Sect. 2 introduces the derivation process and the research status of existing step-up DC-DC topologies based on the impedance network. In Sect. 3, the evaluation system of DC-DC boost converters for FCV is constructed, the comparison and evaluation of typical DC-DC boost converters are performed,

and suggestions for selecting the topology for FCVs are provided. Section 4 summarizes the key problems of DC-DC converters and prospects for future research directions. Section 5 constitutes conclusions.

2 Research Status of DC-DC Boost Converters for FCVs

There exist two types of DC-DC boost converters: isolated and non-isolated DC-DC boost converters. Depending on the presence of a coupling structure, the non-isolated DC-DC boost converter is further divided into DC-DC boost converters based on the coupled inductor and DC-DC boost converters based on impedance network [32].

A transformer is added between DC and DC in the non-isolated DC-DC boost converter to realize DC-AC-DC step-up conversion. A high VG can be achieved by adjusting the turn ratio of the transformer; however, a high turn ratio would lead to a large leakage inductance, increasing the voltage stress (VS), thereby decreasing the efficiency [33]. In addition, the magnetic components would reduce the power density, which proves disadvantageous to a vehicle with less available space [34, 35]. Therefore, the isolated DC-DC boost converter is inapplicable to FCVs.

A high VG topology based on coupled inductor can be obtained by terminating the electrical isolation of the transformer and adding a coupled inductor to the non-isolated converter [36–38]. The VG can also be effectively improved by selecting a high turn ratio. However, the risk of leakage inductance remains; thus, an additional snubber circuit should be added to the converter based on the coupled inductor. This addition, however, increases the cost, complexity,

and size [39–41]. Therefore, the converter based on coupled inductor is not suitable for the FCV powertrain.

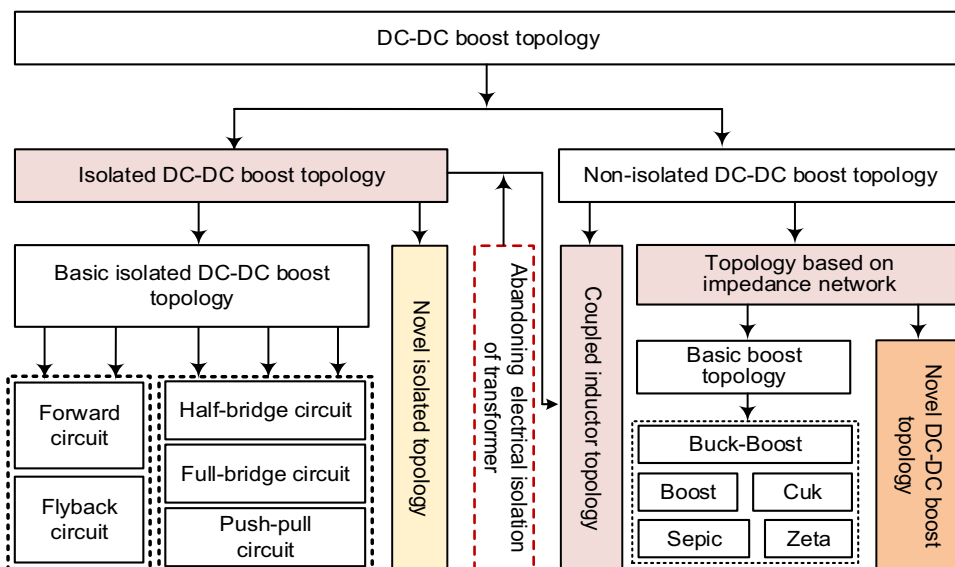
The non-isolated DC-DC boost converter is simple with no leakage inductance. It is, therefore, more suitable for FCVs. To ensure the conversion efficiency of the DC-DC converter, most of the existing converters for FCVs are traditional boost converters, which have few devices [42]. However, owing to the influence of parasitic parameters, the boost converter cannot work under a limited duty cycle. Therefore, it cannot achieve the high step-up ratio required by FCVs in practice [43, 44]. In addition, an interleaved boost converter topology can effectively reduce the requirement for power devices and ICR and improve the lives of FCs. Gao Dawei’s team from Tsinghua University successfully applied an interleaved boost converter to an FC bus and obtained favorable results [45, 46]. However, the low VG renders it unsuitable for a low power FC powertrain.

The step-up converter based on an impedance network (consisting of an inductor, capacitor, diode, and a switch) does not face issues of voltage spikes and low power densities caused by leakage inductance. A topology with high VG, low ICR, and wide IVR can be designed from the perspective of FCV applications. This study classified and discussed this type of converter. The main classification of DC-DC boost converters is shown in Fig. 1.

2.1 Derivation and Classification of Boost Topology Based on Impedance Network

By combining the energy storage elements (inductor and capacitor) with a diode and switch according to the following four principles, boost converter structures based on impedance network can be obtained.

Fig.1 Classification of DC-DC topology



Principle 1: To increase the VG, inductors and capacitors are charged from the power source in parallel and discharged to the load in series.

Principle 2: To increase the VG, when the switch is closed, energy is exchanged between the capacitors, and when it is open, both the capacitors and the power source supply energy to the load together.

Principle 3: To increase the VG, the diode is attempted to be replaced by an inductor without violating the circuit laws.

Principle 4: To reduce the VS of the components, the capacitor should be added into the impedance network, forming a circuit loop with a switch, diode, and load.

Different types of impedance networks mainly include:

(1) Inductor + Inductor

Two inductors are combined according to Principle 1, and their operating states depend on the states of the diodes (or switches). Thus, the switched-inductor (SI) structure can be obtained.

If the input current of SI is pulsating, in order to reduce the ICR, each inductor switches on in turn with the same trigger phase difference. Therefore, only one inductor is charged at a time, and an interleaved topology is obtained. The diode is switched off while the inductors are charging. If this diode is replaced by a capacitor in such a way that the two inductors and the capacitor work according to Principle 1, the structure of the SI combined with a charge pump is obtained.

(2) Capacitor + Capacitor

Two capacitors are combined according to Principle 1, and their operating states depend on the states of the diodes (or switches). The switched-capacitor (SC) structure can, thus, be obtained. According to Principle 2, a voltage multiplier (VM), including Cockcroft–Walton and Dickson VMs, can be obtained by combining the two capacitors. The Z-source structure can be obtained by modifying the SC structure according to Principle 3. The quasi-Z-source structure can be obtained by the impedance transformation of the Z-source structure. The modified structure of the VM can be obtained by modifying the VM according to Principle 3. A three-level (TL) topology can be obtained by combining two capacitors according to Principle 4. The relationship between the topologies of capacitor + capacitor is shown in Fig. 2.

(3) Inductor + Capacitor

According to Principle 1, topologies based on impedance network can be obtained by combining an inductor with a capacitor.

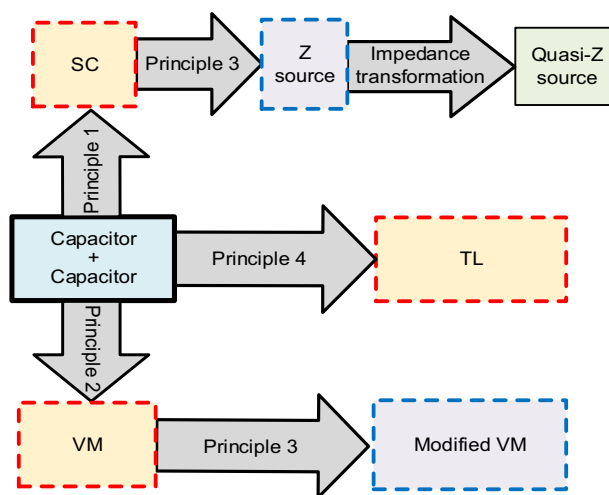


Fig. 2 Relationships among Capacitor + Capacitor topologies

(4) Hybrid / Cascaded

In addition, integrating and cascading the three types of impedance networks above can optimize the performance of DC–DC boost converters and aid in obtaining certain novel topologies.

On the basis of the classification of topologies based on impedance network, as shown in Fig. 3, this study reviews existing literature from recent years, summarizes the advantages and disadvantages of each topology to elucidate its applicability in the FCV powertrain, and provides the basis for designing DC–DC boost converters for FCVs.

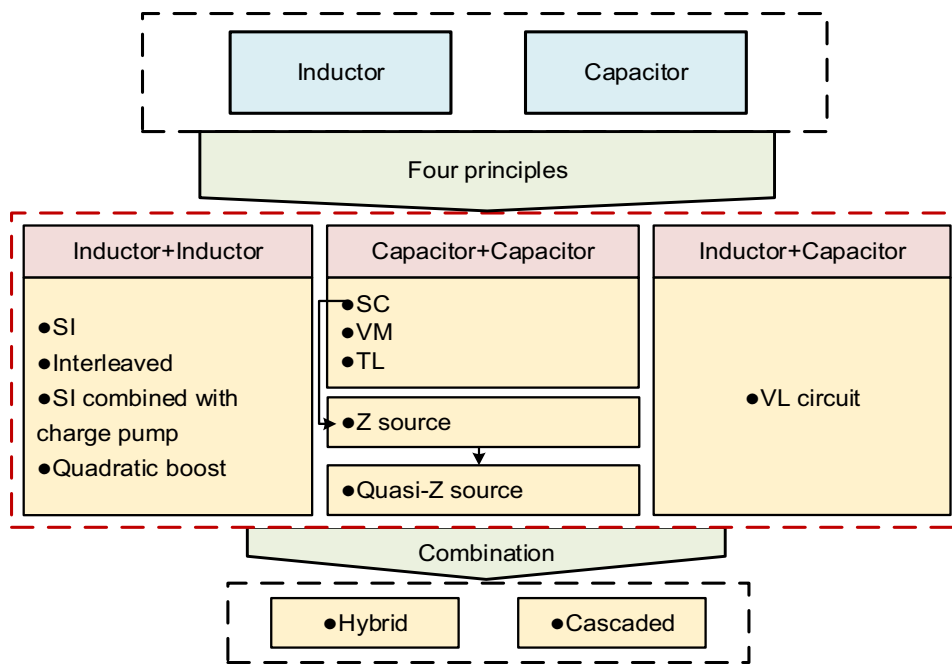
2.2 Impedance Network Composed of Inductor + Inductor

2.2.1 SI Structure

According to Principle 1, an SI structure can be obtained by utilizing two inductors to store and release more energy, as shown in Fig. 4. The components L1–D2 and L2–D1 in Fig. 4a L1–S2 and L2–S1 in Fig. 4b constitute the SI.

The operating principle of SI was extensively analyzed in Refs. [16], [47], and a family of SI topologies with high VG was proposed. In addition, a hybrid SI topology was derived by combining passive and active SI units. In Ref. [48], a transformerless high VG DC–DC boost converter based on the SI structure was proposed for the FC system. Moreover, the capacitor and inductor were connected in parallel in an attempt to enhance the VG. As proposed in Ref. [49], a step-up DC–DC converter combined the traditional switched-boost network with an SI unit, exhibiting the characteristics of high VG, fewer components, low VS, and good scalability. In Ref. [50], a step-up topology was presented by

Fig.3 Novel topologies based on impedance network



combining the active and passive SIs, exhibiting the characteristics of high VG (> 10), low component stress, and high efficiency (95.5%). In Ref. [51], two inductors of quadratic boost were replaced with passive SIs, obtaining four derived structures that were extensively compared.

The SI can replace the inductor in existing DC-DC boost converters, significantly increasing the VG of the topology. It also has the merits of simple and easy control. The DC-DC converter based on SI can effectively match the low output voltage of an FC with the high bus voltage in the powertrain of an FCV. However, on connecting the SI to the FC stack, the output current of the latter would fluctuate, reducing the life of the FC. Therefore, this structure is inapplicable for the FCV powertrain with strict requirements for ICR.

2.2.2 Interleaved Structure

The interleaved structure was also composed of inductor+inductor. Its switches are switched on in turn with the same trigger phase difference; therefore, only one inductor is charged at a time. The energy was evenly distributed to the branches where the switches are located, effectively eliminating the ICR. As shown in Fig. 5, the drive signals of S1 and S2 differ by 180°. When L1 (L2) is charged, L2 (L1) supplies energy to the load.

The two-phase interleaved boost structure was improved in Ref. [52] in the context of renewable energy sources. When different inductors supplied energy to the load, the later-end capacitors worked in different states, effectively improving the step-up ratio with a small ICR. The two- and four-phase floating interleaved structures were investigated

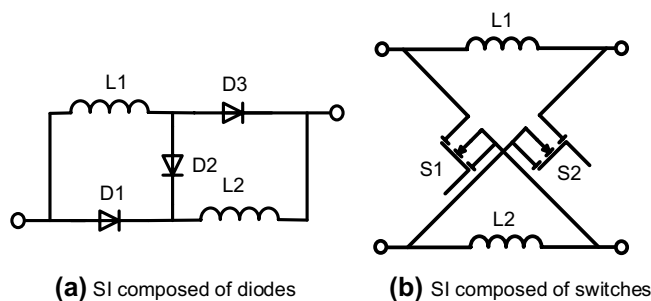


Fig.4 Two types of SI structures

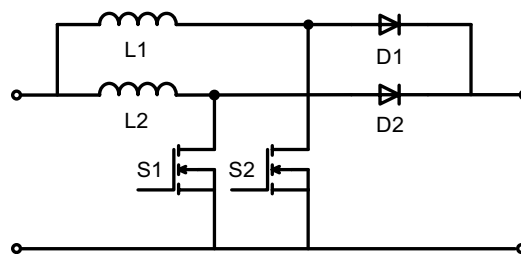


Fig.5 Two-phase interleaved step-up structure

in Refs. [53], [45], respectively. These structures effectively improved the VG of converters; however, they faced the issue of having no common ground (CG). An interleaved converter for FCV was proposed in Ref. [46]. An FC can operate in the boost or buck modes when its voltage was lower or higher than the DC bus voltage, respectively,

reducing the ICR. In Ref. [22], the interleaved structure was implemented at the front-end of the converter to reduce the ICR. In the back-end, two capacitors were combined with a diode-capacitor network to increase the VG and reduce the VS.

The interleaved structure has the advantage of a small ICR. For an n -phase interleaved converter, when the duty cycle is an integral multiple of $1/n$, and the trigger phase difference is $360^\circ/n$, the ICR is eliminated [54]. Therefore, in the field of FCVs, the interleaved (not floating interleaved) structure is suitable for the front-end of the boost converter to reduce the ICR.

Using the interleaved structure in the powertrain of FCVs can effectively reduce the current ripple of the FC stack, reducing the impact on the lives of FCs. Therefore, this structure is suitable as the front-end of the DC-DC converter. However, there are obvious disadvantages that accompany this structure. First, this structure does not significantly improve the VG and is not suitable for low power FC stacks that require high VG converters. Second, the switches switch on alternately, which requires highly precise trigger signals and a control circuit. Third, its input and output do not have a CG, producing additional electromagnetic interference (EMI) in the powertrain. Fourth, there were many switches, which increases the cost of the powertrain.

2.2.3 SI Combined with Charge Pump Structure

To improve the VG, the diode D2 in the SI structure was replaced by a capacitor C1, namely the structure of an SI combined with a charge pump is obtained, as shown in Fig. 6.

In Ref. [55], a structure combining an SI with a charge pump was proposed, which improved the step-up ratio of the converter and provided the circuit with resilience to component tolerance. As demonstrated in Ref. [56], an SI combined with a charge pump replaced one inductor (the inductor that was not directly connected to the power source) in the quasi-Z-source. The new step-up structure exhibited reduced ICR and VS and also a high VG. The novel non-isolated DC-DC topology proposed in Ref. [57] was cascaded with charge pump and SC structures, reducing the VS of the components as well as the switching and conduction losses.

The structure combining an SI with a charge pump can further improve the VG by modifying the SI structure, which renders the structure suitable for the FCV powertrain that requires a high VG converter. However, on connecting this structure with an FC stack, the output current of the FCs would become pulsating current. Moreover, when the switch is switched off, the power source is directly connected to capacitor C1, and the initial inrush current would appear on the side of the power source. From the two points above, it

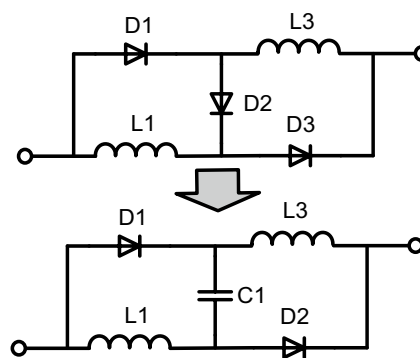


Fig.6 Structure of an SI combined with a charge pump

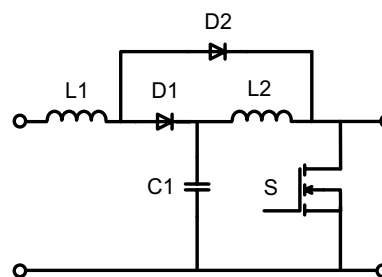


Fig.7 Quadratic boost structure

can be concluded that the structure combining an SI with a charge pump is not applicable for FCV systems.

2.2.4 Quadratic Boost

According to Principle 1, the capacitor is used as another power source to realize charging in parallel and discharging in series of two inductors, significantly improving the step-up ratio. The quadratic boost structure is shown in Fig. 7.

In Ref. [58], the operating principles of the quadratic boost structure were analyzed, the energy transmission modes were investigated, and the ripple characteristics of the quadratic boost converter in the complete inductor supply mode (CISM) and incomplete inductor supply mode (IISM) were analyzed. In Ref. [59], a modified high gain quadratic boost-sepic converter was proposed, which produced a high VG with a low duty cycle and reduced the VSs of the switch and the diodes while exhibiting the advantages of a continuous input current (CIC). In Ref. [60], a modified high VG quadratic boost-sepic converter, having both CIC and a CG structure, was proposed. In Ref. [61], a modified high VG step-up DC-DC topology based on the quadratic boost structure was presented. This converter improved the VG while decreasing the VS across the switches as well as the overall converter losses.

The step-up ratio of the quadratic boost converter, which has both CIC and a CG structure, is the square of that of the boost converter. When the quadratic boost converter is used in the FCV powertrain, it provides a high VG to match the FC and DC bus voltages of the vehicle, and it also maintains the continuity of the FC output current. Moreover, the CG characteristics of the quadratic boost converter can effectively reduce additional EMI in the vehicle powertrain. Therefore, such a converter is suitable as the front-end of the DC-DC boost converter for an FCV.

2.3 Impedance Network Composed of Capacitor + Capacitor

2.3.1 SC Structure

According to Principle 1, two capacitors can be utilized to store and release more energy, obtaining the SC structure. This structure optimizes the topology with regards to the voltage conversion ratio, as shown in Fig. 8.

In Ref. [62], an SC structure was added to boost, buck-boost, and Cuk converters, effectively improving the VGs of the topologies. In Ref. [63], SCs (Fig. 8b) replaced the capacitors in Cuk, sepic, and Zeta converters, improving the VGs of the topologies and also achieving higher conversion efficiencies. After modifying the SC (Fig. 8a) in Ref. [64], a novel topology with a high step-up ratio and a good transient response was obtained. In Ref. [65], a novel DC-DC structure based on the SC network was proposed. This topology could significantly improve the output voltage and possessed smooth input current and output voltage.

The SI structure could effectively improve the VG and is accompanied by the advantages of simple control and easy implementation. However, the input and output of the SC structure do not have CGs. Prior to application in the FCV powertrain, the SC structure should be optimized from the perspective of the CG.

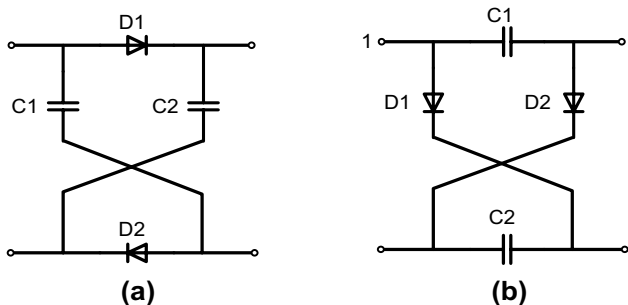


Fig.8 Two types of SC structures

2.3.2 VM Structure

According to Principle 2, a VM can be obtained by transferring energy between two capacitors to multiply the output voltage [66, 67]. The VM includes both Cockcroft–Walton and Dickson VMs, as shown in Fig. 9a and b. The single-stage VM is shown in Fig. 9c.

In Ref. [68], a high VG DC-DC topology with CIC and high efficiency was designed based on a Cockcroft–Walton VM for the FC. The novel topologies designed in Refs. [69], [70] implemented interleaved structures in the front-stage to reduce the ICR, and a Dickson VM lifted the voltage in the post-stage to match the voltage between the DC bus and renewable energy sources. A Dickson VM was first attempted to be applied to a classic non-isolated DC-DC boost converter in Ref. [71], and zero-current-switching was realized. The Dickson VM used in the post-stage of the converter proposed in [69] was improved upon in Ref. [72]. The high VSs on the post-stage capacitors of a multi-stage Dickson VM were reduced.

This VM exhibited the characteristics of a high VG and a simple structure, making it applicable for the post-stage of the DC-DC boost converter for an FCV. However, VSs of components increase with the number of stages in the VM, which, in turn, increases the possibility of component defects and decreases the reliability of the entire FCV powertrain. In addition, the high VS results in the converter requiring components with high rated powers, which increases the cost and power loss in the powertrain. Therefore, when

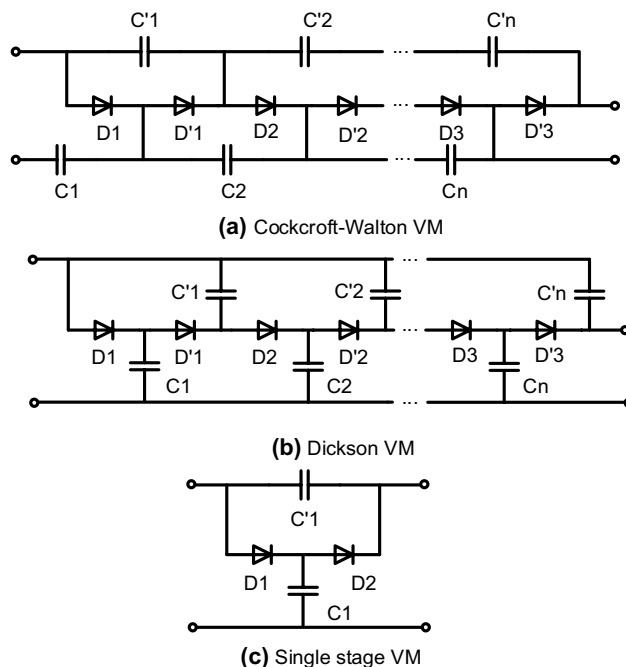
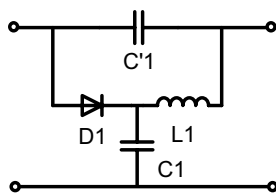


Fig.9 Three types of VM structures

Fig.10 Modified VM



designing DC-DC boost converters based on VMs, the topology should be optimized with respect to reducing VSs of the components.

2.3.3 Modified VM Structure

By replacing the diode D2 in the single-stage VM with an inductor L1 according to Principle 3, a modified VM structure, as shown in Fig. 10, can be obtained.

New energy systems were selected as the research background, and the boost topology was combined with a modified VM in Ref. [73]. This effectively improved the VG and reduced the ICR. The novel step-up DC-DC topology, proposed in Ref. [74], combined sepic topology, a VM, and a modified VM to effectively rectify the voltage mismatch in new energy systems. In Ref. [75], the VM was integrated with a modified VM to obtain a second-order hybrid boost topology, which was suitable for renewable energy sources.

The modified VM can effectively improve the VG of the topology, making it suitable for the FCV powertrain that requires high VG converters. However, when the modified VM is cascaded, VSs of the post-stage components increases. Prior to applying the modified VM structure to FCVs, a new topology should be designed from the perspective of reducing VSs to reduce the cost and power loss in the powertrain.

2.3.4 Z-Source Structure

The Z-source structure can be obtained by transferring the SC structure according to Principle 3, as shown in Fig. 11. When S is closed, C1 and C2 charge L1 and L2, respectively; however, when S is open, the power source charges C1 and C2. The power source, L1, and L2 supply power to the load [76].

A steady-state analysis of a Z-source step-up topology operating in the continuous conduction mode (CCM) was conducted in Ref. [77], and the voltage ripple and loss of the converter were calculated. In Ref. [78], two high VG Z-source DC-DC converters suitable for renewable energy sources were proposed, and an appropriate control method was presented. Moreover, the application prospect in FCV was discussed. As demonstrated in Ref. [79], a CG Z-source high VG converter with low stresses, high efficiency, and small size was designed without inserting additional

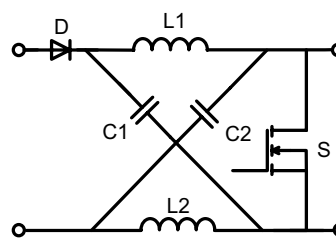


Fig.11 Z-source structure

components into the traditional Z-source structure. In Ref. [80], the Z-source structure was combined with a VM to obtain a novel CG high-gain topology, which was suitable for renewable energy sources. The Z-source structure was integrated with the quasi-Z-source one in Ref. [81], and a combined Z-source DC-DC structure was proposed for the FC and photovoltaic systems. This converter exhibited good step-up capability.

The Z-source structure can provide a high gain under the non-limit duty cycle, which can effectively match the low output voltage of FCs with the high bus voltage. However, using the Z-source structure in the FCV powertrain would generate a pulsating current in the FC, affecting its life. In addition, the input and output of the Z-source structure do not have a CG. The two points above restrict the application of Z-source structures in the FCV powertrain.

2.3.5 Quasi-Z-Source Structure

To overcome the disadvantage of the Z-source structure not having a CG, a quasi-Z-source can be obtained from the impedance transformation of the Z-source structure, as shown in Fig. 12. The operating principles of the quasi-Z- and Z-source structures are similar.

In Ref. [3], the quasi-Z-source structure was used as the front-end of the proposed topology, obtaining a high VG converter for FCVs. In addition, the efficiency of this converter reached 95.13%. Based on the investigations conducted in Ref. [3], a PI controller of the quasi-Z-source structure that combined composite feedforward and feedback controls was proposed in Ref. [82]. The quasi-Z-source converter was subsequently tested under the worldwide harmonized light-duty test cycle. A high voltage boost DC-DC converter composed of a quasi-Z-source converter and a quadratic boost converter was proposed in Ref. [83]. A high VG quasi-Z-source topology for new energy sources was proposed in Ref. [43], not only improving the VG of the quasi-Z-source structure but also maintaining the advantages of CIC and low VSs of capacitors.

The VGs of the quasi-Z-source and Z-source structures were equal. When the duty ratio is nearly 0.5, a high VG can be obtained. Moreover, the CIC of the quasi-Z-source

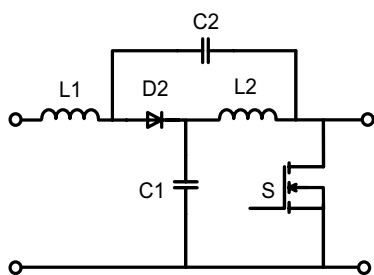


Fig.12 Quasi-Z-source structure

structure is beneficial to FCs, low VSs of the devices are conducive to reducing the cost of the powertrain, and the CG characteristics can effectively reduce the additional EMI in the powertrain. Therefore, this structure is suitable for FCV systems.

2.3.6 TL Structure

A TL structure, which can reduce the VS to half of the output voltage as shown in Fig. 13, can be obtained by combining capacitors according to Principle 4.

In Ref. [84], the TL forms of six basic chopper circuits were derived and then optimized. On this basis, a feedforward control strategy for these topologies was proposed. A TL topology was implemented in Refs [85] and [86] as the post stage of the step-up converter for an FCV, effectively reducing VSs of the components. For the FC composite energy storage system, the VS on the switch of the TL topology presented in Ref [87] equaled to only half of the output voltage, and the dynamic response of the converter was significantly improved.

The effective reduction of VSs of the components makes the TL structure suitable for application as the post-stage of a DC-DC boost converter for an FCV. However, the disadvantages of high control accuracy and a large number of switches necessitates extensive research on developing an optimization scheme to reduce the cost and power loss of the powertrain.

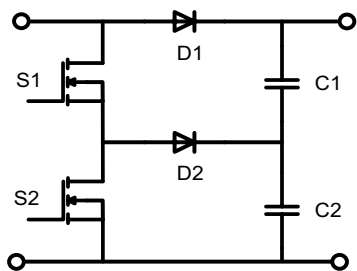


Fig.13 TL structure

2.4 Impedance Network Composed of Inductor + Capacitor

According to Principle 1, a voltage lifting (VL) circuit can be obtained by using an inductor and a capacitor to store and release more energy, as shown in Fig. 14.

Based on the basic boost topology, positive and negative VL circuits, first proposed in Refs [88] and [89], respectively, effectively improved the step-up ratio. Regarding the issue of low VG in the VL circuit, a family of VL topologies with geometrically increasing VG were designed in Refs [90] and [91]. In Ref. [92], the VL circuit was combined with the quadratic boost circuit to lift the VG of the converter and reduce the VS of the switch. In Ref. [93], a novel topology with high VG and CIC was obtained by integrating the conventional boost circuit with a VL circuit. A single switch step-up topology, based on the VL circuit and having high VG, was proposed in Ref. [94]. However, the input and output sides did not have a CG. In Ref. [95], the VL circuit was improved and a converter with a high step-up ratio was proposed, which had fewer switches.

The VL circuit can significantly improve the step-up ratio, and its input and output have a CG. The flexible structure can be easily designed. However, this circuit has a pulsating input current, which is unfavorable for the FC stack. While designing the converter topology for FCVs, optimization with regard to CIC should be performed to improve the durability of the FCV powertrain.

2.5 Hybrid and Cascaded Structure

2.5.1 Hybrid Structure

A hybrid structure can be obtained by replacing a functional unit of the basic topology with one or multiple topologies (or a part of the topology). The novel boost topology can improve the step-up ratio, IVR, component stress, or ICR. Hybrid topology can optimize the performance of the topology according to specific requirements, which is a common method of designing

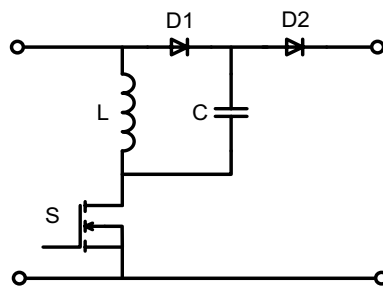


Fig.14 VL circuit

DC-DC converters for FCVs. The schematic diagram of hybrid topology construction is shown in Fig. 15. Moreover, Boost, Cuk, and sepic circuits have CIC, which is appropriate for the basic topology of the hybrid structure.

The characteristics of a few DC-DC boost converters constructed using the hybrid structure are listed in Table 1.

Using a hybrid structure constitutes an important method of generating novel boost converters for FCVs by introducing functional units to optimize the performance of the topology. For instance, when designing DC-DC converters for FCVs, blending can be conducted according to the actual needs. To reduce the impact on the lives of FCs, the topology

with CIC can be used as the hybrid unit. Alternatively, high VG topology can be used as the hybrid unit to effectively match the low output voltage of FCs and the high bus voltage. Furthermore, the CG structure should be maintained as much as possible to reduce the additional EMI in the FCV powertrain. To reduce the power loss of components and improve the reliability of the powertrain, reducing the VSs of components is necessary. However, there are many devices in the hybrid topology, which would increase the cost of the powertrain and decrease the efficiency.

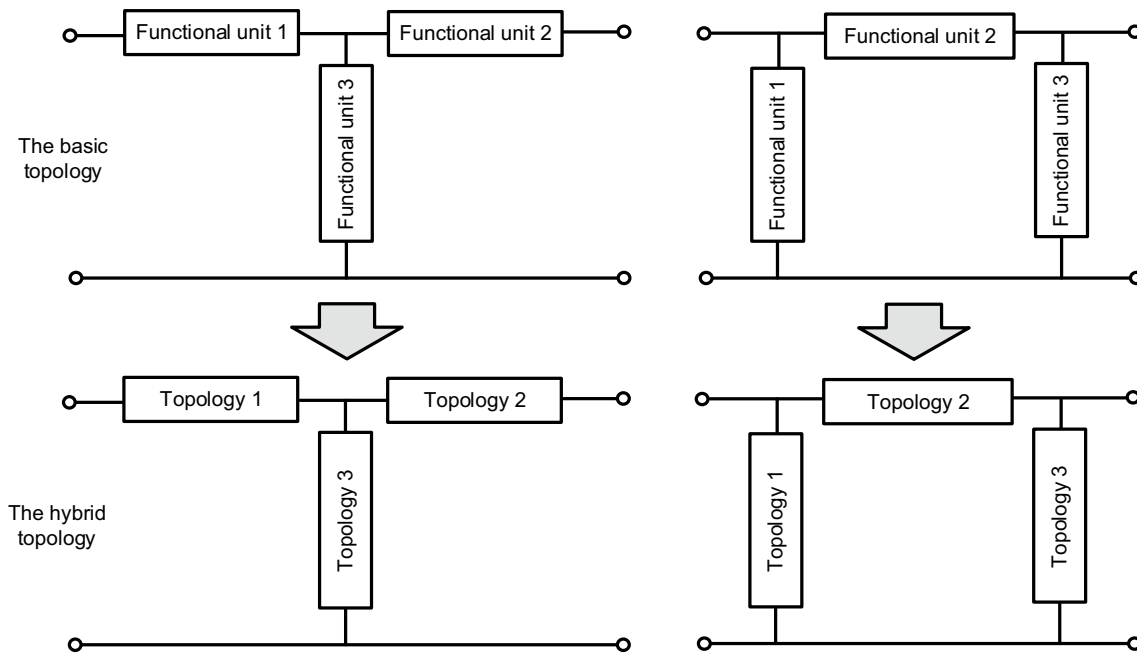


Fig.15 Schematic of hybrid structure construction

Table 1 Configuration and advantages of a few hybrid topologies

Reference	Topology configuration	Advantages	Applicable to FCV
[96]	Boost+Cuk	●Low VS ●CIC	★
[97]	Quadratic Boost+Cuk	●High VG ●CIC ●Low VS	★
[98]	Sepic+Modified VM	●High VG●CIC	★★
[99]	Z-source+Quasi-Z-source	●High VG	★
[100]	Cockcroft–Walton VM+Dickson VM	●Low output voltage drop ●Low capacitor VS●High VG	★
[101]	Interleaved+Multi-level	●High VG●Low ICR	★
[102]	Interleaved+VM	●Low ICR●High VG ●Simple structure	★★★
[103]			
[23]	Boost+Modified VM	●CIC ●High VG●Low VS	★★
[104]	Boost+Modified VM	●CIC●High VG ●Low switch VS	★
[105]	VL circuit+Quadratic Boost	●High VG	★

★ particularly inappropriate, ★★ relatively appropriate, ★★★ particularly appropriate

2.5.2 Cascaded Structure

Cascading more than two topologies (the duplicate part can be shared) can generate a cascaded structure, as shown in Fig. 16. The 1st converter utilizes the FC as its power source, and the subsequent converter, in turn, uses the output voltage of the former one as the power source. Thus, a cascade relationship is formed. The n th converter provides energy to the load. Implementing the cascaded structure constitutes another important method of constructing new DC-DC boost converters for FCVs. The performance of the topology in terms of ICR, VG, IVR, and VS can be effectively improved

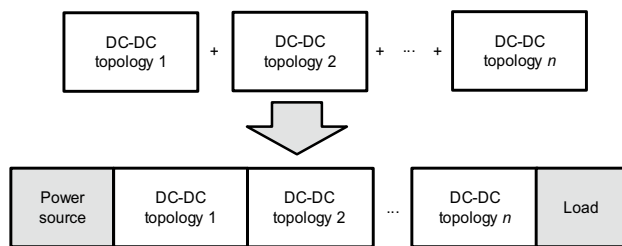


Fig. 16 Schematic of cascaded structure construction

through cascading. The cascaded structure exhibits the advantages of variety and simple implementation.

Many studies have been conducted on utilizing cascaded structures to construct new boost topologies for FCVs. A few configurations and advantages of the cascaded structure are listed in Table 2.

The cascaded structure can flexibly combine sub-topologies, according to the requirements of the particular application, to obtain a new topology. This new topology, thus, inherits the advantages of each sub-topology. To ensure the suitability of the cascaded topology for the FCV powertrain, a topology with low ICR can be used in the front-stage of the cascaded topology, ensuring the low current ripple characteristics of FCs. The cascaded topology can use a high gain structure as an intermediate link to maintain the bus voltage under different FC output powers, and thus, adapt to different driving conditions. To reduce the cost of the powertrain and improve reliability, the TL structure can be used as the end-stage of the cascade topology. However, the efficiency of the cascaded topology is the product of the efficiency at each stage, resulting in reductions in the entire efficiency of the vehicle powertrain [117].

Table 2 Configurations and advantages of a few cascaded topologies

Reference	Topology configuration	Advantages	Applicable to FCV
[69] [70] [106]	Interleaved + VM	●Low ICR ●High VG	★★
[107]	Capacitor clamped circuit + VM	●CIC ●High VG ● Low VS ●Low power loss	★★★
[108]	Interleaved + VM + TL	●High VG ● Low VS ●Zero ICR	★★
[109]	SI + VM	●CIC ●High VG ● Low power loss	★
[3]	Quasi-Z-source + VM	●High VG ●Low VS ●Wide IVR	★★★
[85]	Quasi-Z-source + TL	●High VG ●High conversion efficiency ●Wide IVR	★★★
[86]	Capacitor clamped circuit + TL	●High VG ●Simple control ●CIC ●Low VS	★★
[90] [91]	VL circuit + VL circuit	●High VG	★
[65]	SC + SC	●CIC ●High VG	★
[110] [111] [112]	Quadratic Boost + VM	●High VG ● CIC ●Wide IVR ●High conversion efficiency	★★★
[80]	Z-source + VM	●High VG ● Low VS ●High conversion efficiency	★
[113]	Boost + VM + Modified VM	●High VG ●Low VS ● CIC	★★★
[114]	Boost + VM + VM	●High VG ● Low CS ● CIC ●Working at non-limit step-up ratio	★★★
[115]	Boost + SC + VM	●CIC ● High VG ●Low VS ●High conversion efficiency	★★
[116]	Boost + VL circuit	●High VG ●Low power loss ●CIC ●Few components	★★★

★ particularly inappropriate, ★★ relatively appropriate, ★★★ particularly appropriate

To synopsise, Table 3 systematically summarizes the advantages and disadvantages of typical impedance networks and provides suggestions for constructing DC-DC boost converters for FCVs.

3 Evaluation of DC-DC Boost Converter for FCVs

Existing evaluation indexes for DC-DC boost converters mainly consider the performance of DC-DC converters, while the proposed evaluation indexes also take the requirements of connection with FC into consideration. Therefore, the proposed evaluation system is more suitable for DC-DC converters for FCVs.

The evaluation indexes of the DC-DC boost converter constitute the standard based on which the merits and demerits of the topology are assessed. The performance requirements of the DC-DC boost converter for application in the field of FCVs are reflected by three indexes:

high VG, low ICR, and wide IVR. The universal requirements for a DC-DC boost converter include voltage and current stress, conversion efficiency, power density, number of components, the slope of step-up ratio, and presence of CG.

3.1 Indexes of DC-DC Boost Converter for FCVs

3.1.1 VG

VG of the converter is defined as the ratio of the output voltage to the input voltage. The strength of the step-up capability of the topology increases with the step-up ratio. DC-DC boost converters for FCVs require high VGs no less than ten times. Figure 17 compares the VGs of 13 topologies.

Table 3 Advantages and disadvantages of topologies based on the impedance network

Classification	Impedance network	Advantages	Disadvantages
Inductor + Inductor	SI	●High VG ●Easy to control ●Easy to generate new topologies	●Pulsating input current
	Interleaved	●Low ICR ●Easy to generate new topologies	●No obvious increase in VG ●High control requirements ●Input and output do not have CG (floating interleaved) ●Many switches
	SI combined with charge pump	●High VG ●Easy to control ●Easy to generate new topologies	●Pulsating input current ●Initial inrush current existing in the power source side
Capacitor + Capacitor	Quadratic boost	●High VG ●Low ICR ●Easy to control	●High VS
	SC	●High VG ●High conversion efficiency	●Input and output do not have CG
	VM	●High VG	●High VS ●Output voltage dropping noticeably
	Modified VM	●High VG	●High VS
	Z-source	●High VG in non-limit duty cycle	●Pulsating input current ●Input and output do not have CG ●Narrow duty cycle range
	Quasi-Z-source	●High VG in non-limit duty cycle ●Compared with Z-source, input–output in CG ●Low ICR	●Narrow duty cycle range
Inductor + Capacitor	TL	●Low VS	●High control requirements ●Many switches ●No obvious increase in VG
	VL circuit	●Easy to generate new topologies	●No obvious increase in VG ●Pulsating input current
Hybrid / Cascaded	Hybrid	●High VG ●Easy to generate new topologies	●Many components ●Low conversion efficiency ●Low power density
	Cascaded	●High VG ●Easy to generate new topologies	●Many components ●Low conversion efficiency ●Low power density

3.1.2 ICR

During the high-frequency switching of DC-DC boost converters, the internal energy storage components are also charged and discharged at high frequencies. This would, in turn, generate current ripples at the input side of the converter. The input side of the DC-DC boost converter is directly connected to the FC; therefore, an excessively large ICR of the converter reduces the life of the FC. Therefore, reducing the ICR is imperative [118]. Although the current ripple can be filtered using filters, the input current of the DC-DC boost converter for FCV should not be pulsating considering the limited vehicle space.

3.1.3 IVR

The output power of the FC varies with the road conditions. The DC bus voltage is power battery voltage; therefore, its variation range is small, and the output current of the FC would significantly change. The output voltage of the FC would noticeably drop for increasing output current. In addition, a higher VG of the topology partly implies a wider voltage range that can be inputted. To ensure FCV operation under various road conditions, the width of the IVR is an important index to estimate the performance of the DC-DC boost converter for an FCV.

3.2 Universal Indexes of DC-DC Boost Converter

3.2.1 Voltage and Current Stress

VS constitutes the maximum reverse voltage born by the component when it is switched off. Current stress constitutes the maximum current flowing through the component. The significant increase in the component stress, in turn, increases the possibility of component defects, leading to

low reliability of the entire converter. In addition, the voltage and current stresses determine the rated parameters of power electronic components. Generally, the higher the voltage and current stress the component can withstand, the more expensive and the larger the size. To reduce the cost and size, the power electronic components in the DC-DC boost converter for FCV should have low voltage and current stresses.

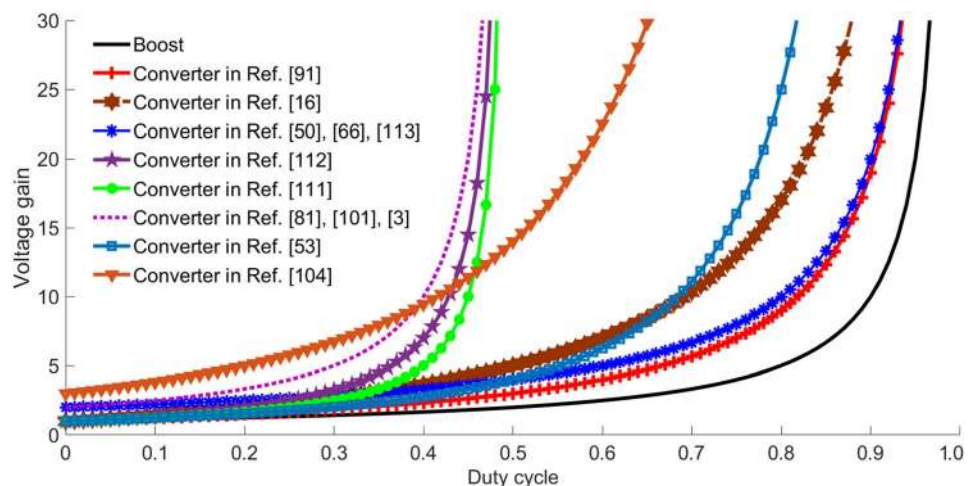
3.2.2 Power Density

The ratio of the rated power to the volume of the step-up converter is defined as the power density. Owing to the limited space in FCVs, the converter is required to process high power at a small size. Utilizing appropriate circuit models and analysis methods to accurately calculate the parameters of inductors, capacitors, switches, and other components in the topology is a common method for improving the power density. Miniaturization and the use of a high-frequency converter constitute the most effective methods of increasing the power density. However, with increasing operating frequencies of the component, severe EMI issues begin to arise.

3.2.3 Number of Components

The complex DC-DC topology can generally improve the performance in one (or several) aspect(s). However, the disadvantages of having many components are evident, especially in the cascaded and hybrid structures. A large number of components increase the cost of the DC-DC boost converter and reduce the power density. The number of components should be reduced as much as possible to meeting the requirements of FCVs.

Fig.17 VG curves of typical novel topologies



3.2.4 Conversion Efficiency

Owing to the parasitic parameters and the frequent switching on and off of the switches, DC-DC converter losses include conduction and switching losses. This not only results in an output power lower than the input power but also raises the temperature of the converter. The conversion efficiency of the DC-DC converter is defined as the ratio of output power to input power. Moreover, high efficiency is the objective behind developing DC-DC topologies. The conduction loss increases with the current. The switching loss of the converter, however, increases with the operating frequency. Soft-switching technology can be used to reduce switching loss.

3.2.5 CG

The du/dt and di/dt caused by switches are the primary EMI sources in the DC-DC converter. Implementing soft-switching technology, designing filters, parasitic parameter optimization, designing shield structure, and adding a CG are effective measures to suppress EMI [119]. When the DC-DC converter does not have a CG, the high-frequency PWM voltage difference would generate additional EMI. Therefore, CG is a key index in evaluating the topology of the DC-DC boost converter for FCVs [120].

3.2.6 Slope of Step-up Ratio

The slope of the step-up ratio is an index that describes the change in the step-up ratio with the duty cycle. A high step-up ratio slope implies that the step-up ratio increases rapidly with a slight increase in the duty cycle. The designers of the DC-DC boost converter tend to favor a gentle slope of the step-up ratio because it indicates that the control requirement of the topology is easy to achieve.

3.3 Comparison and Evaluation of Typical DC-DC Boost Converter

In this section, DC-DC boost converters based on impedance network are compared in terms of eight aspects: the technology used, VG, ICR, duty cycle range, voltage and current stresses, number of components, CG, and maximum efficiency. The power density and conversion efficiency of the topology are affected by many factors, such as the operating frequency, rated power, and the number of components. The distribution of indexes for several existing topologies are summarized in Table 4. The maximum efficiency in Table 4 is the value obtained in the corresponding paper.

To compare the DC-DC boost converter more intuitively, and aid the topology design of FCVs, this study qualitatively

evaluated ten typical impedance network DC-DC boost topologies in terms of eight aspects: VG, ICR, IVR, VS, current stress, number of components, the slope of the step-up ratio, and CG, as shown in Fig. 18. Two points are to be explained: first, the advantages and disadvantages of the indicators of topology are relative. The topologies evaluated in Fig. 18 only reflect the relationship between ten topologies. Secondly, no topology is excellent in all aspects. Certain performances of the topology should be optimized from the perspective of an application when designing the topology.

In Fig. 18, a larger shaded region indicates better indicators. From the inside to the outside, there are three grades: C, B, and A, representing excellent, medium, and poor, respectively. There are only two grades of C (no) and A (yes) in the presence of a CG, and the input current only has two grades: C (pulsating) and A (non-pulsating). The VG function cannot be directly compared; therefore, its value is taken to the one corresponding to duty cycle $d=0.8$ (the topology with duty cycle $0 < d < 0.5$ as the value corresponding to $d=0.4$, and the topology of duty cycle $0.5 < d < 0.75$ as the value corresponding to $d=0.7$). The IVR considers the variable range of the duty cycle an intuitive reference. A better index is shown in Fig. 18 for a larger range of d . The number of components is the sum of the number of switches, diodes, inductors, and capacitors. The stress function cannot be compared directly; therefore, the voltage and current stresses are the values corresponding to $d=0.8$ (the topology for $0 < d < 0.5$ as the value corresponding to $d=0.4$, and the topology for $0.5 < d < 0.75$ as the value corresponding to $d=0.7$). The slope of the step-up ratio is the value corresponding to $d=0.8$ (the topology for $0 < d < 0.5$ as the value corresponding to $d=0.4$, and the topology for $0.5 < d < 0.75$ as the value corresponding to $d=0.7$).

4 Limitations and Prospects of DC-DC Boost Converter for FCVs

Herein, the derivation and research status of DC-DC boost converters are analyzed, and the future research direction of using DC-DC boost converter for FCVs is presented. This is done to further promote the development of FCVs and the applications of DC-DC boost converters. Topologies of DC-DC conversion systems for FCVs have become a research hotspot with the development of new energy vehicles. On the basis of DC-DC topology optimization, designing an advanced DC-DC conversion system while meeting the requirements for FCVs is significantly challenging. The main issues about DC-DC conversion systems for FCVs are as follows:

Table 4 Indexes of typical DC-DC topologies

Topologies	Technology used	VG	Input current	Duty cycle range	Voltage/ current stress of switches		Number of components			Efficiency	Applicable to FCV	
					VS	Current stress	L/C	Q	D			
Boost	-	$\frac{1}{1-d}$	Non Pulsating	(0, 1)	U_o	$\frac{1}{1-d} I_o$	1/1	1	1	Yes	-	★
[96]	Hybrid	$\frac{1+d}{1-d}$	Non Pulsating	(0, 1)	$\frac{1}{1+d} U_o$	$\frac{2d}{1-d} I_o$	2/3	1	2	No	-	★
[97]	Hybrid	$\frac{1+d-d^2}{(1-d)^2}$	Non Pulsating	(0, 1)	$\frac{1}{1+d-d^2} U_o$	$\frac{2d+d^2+d^3}{(1-d)^2} I_o$	3/4	1	4	No	94.07%	★
[16]	SI	$\frac{1+3d}{1-d}$	Pulsating	(0, 1)	$\frac{1+d}{1+3d} U_o$	$\frac{2}{1-d} I_o$	4/1	2	4	No	95.8%	★
[55]	SI combined with charge pump	$\frac{2}{1-d}$	Pulsating	(0, 1)	U_o	$\frac{2}{1-d} I_o$	2/2	2	2	Yes	90%	★
[85]	Quasi-Z-source + TL	$\frac{2}{3-4d}$	Non Pulsating	(0.5, 0.75)	$\frac{U_o}{2}$	$\frac{4}{3-4d} I_o$	2/4	2	3	Yes	95.66%	★★★
[3]	Quasi-Z-source + VM	$\frac{2}{1-2d}$	Non Pulsating	(0, 0.5)	$\frac{U_o}{2}$	$\frac{1+2d}{d-2d^2} I_o$	2/5	1	5	Yes	95.13%	★★★
[121]	Z-source	$\frac{1}{1-2d}$	Pulsating	(0, 0.5)	U_o	$\frac{2}{1-2d} I_o$	2/3	1	2	No	-	★
[122]	Z-source + SC	$\frac{1+d}{1-2d}$	Pulsating	(0, 0.5)	$\frac{1}{1+d} U_o$	$\frac{3+d}{(1-d)^2} I_o$	3/5	1	3	No	82.4%	★
[107]	Capacitor clamped + VM	$\frac{2}{1-2d}$	Non Pulsating	(0, 0.5)	$\frac{U_o}{2}$	$\frac{1-d}{d-2d^2} I_o$	1/4	2	5	Yes	94.72%	★★★
[86]	Capacitor clamped + TL	$\frac{2}{1-2d}$	Non Pulsating	(0, 0.5)	$\frac{U_o}{2}$	$\frac{1}{d-2d^2} I_o$	1/3	2	4	No	95.28%	★★
[110]	Quadratic boost + VM	$\frac{3+d}{(1-d)^2}$	Non Pulsating	(0, 1)	$\frac{1+d}{3+d} U_o$	$\frac{1+3d-d^2-d^3}{d-2d^2+d^3} I_o$	2/4	2	7	Yes	95.04%	★★★
[123]	Interleaved	$\frac{2}{1-d}$	Non Pulsating	(0, 0.5); (0.5, 1)	$\frac{U_o}{2}$	$\frac{1.5}{1-d} I_o$	2/3	2	4	Yes	92.6%	★
[70]	Interleaved + VM	$\frac{6}{1-d}$	Non Pulsating	(0, 1)	$\frac{U_o}{6}$	$\frac{3}{1-d} I_o$	2/6	2	6	No	96%	★★
[71]	VM	$\frac{2}{1-d}$	Non Pulsating	(0, 1)	$\frac{U_o}{2}$	$\frac{1+d}{d-d^2} I_o$	2/3	1	3	Yes	-	★
[90]	VL circuit	$\frac{2-d}{1-d}$	Pulsating	(0, 1)	$\frac{1}{2-d} U_o$	$\frac{1}{d-d^2} I_o$	1/2	1	2	Yes	-	★
[58]	Quadratic boost	$\frac{1}{(1-d)^2}$	Non Pulsating	(0, 1)	U_o	$\frac{2-d}{(1-d)^2} I_o$	2/2	1	3	Yes	-	★★

★ particularly inappropriate, ★★ relatively appropriate, ★★★ particularly appropriate

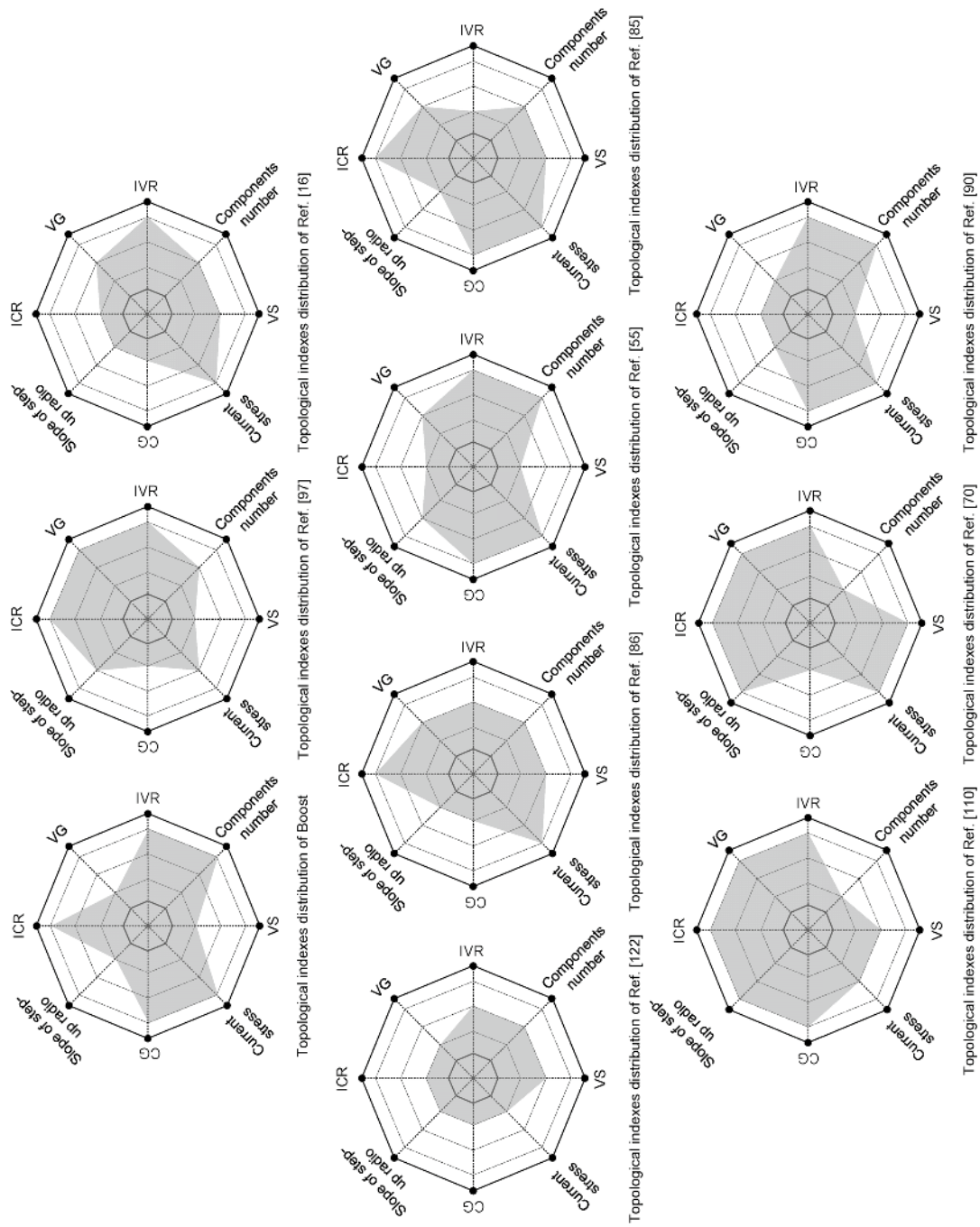


Fig.18 Distribution of indexes of typical novel topologies

- (1) With continuously improved bus voltage levels in the powertrain of FCVs, a step-up converter is required to continuously improve the VG to match the FC and DC bus voltages. With continuously improved energy efficiency requirements of the vehicle, stricter requirements are presented for the power conversion efficiency of DC-DC converter. Therefore, optimizing topologies of converters are complicated considering the system loss and stresses in the power electronic components.
 - (2) The output characteristic of an FC is soft (the voltage is lower for a heavier load), resulting in a wide range of FC voltages and a large output power fluctuation. A large current ripple reduces the life of an FC. Therefore, it should be ensured that the DC-DC converter can maintain the output voltage in a wide IVR and reduce the ICR. It is important to address issues pertaining to topology design, accurate modeling, and optimal control of the DC-DC boost converters for FCVs that need to be solved urgently.
 - (3) A DC-DC converter is a time-varying and strong nonlinear system. Under certain specific conditions, there would exist various types of bifurcation, chaos, and other nonlinear phenomena. These are embodied in the increased voltage and current ripple of the converter, the increased harmonics, the decreased working efficiency, noise, oscillations, and even system collapse. The procedure for performing nonlinear modeling of DC-DC converters, analyzing converter stability, and implementing chaos control, constitute important research topics related to DC-DC converters.
 - (4) The operation state of the FC stack determines the performance of FCVs. Internal resistance represents the difficulty in the proton and electron transport within the electrode. It also determines the efficiency of FC power generation, which directly reflects the health of the FC stack. The humidity inside FCs is a factor that affects this internal resistance. Although DC-DC converters can achieve voltage conversion and power decoupling, utilizing them to realize online monitoring of the water content in FCs constitutes the research direction of future DC-DC converters.
 - (5) When the FC stack is operated at low temperatures, the fuel supply pressure needs to be increased, leading to a low FC efficiency. When the temperature is below zero, the water in the FC stack would freeze, hindering gas diffusion and causing FC shutdown. Using DC-DC converters to directly control the warm-up operating voltage of FCs and realizing the regulation of cold starts both constitute issues to be considered in future design of DC-DC converters.
 - (6) Using components with wide band gaps (SiC, GaN) can result in the circuit operating with a high switching frequency, significantly reducing the size of energy storage components in a converter. This is an effective means to improve the power density. However, when the operating frequency of a circuit is too high, the EMI would become severe. Balancing the relationship between the operating frequency and the electromagnetic compatibility of a system in the application of semiconductor components with wide band gaps would also be an important topic in the research on topology design and the modeling and control of DC-DC boost converters for FCVs.
 - (7) The reliability of a DC-DC converter for an FCV is an important factor that seriously affects the development of the FCV industry. Completely combining the research of system detection, modeling, control strategy, and fault diagnosis methods to realize the safe and reliable operation of DC-DC conversion systems would also be an important research problem regarding DC-DC converters for FCVs.
 - (8) Installing high-power FCs on commercial FCVs with relatively sufficient space have become increasingly popular, and the "voltage window" wherein the voltage of the FC stack equals the DC bus voltage also appears. Considering the function of step-up and step-down converters, designing and controlling DC-DC converters with wide step-up/down voltage ranges and low ICRs is a challenge in developing commercial FCVs.
- Considering the abovementioned problems faced during research on DC-DC boost converters for FCVs, related studies on the following aspects can be conducted.
- (1) With regards to the issue of high VG and efficiency operation of the DC-DC boost converter for an FCV, the advantages of components with wide band gaps, such as high frequency and low power loss, can be utilized. The optimization calculation method of the system can be used to improve and optimize DC-DC converters based on existing SI, SC, cascaded boost, and other topologies. This can be done in terms of decreasing the size of energy storage components, reducing the stress of semiconductor components, and reducing switching loss.
 - (2) To solve the issue of a wide-range operation and a low ICR of the DC-DC boost converter for FCVs, the dynamic response and anti-interference ability of this converter can be synthetically improved based on existing topology optimization, such as implementing an interleaved parallel structure, combined with research on accurate modeling and the adaptive control method.
 - (3) To solve the issue of nonlinear modeling and control of the DC-DC converter for FCVs, based on the study of nonlinear dynamics and combined synthetic modeling methods, such as state variable equation

and discrete mapping, the nonlinear behavior caused by changes in the DC-DC converter parameter can be revealed by qualitative and quantitative methods. This is done to apply chaos control to the converter and realize the expected periodicity.

- (4) To solve the issue of online water content monitoring in the FC stack, based on the analysis of the equivalent model of FC, the basis of determining the water content using the internal resistance of an FC can be mastered. Additionally, the detection principle of the internal resistance of an FC can be summarized to construct an online monitoring model of water content in FCs. Subsequently, the integration of DC-DC converters and health monitoring systems is realized.
- (5) To control the warm-up operating voltage using the DC-DC converter and achieve a cold start, based on the mastering of FC warm-up operating characteristics combined with the characteristics of the DC-DC converter, the working frequency, inherent parameters, and given parameters of the converter can be comprehensively optimized. Thus, this provides a basis for designing DC-DC converters with warm-up functions.
- (6) Considering the issues regarding the application of semiconductor components with wide band gaps in DC-DC boost converters, the electromagnetic compatibility characteristic of the system in different frequency domains can be analyzed, and an accurate EMI model can be subsequently built on the basis of EMI modeling. This provides a reference for the topology optimization design of DC-DC converters utilizing semiconductor components with wide band gaps.
- (7) To improve the reliability of the DC-DC boost converter for FCVs, the typical dynamic behavior of the converter under different fault conditions, its fault behavior laws under different control strategies, its fault characteristics and influencing factors, and the quantitative extraction of key fault feature information of fault external characteristics in each stage are analyzed. This is to realize the construction of a fault generation model of the DC-DC converter, providing a model basis for the fault diagnosis of DC-DC converters.
- (8) To design a buck-boost DC-DC converter suitable for high-power commercial FCVs, based on the topology optimization of existing buck-boost DC-DC converters combined with the advanced modeling theory, research on the precise control of the output voltage and the dynamic regulation of the output power of the converter can be conducted. Therefore, the comprehensive improvement in the performance of the DC-DC converter with wide ranges of step-up and step-down can be realized.

5 Conclusions

The requirements of the DC-DC boost converter for FCV powertrains are summarized according to the characteristics of the powertrain and output characteristics of the FC, which mainly include high voltage gain, low input current ripple, and wide input voltage range.

According to the different types of impedance networks, DC-DC boost converter topologies can be divided into inductor + inductor, capacitor + capacitor, inductor + capacitor, and hybrid / cascaded. Based on the derivation and classification of 12 types of existing DC-DC impedance networks, the research status and characteristics of various impedance networks are reviewed. Among them, interleaved, quasi-Z-source, and quadratic boost structures have continuous input current, which render them suitable for connecting with FCs. Voltage multiplier, switched-inductor switched-capacitor, and voltage lifting circuits can effectively improve the voltage gain. The TL structure reduces the voltage stress of the device and is suitable for the post-stage of high voltage gain DC-DC converters. Hybrid and cascading are common methods for constructing DC-DC converters, but the conversion efficiency and power density need to be considered.

On this basis, an evaluation system for the DC-DC boost topology for FCV is constructed from eight evaluation aspects: input current ripple, voltage gain, input voltage range, voltage stress, current stress, number of components, common ground, and slope of the step-up ratio. Moreover, the typical topologies proposed in existing literature are compared and evaluated, providing a guideline for designing DC-DC converters for the FCV powertrain.

Lastly, the issues regarding DC-DC converters for FCVs are summarized. To facilitate the development of FCVs, future research directions are proposed, i.e., utilizing a DC-DC converter to realize online monitoring of the water content in FCs and designing buck-boost DC-DC converters suitable for high-power commercial FCVs.

Acknowledgements This work was sponsored through the International Science & Technology Cooperation of China under 2019YFE0100200 and the Fundamental Research Foundation for Universities of Heilongjiang Province (2018-KYYWF-1672).

Declarations

Conflict of interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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