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A Comprehensive Review of DC-DC Converters for EV Applications

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1. Introduction

Since the invention of electric vehicles (EVs), there was always a perception that EVs will dominate the future of vehicular transportation [1]. The importance of reducing industrial and vehicular emissions to minimize the effects of global warming, along with the fact that EVs have improved significantly in terms of technology and performance in recent years, has attracted many companies and people to investigate further on EVs [2, 3]. Even though, internal consumption engine vehicles (ICEV) are still superior to EVs in terms of performance and costs. However, sales of different kinds of EVs are growing rapidly [4].

Fig. 1 shows the four main types of prevailing EVs [5]. Electricity is the only energy source in battery electric vehicles (BEV). Due to the replacement of patrol and gasoline tanks with big batteries, BEVs are completely environmentally friendly. Low driving range, the high cost of the batteries, and the long time required for the batteries to be fully charged are some of the main problems of BEVs. Required energy in hybrid electric vehicles (HEV) is supplied through two energy systems. Main energy system (MES), which generally is a fuel cell (FC), and rechargeable energy storage system (RESS), which can be either batteries or ultra-capacitors. Both gas and electric motors are utilized in HEVs structure. HEVs are highly efficient and have rather long driving ranges among different kinds of EVs. Different types of HEVs are categorized based on the type of hybridization and connection of energy systems [6] in their structure. Compared to HEVs, plug-in hybrid electric vehicles (PHEV), due to the usage of bigger batteries, are more reliant and can drive longer periods supplied only by the RESS. The main advantage of PHEVs is the possibility of charging the batteries by plugging the car into an outlet [7]. Similar to HEVs, extended-range electric vehicles (EREV) have both MES and RESS as energy systems. The difference is that only an electric motor is considered in EREVs and the produced energy by the internal consumption engine (ICE) is used to charge the RESS through a generator [8]. This paper reviews DC-DC Convertors for EV Applications based on different terms such as; isolation and type of switching. Moreover, the control strategies, comparative factors, selection for a specific application, and recent trends are reviewed too. It is organized as follows. In the first section, different types of DC-DC converters are considered. DC-DC converters that can be used in EV applications are presented in section 2. Control devices and strategies are described in the third section. The selection of components and Comparative factors for DC-DC converters in EV application are presented in the fourth and fifth sections, respectively. The main aspects of designing DC-DC converters in EV applications are deliberated in section 6. Section 7 introduces the latest trends and developments of DC-DC converters in EVs. Conclusions drawn from this paper are presented in the last section.

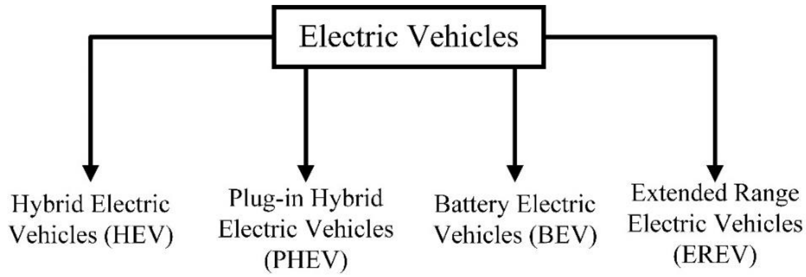


Fig. 1 Main Types of EVs

2. DC-DC Converters

The usage of DC-DC converters to change the input DC voltage to the required output DC voltage are very common in many applications [9]. DC-DC converters are capable of providing either voltage step-up or step-down and can be classified into two main categories; isolated and non-isolated. Non-isolated converters are mostly used when the required change in the voltage is small, and contain six basic types that are shown in Fig. 2. The main problem of the non-isolated converters is that they offer lower protection for high voltage levels in comparison with the isolated DC-DC converters. The main components used in these converters are switching power MOSFETs, flywheel diodes, inductors, and capacitors. A control circuit is usually applied to these converters to monitor the output voltage and maintain it at the desired level by controlling the switching frequency and duty cycle of the switches [10,11].

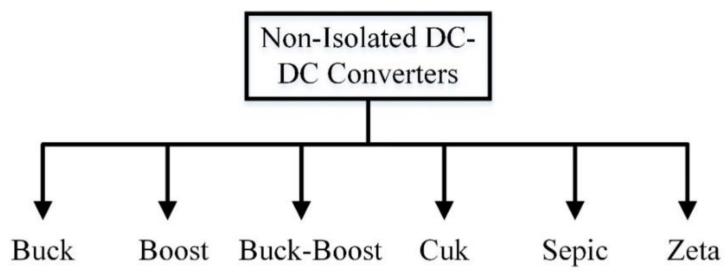


Fig. 2 Basic topologies of non-isolated DC-DC converters

In isolated DC-DC converters the input and output terminals are separated. High isolation voltage is one of the main features of these types of converters. Furthermore, it is possible to use these converters as a floating ground for different types of devices. Besides the fact that isolation has made these converters a safer choice, unlike the non-isolated type, isolated converters are also capable of blocking noise and other interferences. Therefore, a clean-up output voltage can be expected. Fig. 3 shows four basic types of isolated DC-DC converters. The main components used in isolated DC-DC converters are quite similar to non-isolated converters, except that in isolated converts a transformer is also used to provide isolation. So, their topologies are usually more complex than non-isolated DC-DC converters. Moreover, their control circuit has higher complexity and requires much more attention [11].

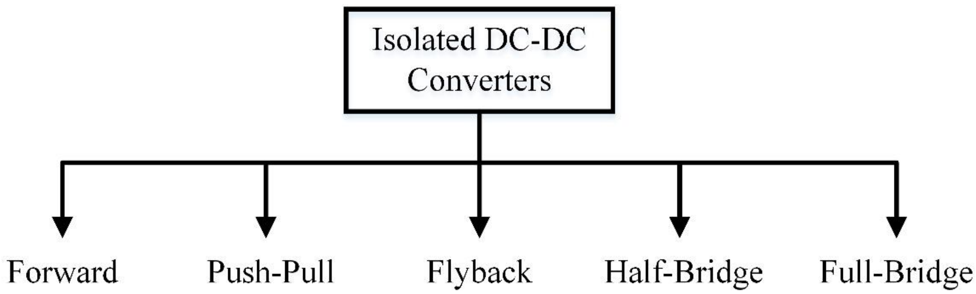


Fig. 3 Basic topologies of isolated DC-DC converters

The development of high-efficiency DC-DC converters is important in many applications [12–16]. To design a DC-DC converter with high efficiency it is necessary to reduce energy losses in the converter as much as possible. These losses contain different conduction losses, switching losses, output losses, operation losses, etc. The reduction of mentioned losses hugely depends on the specification of the converter [17,18]. One of the main losses in DC-DC converters is switching loss which depends on the switching method used in the converter. Two main types of switching which can be used in DC-DC converters are soft and hard switching. Hard switching means that there is an overlap between voltage and current when the switching happens. This overlap can cause energy loss in the converter and decrease the overall efficiency. Hard switching technique is usually used in Flyback, Forward, 2-SW Flyback, 2-SW Forward, and Full-bridge converters [19]. In soft switching technique either voltage (ZVS) or current (ZCS) is brought to zero before the switching occurs which will hugely decrease the amount of energy losses in comparison with the hard switching technique. This technique will also minimize the EMI in the converter. The sample topologies of soft switching converters are LLC-HB resonant, active clamp Forward, active-clamp Flyback, asymmetrical Half-bridge, and Full-bridge with phase shift [18,20]. There are also some other parameters which should be considered for designing a DC-DC converter such as; bi/uni-directional operation, weigh, efficiency, switching frequency and etc.

In recent years DC-DC converters have reached an acceptable condition in terms of quality, volume, weigh, performance, isolation, safety, etc. Also, they are feeding various loads with different power ratings in a large number of applications [21–

23]. High efficiency, low number of active and passive components, and simple control circuit are the main parameters in the DC-DC converters, recently [24–26].

3. Different kinds of DC-DC converters for EV application

DC-DC converters find applications in various functions related to EVs. They are used for charging the batteries [27,28], interfacing different DC-links and distribution systems [29,30], interfacing the power sources to DC-link [31,32], etc.

Due to increased electrical needs in vehicles, automotive industries are usually using 42V/300V systems in the vehicles [33]. However, a 14V bus is still available in some EVs. A DC-DC converter is the device used in all configurations to enable the power flow between these buses [34].

An electrical or hybrid vehicle's power train contains a combination of two or more energy sources (fuel cell and battery or super capacitor), a motor drive system, and in many cases a bidirectional DC-DC converter placed between the battery and the motor drive, to power an electric drive system as shown in Fig. 4. In this condition, MES provides an extended driving range, and RESS provides good acceleration and rechargeable braking. RESS can be connected to MES in many ways (parallel, series, series-parallel). A simple configuration is to connect two devices in parallel. But, in this configuration, the power drawn from each energy system cannot be controlled and is determined by the impedance of the power systems which depends on many parameters, e.g. temperature, state-of-charge, health, and point of operation [35]. The possibility of choosing different voltages for the power systems and also, controlling the power of each device are two advantages of using DC-DC converters in EVs. The different combination and configuration of the MES with the RESS and their comparison is discussed in many research papers [36]. It can be said that having both MES and RESS results is the best type of EV. Therefore, using a minimum of one DC-DC converter is necessary for EVs. DC–DC converter enables independent optimization of the battery system and reduction of the electric machine size [37,38]. The DC bus voltage of the motor drive can be increased, which leads to extensions to the motor speed range without field weakening. Consequently, the efficiency of both motor and the inverter are improved [39]. Also, the converter can adjust the DC bus voltage dynamically, so that the system efficiency can be further optimized [40]. The power train architecture using a DC-DC converter has been successfully incorporated into commercial vehicle systems [41–44].

Based on what discussed above, the applications of DC-DC converters for an HEV can be summarized as is shown in Fig. 5.

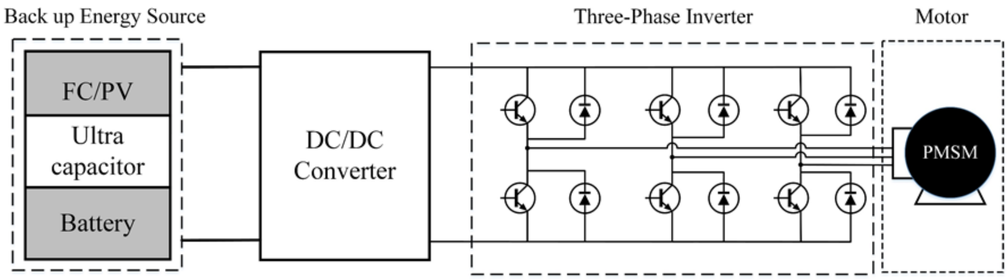


Fig. 4 Main role of DC-DC converter in EVs

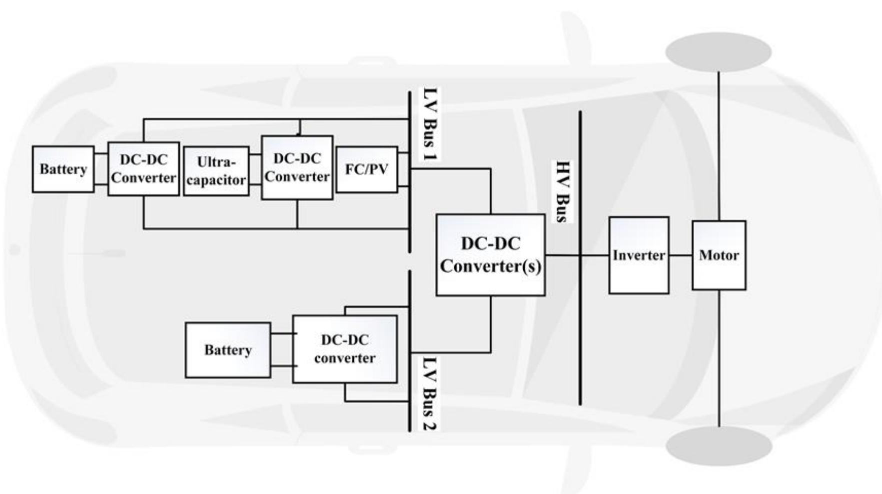


Fig. 5 The application of DC-DC converters in EVs

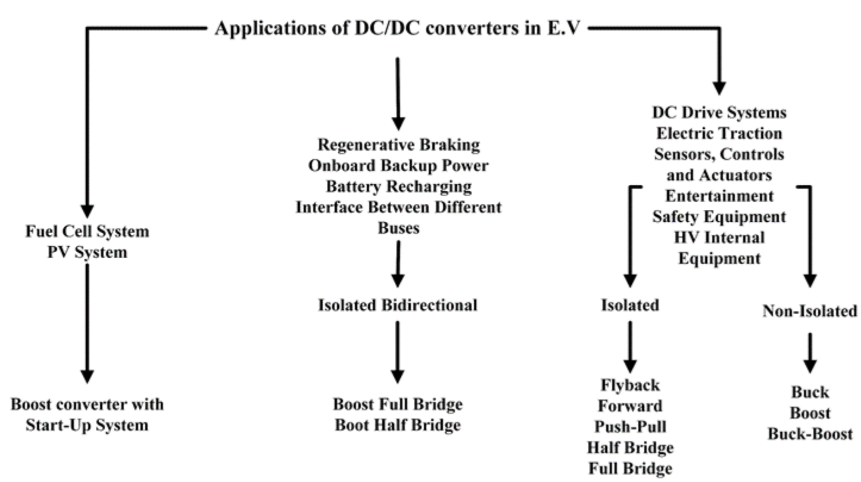


Fig. 6 Different applications of DC-DC converters in EV [34]

Different configurations and topologies of DC-DC converters that are used in many systems inside the car are shown in Fig. 6 [45]. Unidirectional DC-DC converters are usually used in parts like; sensors, entertainment, safety, and control. They are also used in DC motor drives and electric traction. Bidirectional DC-DC converters find their application when regenerative-braking and recharging of the battery or super-capacitors are needed. The power flow in a bidirectional converter is usually from a low-voltage side (battery or a super capacitor) to the high-voltage side (DC link) and vice versa with high gain. The best way to reach high voltage gain is using transformer-based converters such as Flyback, Full-bridge, Half-bridge, and Push-pull. However, using the large transformer turns ratio increases the voltage and current stress on primary elements. During regenerative braking, the power flows back to the low-voltage side to recharge the battery (Buck mode). As a backup power system, the bidirectional DC-DC converter facilitates the safe operation of the vehicle when ICEs or electric drives fail to drive the motor. Due to the aforementioned reasons, the attention to design high-power BDCs is increased in recent years. Moreover, the various approaches have been proposed to improve the efficiency of them. As a result, different methods to reduce switching losses [46–53], different methods to improve magnetic features [54–58] and approaches to implement devices having lower rating of voltage [59,60] are proposed in the literatures.

To ensure the safety of the loading devices, isolation is recommended for either BDCs or unidirectional DC-DC converters [61]. Due to the increased power capability of the converters over the last decade which has led to high current stress, high conduction and switching losses, high-frequency transformers are used in their structures [62]. But, the high-frequency transformer leads to some problems:
It is preferred in either unidirectional or bidirectional DC-DC converters, to ensure the safety of the loading devices, to be isolated [61]. The increased power capability of the converters over the last decade has led to high current stress in these converters and consequentially led to a significant increase in the conduction loss and switching loss of the switching devices [62] and also to obtain isolation a converter incorporates a high-frequency transformer. The inclusion of the high-frequency transformer leads to some problems:

- The leakage inductance of the transformer leads to high voltage stresses across the converter switches and diodes due to ringing caused by the leakage inductance and the transistor/diode output capacitance.
- Increases converter area, volume, weight, and cost.
- Increases Electro Magnetic Interface (EMI).

In DC-DC converters, designs are aimed to solve these problems and to obtain an efficient, cost-effective, and high-quality converter. To solve the problems caused by the energy stored in the transformer leakage inductance which leads to high voltage/current stress, active-clamping, active commutation, passive snubbers, soft commutation, and soft-switching solutions have been incorporated. However, the setback of these solutions is that the converter will need more components and gets more complex. Since in bidirectional DC-DC converters, power needs to be able to flow in both directions so many full-bridge-based topologies have been introduced and to minimize the components used in the converter many half-bridge-based topologies have also been developed. Many approaches based on voltage-fed converters [63–68] (used in many applications), current-fed converters [69–81] (due to their intrinsic characteristic of low current ripple are mainly used in high-voltage gain step-up applications, and usually active-clamping technique is used in these converters), interleaved converters [74,75], and some other topologies [76–81] have also been proposed by designers and researchers.

In this paper, based on isolation and the switching method used in the topologies, DC-DC converters are classified into four main groups. Fig. 7 shows the proposed classification.

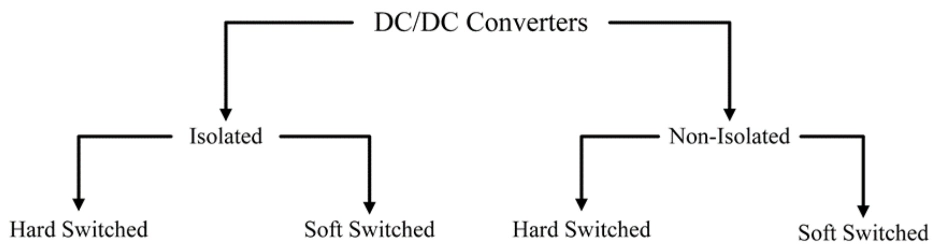


Fig. 7 Classification of DC-DC converters for EV application

3-1. Isolated, Soft-switched DC-DC converters

Galvanic isolation, by improving the safety of the loads, and soft-switching technique (ZVS, ZCS, ZVZCS), by reducing the losses in the converter, has made this class suitable for many applications of EVs. Based on these features, for applications that contain a high voltage bus, on the input or output, and also applications that include sensitive loads or are in direct contact with passengers, it is preferable to use this class of converters. Using transformers in these converters will cause the problems mentioned before, even though by using the soft switching technique designers have tried to minimize the problem caused by a transformer. But still using both isolation and soft switching means increasing the number of components, weigh, and volume of the converter. These are the setbacks that can persuade designers to use different classes of converters in their vehicles. Different converters in this class proposed for various applications in EVs, are studied in this paper.

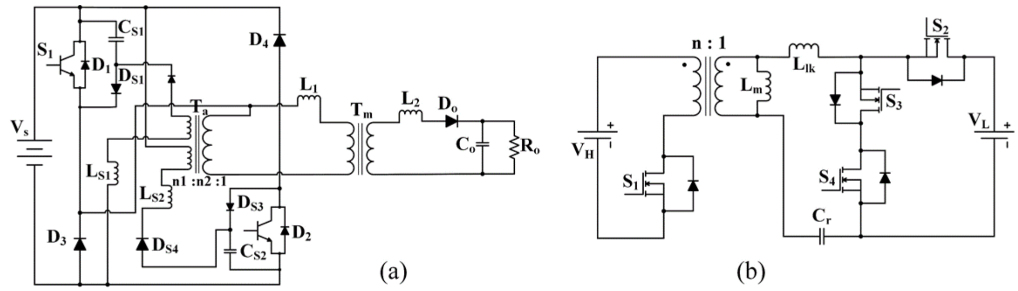


Fig. 8 Proposed converters based on (a) Flyback [82] and (b) Forward [83] topology

In [82] C.Y. Inaba et al. have proposed a unidirectional two-switch high-frequency Flyback transformer linked zero voltage soft switching PWM DC-DC power converter, shown in Fig. 8 (a). The circuit of this converter is mainly composed of two active power switches and a Flyback high-frequency transformer. In addition, soft switching from light to full load conditions is realized by using two passive lossless resonant snubbers. By connecting an additional diode and inductor at the output side, this converter can also function as a forward-type DC-DC power converter. Results of experimenting with a 1kW prototype show that, compared to a hard-switched design of this converter, the efficiency is approximately 1.3 to 3.0% higher.

In [83] Ehsan Adib et al. have proposed a forward-type resonant bidirectional DC-DC converter which is illustrated in Fig. 8 (b). As this figure shows, the transformer is modeled by a magnetizing inductor, a leakage inductor, and an ideal transformer. Other components of the converter contain four switches and a resonant capacitor. ZCS is achieved for all switches by resonance between the leakage inductor of the transformer and the resonant capacitor. No other extra element is utilized for the resonant technique in the converter. Since the transformer in the converter is forward type, it has a low volume and hence has less effect on the volume of the converter. Moreover, the results of the simulation show that the branch that contains two series switches has a small current which proves the possibility of reducing the number of switches in the converter as explained in [83].

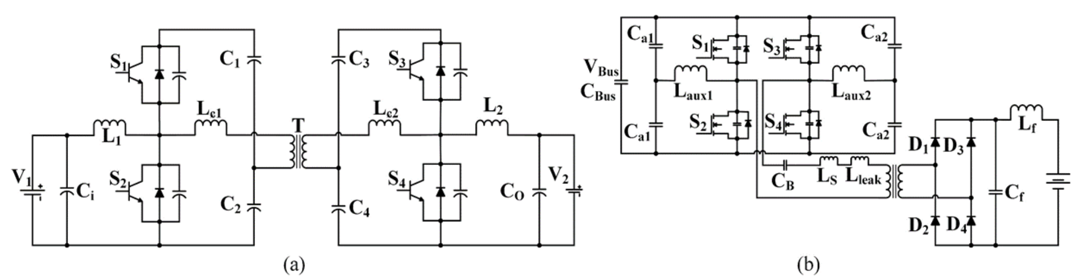


Fig. 9 Proposed converters based on (a) half-bridge [84] and (b) full-bridge [85] topology

Gang Ma et al. have proposed a bidirectional DC-DC converter based on the half-bridge converter in [84]. The proposed converter achieves ZVS for the entire main switches and ZCS for the rectifier diodes in the large-load range. In the circuit of the proposed converter shown in Fig. 9 (a), the primary and secondary sides of the circuit are symmetrical and switches conduct complimentary, capacitors are identical and inductors are important for energy transfer. A 1kW experimental prototype of the proposed converter in [84] is compared with the hard-switched half-bridge DC-DC converter. Even though the proposed converter has a slightly lower efficiency than the hard-switched prototype in light loads, overall the results show that the proposed soft-switched converter is about 2% more efficient than the half-bridge hard-switched prototype.

A converter based on the unidirectional full-bridge topology is proposed in [85] (Fig. 9 (b)). Full- bridge topology is considered the most popular topology in the range of 1-5kW for DC-DC converters. The proposed converter in [85] can efficiently deliver power over a very wide range of loads. Pahlevaninezhad et al. have employed a symmetric passive close to the lossless auxiliary circuit of the converter, which by providing a reactive current for the full-bridge switches will guarantee ZVS at turn-on at switches for all load conditions. Moreover, to overcome the problems associated with voltage-driven rectifiers, the converter is based on a current-driven rectifier, ensuring ZVZCS operation for all load conditions.

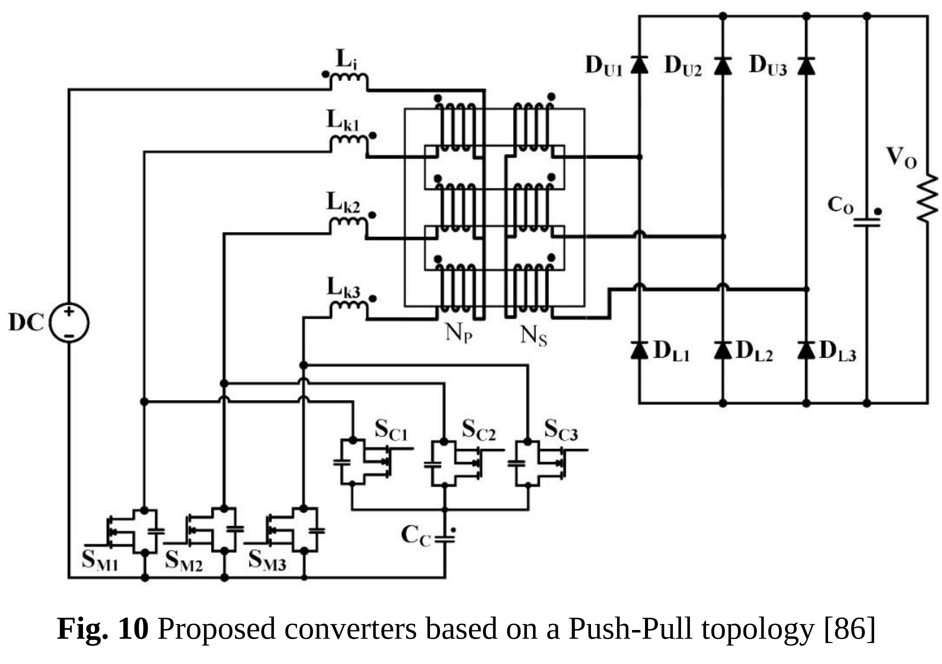


Fig. 10 Proposed converters based on a Push-Pull topology [86]

In [86] a unidirectional current-fed push-pull DC-DC converter is proposed for high-power applications such as EVs, illustrated in Fig. 10. As this figure shows, the proposed converters are composed of; an input filter inductor, three main switches, a clamp circuit which contains three clamp switches and a clamp capacitor. Moreover, a diode bridge is also designed on the HV side. The proposed converter by Sangwon Lee et al. has features like; active clamping of the transient surge voltage caused by transformer leakage inductance, natural ZVS turn-on of main switches, and ZVZCS of clamp switches, etc. which in an improvement the overall efficiency of the proposed converter. A 5kW prototype of the proposed converter has been experimented proving the practicality of the converter.

Details of some isolated soft switched papers and experimental porotypes in these papers are given in Table. 1.

3-2. Isolated, Hard-switched DC-DC converters

Galvanic isolation is the feature that is considered in both class 1 and class 2 of DC-DC converters. To achieve this, a transformer is used in the converter which means that the safety of the loads will be obtained. As it was discussed in class 1 of converters, utilizing a transformer in the circuit of the converter has disadvantages like increasing stress on the switches and EMI in the converter. To reduce these effects soft switching technique is used in class 1 of converters which further increased the number of components and size of the converter in this class. Different from what was done in class 1, soft switching is not considered in this class. Instead in this class, it is tried to reduce these effects as much as possible when choosing different parameters of the converter or designing the control method. Overall, it is expected for the converters in class 2 to have a lower price, volume, and weigh compared to class 1.

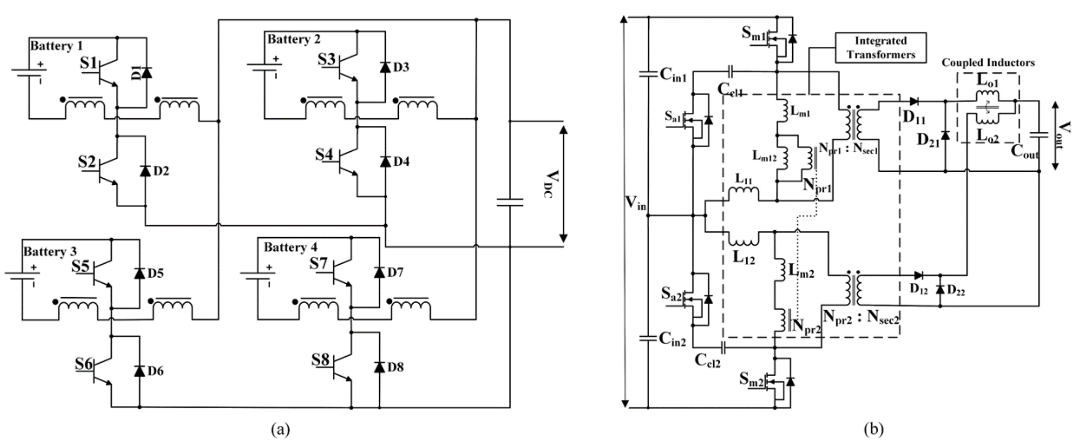


Fig. 11 Proposed converters based on (a) Flyback [130] and (b) Forward [131]

Table. 1 Some isolated soft switched DC-DC converters for EV application

Paper	Base Type	Nominal Power	Switching Frequency	Input Voltage	Output Voltage	Max Efficiency	Number of Switches	Number of Passive Elements	Application
Claudio Y. Inaba et al. 2003 [82]	Flyback	1kW	25kHz	300V	100V	93.3%	2	16	Interfacing DC-link and Traction System
Ehsan Adib et al. 2016 [83]	Forward	40W	142kHz	200V	48V	≈ 93%	4	5	Interfacing Battery and DC-link
Gang Ma et al. 2009 [84]	Half-Bridge	1kW	20kHz	60V	144V	93%	4	11	Interfacing Battery and DC-link
Majid Pahlevaninezhad et al. 2012 [85]	Full-Bridge	3kW	220kHz	400V	300V	≈ 97%	4	16	Interfacing DC-link or Fuel Cell with Traction System
Sangwon Lee et al. 2010 [86]	Push-Pull	5kW	50kHz	60-110V	380V	—	6	12	Interfacing Battery and Traction System
Roman Kosenko et al. 2016 [87]	Push-Pull	300W	100kHz	20-30V	400V	96.3%	6	7	Interfacing Battery and Traction System
Ankur Patel 2016 [88]	Forward	1.65kW	1.1Mhz	384V	48V	97.94%	6	10	Interfacing Battery and Traction System
Sina Salehi Dobakhshari et al. 2016 [89]	Half-Bridge	150W	100kHz	24V	380V	96.3%	2	13	Interfacing Battery and Traction System
Fei Shang et al. 2016 [90]	Full-Bridge	3kW	—	24V	400V	≈ 94%	4	14	Interfacing Battery and Traction System
Alexander Isurin et al. 2016 [32]	Full-Bridge	3.1kW	120kHz	30V	380V	94.1%	4	9	Interfacing Battery and Traction System
Saeed Anwar et al. 2016 [31]	Dual-Active-Bridge	5kW	50kHz	200V	450V	≈ 98.5%	8	7	Interfacing DC-link and Traction System
Sven Bolte et al. [29]	Dual-Active-Bridge	2kW	25-75kHz	400V	14V	98.2%	6	7	Interfacing Battery and Traction System
Kumar Goswami et al. 2016 [94]	Dual-Active-Bridge	2.5kW	50kHz	380V	50V	—	8	8	Interfacing battery and Traction System

Fig. 11 (a), illustrates a converter designed based on the bidirectional Flyback topology proposed in [130]. Bhattacharya et al. have proposed a multi-power-port DC-DC converter capable of handling multiple power sources while maintaining the simplicity of the converter. High gain, wide load variations, and lower output-current ripple are other features of the proposed converter by Bhattacharya. The transformer winding used for the converter has drastically reduced the leakage inductance in the converter. A 6kW prototype of the converter has experimented and the results show an efficiency of 96% for the proposed converter.

A unidirectional Forward topology-based DC-DC converter proposed in [131] is shown in Fig. 11 (b). An interleaved series input parallel output active clamp forward topology is designed and experimented by Kimura et al. The proposed converter has a superior performance and configuration in terms of size and losses compared to conventional similar forward topologies. The performance of the proposed converter is experimented by a 500W prototype and based on the results the efficiency of the converter is close to 86%.

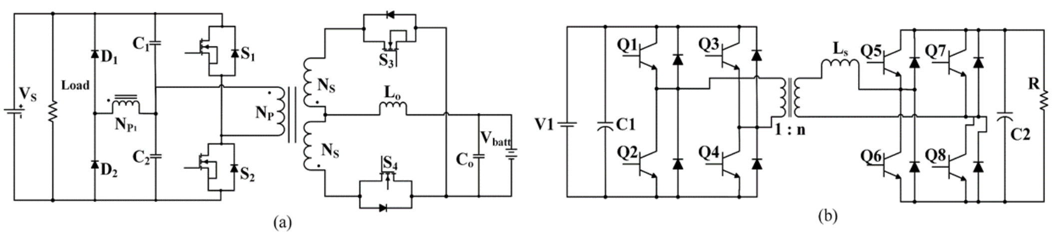


Fig. 12 Proposed converters based on (a) half-bridge [132] and (b) full-bridge [133] topology

[132] proposes a bidirectional DC-DC converter suitable for low-power applications. The proposed topology by Manu Jain et al. is based on a half-bridge converter on the primary side. The secondary side of the converter is based on a current-fed push-pull DC-DC converter, and a high-frequency transformer is used between the two sides. The proposed converter, illustrated in Fig. 12 (a) has advantages like; a reduced number of parts due to the usage of the same components in both directions of power flow, low stress on switches without using the soft-switching technique, low current ripple, and the minimal number of switches. An experimental prototype of the converter is tested and the efficiency of the converter is reported as 86.6% in forward mode and 90.5% in backup mode.

Operation, design, and control of a bidirectional full-bridge isolated bidirectional DC-DC converter for HEVs are discussed in [133]. Mathematical relations of important parameters of the converter, simulation, and experimenting a test prototype to approve simulation results have also been carried out by Mi et al. Fig. 12 (b) illustrates the converter proposed by them.

Fig. 13 illustrates a unidirectional push-pull DC-DC converter proposed by Marek Galek et al. The authors in [134] aim to obtain a flexible DC/DC converter block that can be used to cover a wide power range as well as a wide input and output voltage range. The primary side of the proposed converter is based on a half-bridge push-pull converter and the secondary side contains a center-taped transformer with a midpoint rectifier.

Details of some other non-isolated soft-switched papers and experimental porotypes in these papers are given in Table. 2.

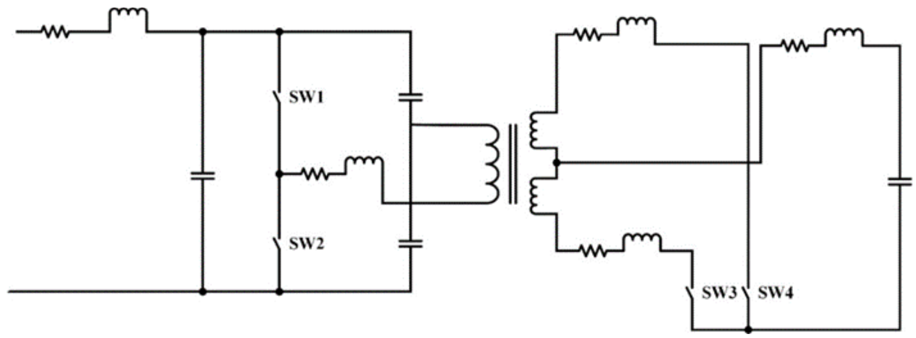


Fig. 13 Proposed converters based on a Push-Pull topology [134]

Table. 2 Some isolated hard-switched DC-DC converters for EV application

Paper	Base Type	Nominal Power	Switching Frequency	Input Voltage	Output Voltage	Max Efficiency	Number of Switches	Number of Passive Elements	Application
Tanmoy Bhattacharya et al. 2009 [130]	Flyback	6kW	20kHz	60V	330V	96%	8	2	Interfacing battery and traction system
Shota Kimura et al. 2017 [131]	Forward	500W	175kHz	202V	12V	≈ 86%	4	20	Interfacing battery and DC-link
Manu Jain et al. 2000 [132]	Half-Bridge	100-300W	100kHz	300-400V	48V	≈ 91%	4	9	Interfacing battery and traction system
C. Mi et al. 2008 [133]	Full-Bridge	10kW	10-20kHz	100V	600V	—	8	6	Interfacing DC-link and traction system
Marek Galek et al. 2014 [134]	Push-Pull	—	—	600-800V	24V	≈ 92%	4	9	Interfacing battery and traction system
Fu-Ming Ni et al. 2014 [135]	Full-Bridge	1.2kW	20kHz	350V	42-58.4V	≈ 95.5%	9	26	Interfacing battery and traction system
Thummala et al. 2014 [146]	Flyback	—	—	24V	0-250V	89.2%	2	12	Interfacing battery and DC-link
Saeed Rahimpour et al. 2017 [136]	Full-Bridge	500W	50kHz	10-30V	60V	—	8	7	Interfacing battery and distribution system
Siwakoti et al. 2013 [137]	Push-Pull	500W	6.1kHz	40-80V	400V	97.4%	2	8	Interfacing battery and traction system
Kwon et al. 2009 [73]	Half-Bridge	1kW	50kHz	20-50V	350V	96%	4	8	Interfacing battery and traction system

3-3. Non-Isolated, Soft-switched DC-DC converters

In these converters, high-frequency transformers have been removed from the vehicle which makes the converter a lot lighter. Non-isolated DC-DC converters are common and have a lower cost. they are used in most negative ground applications in vehicles for various DC-powered appliances and equipment. However, they have one big disadvantage in the electrical connection between the input and output which offers little or no protection to the load for any high electrical voltage, current, etc. occurs on the input side. They also have less noise filtering blockage. Soft switching, by reducing voltage stress and losses in the converter, improves the efficiency and performance of the converter. Overall, converters of this class are expected to cost less and be smaller than class 1 and class 2 of DC-DC converters.

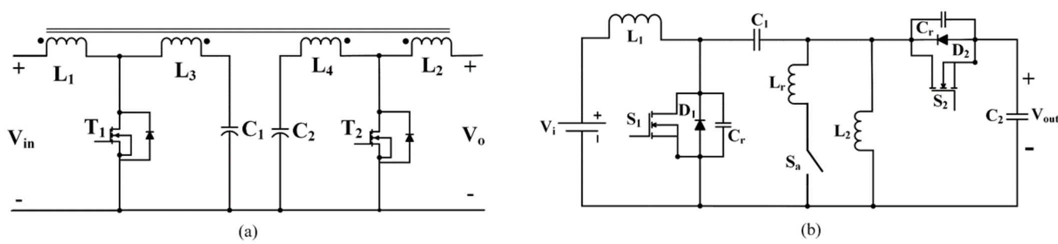


Fig. 14 Proposed converters based on (a) Cuk [147] and (b) Sepic-Zeta [148] topology

Zero ripples of both input and output currents are the advantage that Cuk converters with integrated magnetics benefit from. [147] proposes a simple bidirectional ZVS scheme for a Cuk converter containing only passive components which is based on a basic buck-boost converter. The proposed scheme by Philip Jose et al. is simulated and the results show improved efficiency of the converter with 1.4% current ripple at output and 2.1% current ripple at input. The proposed converter, shown in Fig. 14 (a) is ideal to regulate power flow between available 14V and 42V DC buses in the EV.

In-Dong Kim et al. have proposed a bidirectional Sepic/Zeta converter with low switching loss and low conduction loss in [148]. The circuit of the proposed converter, illustrated in Fig. 14 (b), can be divided into two parts of hard switched Sepic/Zeta DC-DC converter and an auxiliary resonant commutated pole circuit (ARCPC). The operation of the converter for forward power flow is like a conventional hard-switched Sepic converter, and for backward power flow is like a Zeta converter. The ARCPC provides ZVS operation for the hard-switched Sepic/Zeta converter.

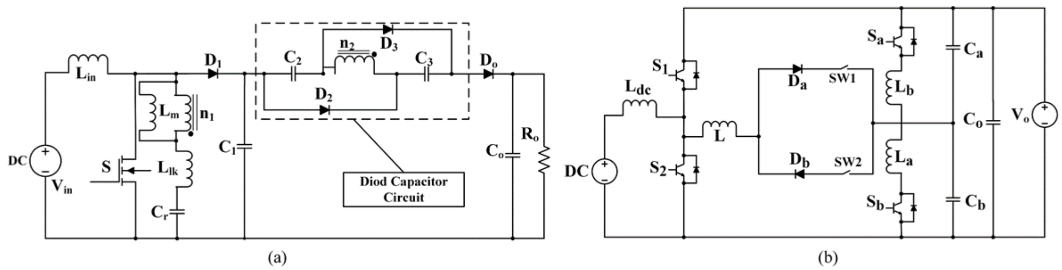


Fig. 15 Proposed converters based on (a) Boost [149] and (b) Buck-Boost [150] topology

[149] presents a single switch high step-up unidirectional Boost DC-DC converter. The proposed converter by Bhajana et al. is capable of achieving high voltage gain without a large duty cycle, which is mainly due to using coupled inductors and switched capacitor techniques. The converter is composed of one switch, five capacitors, four diodes, two coupled inductors, and an input filter inductor, as is shown in Fig. 15 (a). A 200W prototype of the converter is examined to prove the capabilities of this converter.

The proposed bidirectional converter in [150] contains two main switches, two auxiliary switches, and two switches, input and resonant inductors, and resonant capacitors as shown in Fig 15 (b). The proposed converter by Bhajana et al. is developed to achieve high efficiency at high output levels with a high switching frequency. Soft switching minimizes the current stress and switching losses in this converter, which leads to the possibility of reducing the size and volume of components and the converter. ZCS is achieved because the resonant current does not flow through the main switches. A 5kW prototype of the converter has been built and the results show an efficiency close to 98.6%. Details of some non-isolated soft-switched papers and experimental prototypes in these papers are given in Table. 3.

Table. 3 Details of some non-isolated soft-switched DC-DC converters proposed for EV application

Paper	Base Type	Nominal Power	Switching Frequency	Input Voltage	Output Voltage	Max Efficiency	Number of Switches	Number of Passive Elements	Application
In-Dong Kim et al. 2007 [148]	Sepic-Zeta	1kW	40kHz	48V	100V	≈ 89%	3	6	Interfacing battery and DC bus
Masoume Amirbande et al. 2016 [149]	Boost	200W	50kHz	25V	400V	—	1	12	Interfacing Battery and traction system
Bhajana et al. 2015 [150]	Buck-Boost	5kW	75kHz	200V	400V	≈ 98.6%	6	7	Interfacing DC bus and HV inverter
Binxin Zhu et al. 2017 [151]	Interleaved Boost-Boost	800W	40kHz	30V	400V	≈ 96.2%	2	14	Interfacing Battery and traction system
Rajesh Thumma et al. 2016 [152]	Buck-Boost	4kW	50kHz	70V	400V	—	7	8	Interfacing Battery and traction system
Chenhao Nan et al. 2016 [153]	Interleaved Buck-Boost	250W	1MHz	14V	48V	92.99%	8	10	Interfacing distribution buses
Muhammad et al. 2015 [154]	Boost	250W	50kHz	20V	190V	94.8%	2	9	Interfacing battery and DC bus
Aamir et al. 2015 [155]	Buck-Boost	300W	20kHz	24V	200V	≈ 96%	3	12	Interfacing battery and DC bus
Mishima et al. 2015 [156]	Buck-Boost	500W	50kHz	150V	300V Duty Cycle: 50%	94.9%	6	7	Interfacing DC bus and HV inverter
Xuefeng Hu et al. 2014 [157]	Interleaved Boost	500W	40kHz	18-36V	200V	94.37%	2	14	Interfacing battery and DC bus

3-4. Non-Isolated, Hard-switched DC-DC converters

Generally, this class of DC-DC converters has the lowest price, volume, and weight. Since both isolation and soft switching methods are overlooked in this class, converters have much simpler circuit configurations compared to other classes of DC-DC converters. Even though this class of DC-DC converters is more suitable in terms of simplicity, weight, and volume, but, with no isolation and soft switching, these converters suffer from higher amounts of losses, and also safety in this class of converters is not very high. These setbacks make them suitable for the limited number of applications in EVs.

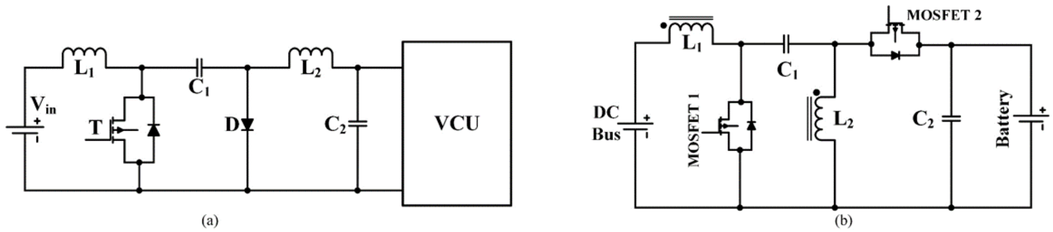


Fig. 16 Proposed converters based on (a) Cuk [175] and (b) Sepic-Zeta [176] topology

[175] studies the application of a proposed bidirectional Cuk converter in EV applications. In Fig. 16 (a), batteries serve as the input voltage of the converter while the output voltage of the converter is connected to the vehicle control unit which usually has a voltage rating of around 20V. due to the characteristics of the Cuk converter, the output voltage can be larger or smaller than the input voltage. Which means more freedom in selecting and designing the battery unit. A 48V to 20V circuit of the proposed converter is simulated and examined to show the good working condition of the proposed converter.

In [176] Dimna Denny C et al. have introduced some additional features to the conventional Sepic/Zeta converter. Considering the advantages of a coupled inductor converter like reduced voltage stress on power switches and improved output voltage quality, authors have modified the conventional Sepic/Zeta converter, by replacing the individual inductors with a coupled inductor, which reduces the overall size and improves the performance of the converter. A 24V to 200V bidirectional module of the proposed converter, shown in Fig 16 (b), is designed and simulated which confirms the increased reliability of the modified coupled inductor converter.

Xuefeng Hu et al. have proposed a unidirectional DC-DC Boost converter topology based on three-winding coupled-inductor and diode-capacitor technology for high step-up, high power density, and high-efficiency conversion in [177]. As Fig. 17 (a) shows, the equivalent circuit of the proposed converter topology contains a three-winding coupled inductor modeled by a magnetizing inductor L_m, leakage inductance, and an ideal transformer. The converter is simulated and examined and proved to be ideal for different high-power applications.

A non-isolated bidirectional hard-switched Buck-Boost DC-DC converter for EV application is proposed in [178](Fig. 17 (b). Abhijeet Sah et al. have discussed a complementary gate signal control strategy, to achieve a high power efficiency in the proposed converter. Both the regenerative and motoring mode of the EV is considered. Different simulations have been done and an ideal control strategy for the proposed Buck-Boost converter is concluded.

Details of some other Non-isolated hard-switched papers and experimental prototypes in these papers are given in Table. 4.

Table. 4 Some non-isolated hard-switched DC-DC converters for EV application

Paper	Base Type	Rated Power	Switching Frequency	Input Voltage	Output Voltage	Max Efficiency	Number of Switches	Number of Passive Elements	Application
Dimna Denny C et al. 2015 [176]	Sepic-Zeta	200W	50kHz	24V	200V	—	2	1	Interfacing battery and DC bus
C.-C. Lin et al. 2013 [179]	Buck-Boost	200W	50kHz	24V	200V	≈ 94.8	4	4	Interfacing battery and DC bus
Paul Davis et al. 2016 [180]	Multiport DIDO Boost	200W	10kHz	38V 48V	80V 40V	—	4	9	Interfacing Different LV Distribution buses and Batteries
Miaomiao Feng et al. 2016 [181]	Boost	21W	100kHz	14V	56V	—	2	12	Interfacing Distribution Buses and Batteries
Moonson M. Chen et al. 2016 [182]	Buck-Boost	400W	100kHz	66V	400V	—	5	4	Interfacing Batteries and Traction System
Bussa Vinod Kumar et al. 2016 [183]	Buck-Boost	250W	100kHz	12V	48V	—	2	6	Interfacing Distribution Buses and Batteries
Jung-Woo Yang et al. 2016 [184]	Interleaved Boost	53kW	60kHz	220-400V	700V	98.6%	4	6	Interfacing DC-Links with Traction System
Sivaprasad et al. 2015 [185]	Multiport DISO Buck-Boost	—	5kHz	36V 48V	240V	—	2	2	Interfacing Different Batteries and Distribution Links with HV Bus
Xiaoyu Jia et al. 2015 [186]	Boost	40.kW	20kHz	200-375V	600V	97.5%	2	3	Interfacing DC-links with Traction System
Hiba Al-Sheikh et al. 2014 [187]	—	30kW	15kHz	200V	300V	—	4	5	Interfacing DC-links

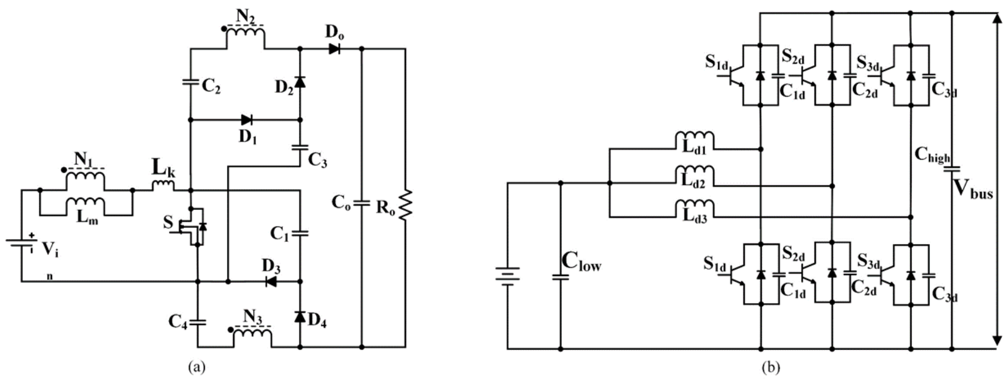


Fig. 17 Proposed converters based on (a) Boost [177] and (b) Buck-Boost [178] topology

4. Advanced Topologies

Different topologies of DC-DC converters have been proposed to be used for EVs. Apart from the introduced basic topologies for isolated and non-isolated DC-DC converters, some other topologies can be useful for the application of EVs. These topologies that are generally more complex than basic ones include; interleaved, hybrid, and multi-port DC-DC converters.

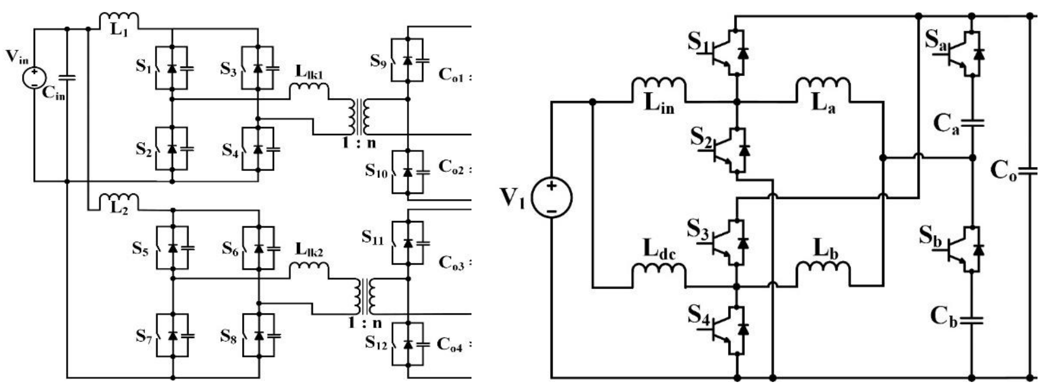
4-1. Interleaved DC-DC converters

Interleaving is a technique in which multiple switching cells are interconnected. This technique will increase the effective pulse frequency by synchronizing several smaller sources and also by operating them with relative phase shifts. An interleaving technique helps the system save more energy and improves power conversion without affecting efficiency [229]. By using the interleaved method in DC-DC converters, the system can achieve a high voltage step-up and a smaller ripple of voltage and current at the output [241]. Generally, the switching loss in these converters is low and the transient response is faster. Since the two parallel converters are identical, the design and analysis of the converter are quite simple [242]. Also, interleaved DC-DC converters offer better power handling capacity and reliability. Another advantage of these converters is that in case one of the cells faces failure, the system still can work with the other cell of the converter. Fig. 18 illustrates two different types of isolated and non-isolated interleaved DC-DC converters used for EV applications.

Fig. 18 (a) shows an isolated interleaved soft-switching bidirectional snubber-less current-fed full-bridge DC-DC converter. The proposed converter by Pan

Xuewei et al. [239] consists of two interleaved cells; a current-fed full-bridge cell is connected in parallel on the low-voltage side, and a half-bridge converter is connected in series on the high-voltage side.

A ZCS interleaved bidirectional Buck-Boost DC-DC converter is illustrated in Fig. 18 (b). The circuit of the proposed converter by Kumar et al. [174], contains four main switches, two input inductors, auxiliary resonant cell switches, resonant inductors, and resonant capacitors.



(a) (b)

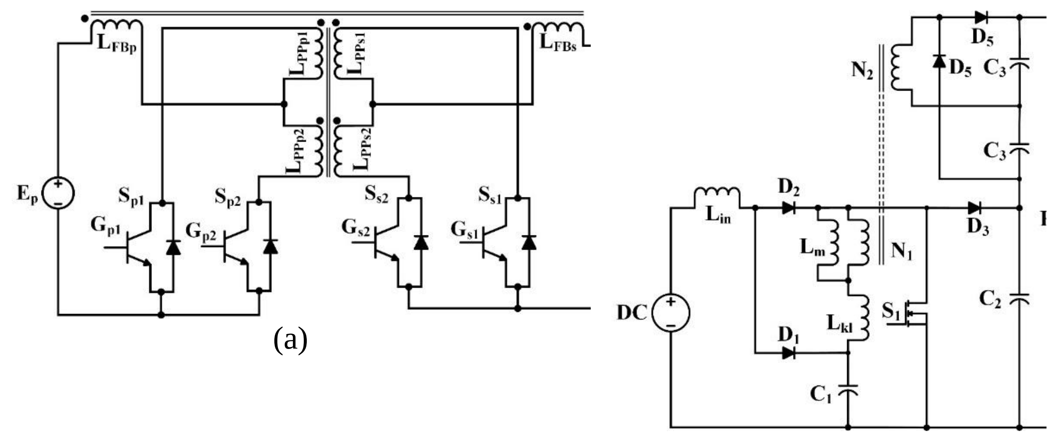
Fig. 18 Proposed interleaved converters; (a) Full-Bridge [239] and (b) Buck-Boost [174] topology

4-2. Hybrid DC-DC converters

Generally, hybrid DC-DC converters include a PWM switched-inductor DC-DC converter which is a cascaded switched capacitor DC-DC converter [247,248]. Hybrid converters include most of the advantages of the basic PWM switched inductor converter. Furthermore, these converters can achieve a much higher conversion ratio in both Buck and Boost modes. Apart from a higher total conversion ratio, low stress on the switches and higher total conversion in continuous conduction mode (CCM) are other important attributes of these converters [249]. In non-isolated hybrid DC-DC converters, capacitor multipliers replace the transformer which is required in isolated converters. As a result, possible losses caused by the transformer are depleted from the system and also the HV diodes required in isolated converters are not needed anymore. Moreover, the control strategy in hybrid structures is simpler and more flexible. All of these advantages have made hybrid converters suitable for many applications like EVs [249,250]. Fig. 19 illustrates two different types of isolated and non-isolated hybrid DC-DC converters used for EV applications.

De Souza et al. have proposed an isolated bidirectional DC-DC current-fed topology [243] which is based on a unidirectional current-fed Flyback-Push-Pull converter proposed in [251]. As Fig. 19 (a) shows, the proposed converter circuit is composed of; a Flyback transformer, a Push-Pull transformer, and four switches (bidirectional for current, unidirectional for voltage).

[245] proposes a Boost-Forward-Flyback converter with a single switch and high voltage gain. The development of this converter is based on an integrated Boost-Flyback step-up converter. The circuit of the proposed converter by Liu et al. is based on a coupled-inductor, clamped circuit, and pumping capacitor. The circuit contains; an input inductor, a pumping capacitor, a power switch, a two-winding coupled-inductor, rectifier diodes, clamp capacitor and clamp diode, and a Flyback output capacitor, as is shown in Fig. 19 (b).



(b)

Fig. 19 Proposed Hybrid converters; (a) Flyback-Push-Pull [243] and (b) Boost-Forward-Flyback [245]topology

4-3. Multi-port DC-DC converters

For some types of EVs, which use more than one energy source to provide a more stable DC voltage or there is more than one DC bus available in the vehicle, using multiport converters is ideal and can be beneficial [262,263]. The multiport DC-DC converters can be divided into three different types. The converter can have a single input and multi-output (SIMO), multi-input and single-output (MISO), and multi-input along with multi-output (MIMO). Generally, these kinds of converters have simple topology, low construction cost, high reliability, and central control [265]. Conventional multiport converters were made of several single-input single-output (SISO) converters, which on the output were connected to a common DC bus [266]. The problem with the conventional multiport DC-DC converters included a high number of elements, complexity of the circuit, high cost, complexity of the control system, and problems in the stability of the DC bus. But in recent years, multiport converters have changed a lot and now are suitable to use in many applications including EVs.

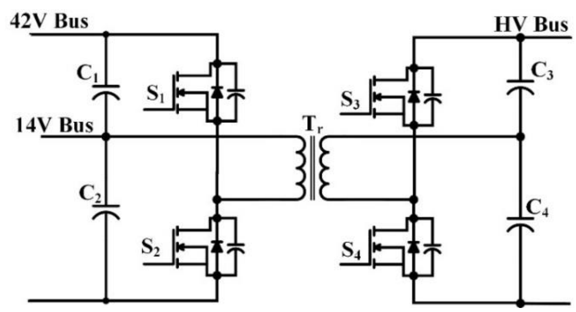


Fig. 20 Proposed topology of an isolated multi-port topology [253]

In [253] Gui-Jia Su et al. have proposed a soft-switched, bidirectional DC-DC converter using only four switches for interconnecting a triple voltage bus (14V/ 42V/ HV) system in an EV. The proposed double input single output (DISO) converter is a reduced-part topology of the converter proposed in [126]. The schematic of the proposed converter, shown in Fig. 20, is composed of; dual half-bridges and a high-frequency transformer to ensure the galvanic isolation between low voltage and HV buses, and the 14V bus is derived by tapping the capacitor leg at the midpoint. Furthermore, the 14V and 48V buses share a common ground.

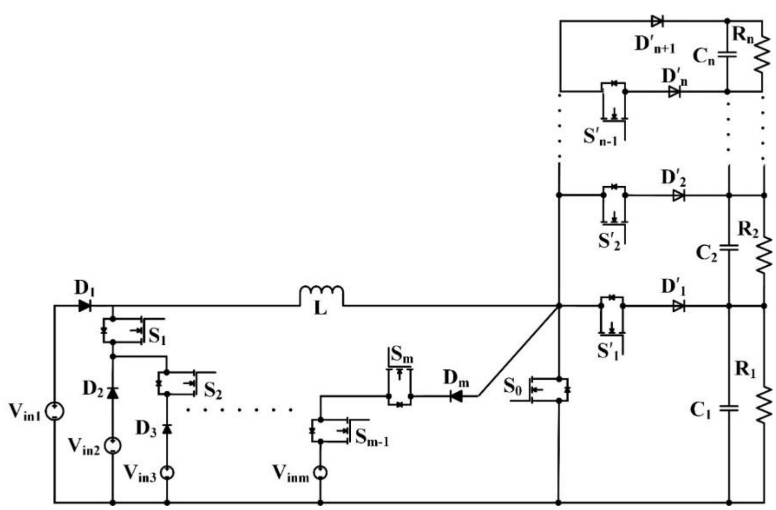


Fig. 21 Proposed topology of a non-isolated multi-port topology [258]

Nahavandi et al. have proposed a multi-input multi-output non-isolated DC-DC converter in [258]. The proposed converter is based on a combination of a multi-input converter [267], and a multi-output converter [268]. The structure of the proposed converter is illustrated in Fig. 21. As this figure shows, the converter is capable of interfacing *m* input sources. The converter has one inductor, *n* capacitor at the output side, and *m+n* switches. Also, n resistances represent the equivalent power feeding a multilevel inverter in the EV. Output voltages can be either different or equal which is appropriate for connection to a multilevel inverter. The proposed converter is suitable for hybridizing alternative energy sources such as FC, battery, or supercapacitor, in EVs.

The comparison between all types of DC-DC converters that are mentioned in terms of; gain, volume, safety, efficiency, switching frequency, and complexity are summarized in Table 5.

Table. 5 Provides a summary of these 10 categories' properties and features

	High Gain	High Volume	High Safety	High Efficiency	High Complexity	High Switching Frequency
Isolated, Soft switched	✓	✓	✓	Almost	✓	✓
Isolated, Hard switched	✓	Almost	✓	×	Almost	×
Non-isolated, Soft switched	×	Almost	×	✓	Almost	✓
Non-isolated, Hard switched	×	×	×	×	×	×
Interleaved, Isolated	✓	✓	✓	Almost	✓	×
Interleaved, Non-isolated	Almost	Almost	×	Almost	Almost	×
Hybrid, Isolated	✓	✓	✓	×	✓	×
Hybrid, Non-isolated	Almost	Almost	×	×	Almost	×
Multiport, Isolated	✓	✓	✓	×	✓	×
Multiport, Non-isolated	×	Almost	×	×	Almost	×

5. Control strategies

5-1. Brief review

Among various modulation techniques designed for controlling DC-DC converters, two common modulation techniques have found the most application: Pulse-width modulation (PWM) and phase-shift modulation (PSM). Between these two, PWM has found much more applications and is the most common control scheme for switching-mode DC-DC converters. The major setback in VF-PWM is the unpredictability of EMI in this method. On the other hand, in FF-PWM the EMI can easily be filtered out [269]. The exact operational principle of FF-PWM and VF-PWM is described in [270,271].

Fixed-frequency (FF) and variable-frequency (VF) PWM are the most popular PWM control methods [272]. PWM control methods can also be classified into two groups: voltage-mode control (VMC) and current-mode control (CMC) which are based on output voltage/current measurements. [273]. Studies on these two groups have resulted from different control methods such as feed-forward VMC (FFVMC), peak CMC (PCMC), average CMC (ACMC), etc.

PSM is also suitable and attractive for different DC-DC converters. Some extensions of PS control techniques like single-PS (SPS) [274–276], extended-PS (EPS) [277–279], dual-PS (DPS) [280–282], and Triple-PS (TPS) [283–285] have the benefits of improved performance and characterization. Each of these PS control extensions is briefly explained in [286].

Both closed-loop control (CLC) and open-loop control (OLC) control techniques can be used for DC-DC converters in high-power applications. Using CLC in high-power applications is possible but faces electromagnetic compatibility (EMC) and lower efficiency issues. By using OLC it is possible to prevent such issues. To be able to use the OLC technique for high-power applications, output resistance should be as low as possible [287].

5-2. Control devices

Various control devices such as digital sensor processors (DSP), Field programming gate array (FPGA), other custom hardware, or a combination of custom hardware can be used to digitally control the different modulation and control techniques. Each of these devices can be suitable depending on the designer's preferences. DSP chips are superior in terms of the possibility of reprogramming, the capacity of tending, and numerous functions that DSPs are capable of doing. High cost and low speed are the downsides of the DSPs which have counterbalanced the advantages of DSPs. On the other hand, FPGA, compared to DSP, has the ability of quicker operation but still FPGA is considered an expensive option. These downsides have led to additional consideration and attempts to solve these problems. The design of devoted custom ICs is one solution that is considered to be a less expensive device than DSPs and FPGAs and also offers better functioning. A combination of software and custom hardware is another device used in the design of DC-DC converters [286].

6. Design Considerations

With the addition of intelligent power modules (IPMs) to design DC-DC converters, it is now easier for designers to develop cost-effective and compact-sized DC-DC converters. But still, some important parameters should be considered when selecting components for the circuit of a DC-DC converter. One of the main choices in circuit components of DC-DC converters is a selection of the solid-state power devices which are one of the costliest components of the circuit as well. Generally, MOSFETs are used in low-power rating converters, due to their high switching rate and insignificant losses, IGBTs together with PWM technology are ideal for medium-power rating converters, and GTOs are used in high-power applications. Further information about the selection of the transistors is given in [288]. Another important selection in DC-DC converters is choosing the right inductance (L) for the application. The chosen inductor must be able to handle the peak switching current without being saturated. To select the best possible inductor which minimizes the losses of the inductor, analyzing the quality-frequency graph of the inductors can be helpful. The proper inductor for the application will only degrade efficiency by a small percentage. Choosing an inductor generally depends on price, size, or other electromagnetic requirements in the circuit [289]. To help developers design the proper inductor for their application, different methods and tools have been designed. In [290], The Murata Power Inductor Selection Tool (MPST), is described. On the other hand selection of the output capacitor is based on the ripple current, ripple voltage, and stability considerations of the system [289].

A proper switching frequency is essential to achieve a high level of performance. Switching frequency can have a huge impact on different properties in the circuit of the DC-DC converter as it is shown in Table 6.

After choosing a DC-DC converter that has the appropriate switching frequency for our application, choosing other components is made based on the switching frequency and other parameters of the system like characteristics of the load and output of the converter. Some points should be considered about the FET used in the external circuit. The amount of input capacitor and output capacitor must be rather small in the light load applications. This can be said about the ON resistance between the drain and source when the load has a higher value but it can affect the input and output capacitance. Overall, these parameters need to be designed carefully to minimize the loss in the converter. The cut-off voltage of the gate to the source should be much smaller than the input voltage in the application. The switching speed of the selected component should be as high as possible to increase the efficiency of the converter. The rated voltage should be about 1.5 times bigger than the rated voltage of the application. Also, it can be said that choosing a MOSFET, GTO, or IGBT with a driving capability of unnecessarily large current is not appropriate.

Table. 6 Effect of switching frequency on different circuit properties in DC-DC converters

Circuit Properties	Switching Frequency	
	Low	High
Maximum Efficiency	High	Low
Current Ripple	Large	Small
Response Speed	Slow	Fast
Output Current (at Max Efficiency)	Light Load	Heavy Load

The selection of the L value in the converter is based on the output current and has a huge impact on the efficiency of the converter. If the selected value is too small, the current will increase when the solid-state power device is activated which will increase the heat losses of the device, coil, and will also reduce the efficiency. On the other hand, choosing a high value of L will also lead to the increase of RDC, decreasing the efficiency and occurrence of magnetic saturation in the ferrite coil. This will rapidly decrease the L value which is very dangerous. To avoid this phenomenon, designers have to increase the dimension of the coil which is not preferable in the converter either. So it is very important to find the right amount for L value of the converter.

Moreover, Schottky Barrier Diodes (SBD) are used in some converters. The absolute maximum ratings for this component should be 1.5 to 2 times the working ratings. Choosing the most appropriate SBD is dependent on the load current of the application. But it is desirable to choose the one with the least amount of forward heat loss and reverse leakage current [291].

The description of the perfect load capacitance differs depending on the type of capacitor being used in the application. There are different properties for aluminum electrolytic capacitors, tantalum capacitors, and ceramic load capacitors. The value of load capacitance should be chosen according to the targeted ripple level. Choosing an unnecessarily high value for the process will increase the volume and cost of the converter which is not acceptable [291].

Input capacitance, even though it does not have a significant impact on the stability of the output like load capacitance, is another important part of the converter. Commonly, the value of input capacitance is selected about half the amount of load capacitance at the start. Using a capacitor with the smallest equivalent series resistance (ESR) possible is recommended in DC-DC converters. There are other important components like feedback capacitance, feedback resistance, control circuit, etc. which require great attention to detail for selecting the best possible combination.

Overall, it is important to consider all the parameters when selecting different components to design a DC-DC converter. Some components based on the life assessment analyses made on DC-DC converters need more care and should be selected with great attention to detail to achieve a high level of performance. The key components of life assessment for the DC-DC converter based on three different simulation methods made in [292], include power switches, transformers, diodes, and optocouplers.

7. Comparative factors of DC-DC converters

Choosing a DC-DC converter depends on a lot of parameters and devices used in the design of the vehicle. Therefore, the suitability of converters differs from one application to another. Hence, comparing them without having enough information about the vehicle is not possible. Each of the four categories mentioned in previous sections has different features which makes them ideal for several applications. But within the same category, there are many circuits available and comparable to the ideal characteristics. Some circuits have better quality or more configurations and features which makes them more expensive. Subsequently, the designer is the person who should decide between performance, quality, or costs. For example, if the vehicle contains many sensitive DC loads and the EMI might disturb and influence their function and vehicle it is necessary to use an isolated DC-DC converter. But, there is no problem if the designer decides to use a cheaper solution by applying the non-isolated converter (as long as it satisfies the minimum requirements in the vehicle) with the cost decreasing the safety of the vehicle to some amount. Similar to isolation, depending on the vehicle requirements and budget one can choose various configurations of soft or hard switching methods. [81] Has discussed the soft switching effect in the vehicle and its effect on total energy saving and efficiency of EVs and HEV. It is concluded that soft switching does not have that much of an effect and it might just be for filtering different noises and lowering audible noises [81]. Similar situations and choices might occur and the designer should be well aware of different features of the vehicle to be able to choose a converter between different categories and within various configurations of one category to be able to make the best choice.

8. The main aspects of designing DC-DC converters in EV application

The selection of DC-DC converters is an important decision that depends on many aspects of the designed vehicle. Here are some of the factors that can have an effect when choosing a converter for a specific application:

- Required number of output voltages (number of loads supplied by the converter)
- Range of input voltage
- Power flow (unidirectional or bidirectional)
- Required DC output level (should the converter be boost, buck, etc.)
- Efficiency
- Cost
- Weigh and volume
- Noise level
- Power rating (Watt, kilowatt, etc.)
- Reliability
- Environmental conditions which influence the operation of the converter (such as; heat, humidity, pollution, etc.)
- Acceptable quiescent current (<300μA in some cases)

These are just some of the factors in choosing a DC-DC converter for specific EV applications. There are also some special requirements like a low current ripple in fuel cell applications (because the current ripple may affect the fuel cell lifetime) [293], and some more factors like complexity of control procedure, protection, magnetic devices used in the converter, etc. which can influence the selection of a converter required for the specific application.

9. Latest trends and further developments in DC-DC converters

DC-DC converters have reached an acceptable level in terms of technology in EV systems. Even though still many approaches are being studied to develop a converter with high efficiency, small size and lower weight, high noise filtering, and safety. Many approaches have been employed to achieve high efficiency converters such as; switched-capacitor or switched-inductor techniques [294–297], inserting diode-capacitor voltage multipliers to serve as built-in voltage gain extension cells [298–301], and coupled-inductor based converters have been proposed (like coupled-inductor converters with an active clamp circuit or three winding coupled inductor converters) [302–307]. These approaches have offered limited improvements in size, cost, and efficiency of the converter which has led the researchers to develop and propose a new composite DC-DC converter architecture [25,25,308]. This approach utilizes several smaller converter modules combined to process the total system power effectively. This approach is a modular multilevel system employing dissimilar Module types. Each converter module processes a fraction of the system power, with effective utilization of the semiconductor and reactive elements. The ability to optimize each module independently at certain critical operating points leads to substantially increased average efficiency. Depending on operating conditions, modules can operate in shutdown or pass-through modes to further reduce AC power losses. Overall, the loss mechanisms associated with indirect power conversion are addressed explicitly, resulting in fundamental efficiency improvements over wide ranges of operating conditions [309].

10. Conclusion

DC-DC converters are an important part of an electric vehicle's powertrain controlling the power flow between different DC buses, batteries, power inverters, and traction systems. In this paper over 200 papers studying different topologies for different applications in EVs are reviewed and structured in four main classes: isolated soft-switched, isolated hard-switched, non-isolated soft-switched, and non-isolated hard-switched DC-DC converters. Isolated DC-DC converters can provide galvanic isolation and improve safety for the loads which is an important factor for sensitive loads and electric systems in the vehicle which are directly related to passenger safety. Non-isolated converters have reduced safety, but due to the removal of the high-frequency transformer in the converter, weigh, volume and cost of the converter are rather low compared to isolated DC-DC converters. Soft-switched DC-DC converters have the advantage of reduced switching losses which improves the efficiency of the converter. Soft switching can be achieved by either ZVS or ZCS methods. On the other hand, hard-switched converters have fewer components compared to soft-switched ones which reduces design complexity and weight and cost of the converter. Apart from the introduced basic topologies for isolated and non-isolated DC-DC converters, some other topologies that can be useful for the application of EVs such as; interleaved, hybrid and multi-port DC-DC converters are presented in this paper. Also, control strategies, design considerations, comparative factors, selection for specific applications, and the latest trends are discussed in this paper.

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