This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TTE.2020.3009152, IEEE Transactions on Transportation Electrification

An Overview of High-Conversion High-Voltage DC-DC Converters for Electrified Aviation Power Distribution System

Niraja Swaminathan, *Member, IEEE* and Yue Cao, *Member, IEEE*

***Abstract*—This paper presents the state-of-the-art review of high-conversion high-voltage (HCHV) DC-DC converters for a modern aerial vehicle's power distribution system. Higher DC bus voltages have become a trend in recent aerial vehicle development because of the potential reduction in size and weight of the rest of the power system and an increase in power density. Some front-end DC energy sources, such as fuel cells, batteries, and supercapacitors, may level at a low-voltage and require HCHV DC-DC converters to integrate with the high-voltage DC bus. On the other hand, high-conversion step-down converters are required between the DC bus and various low-voltage electronic loads. A detailed review of HCHV DC-DC converters for an aviation power distribution system is limited in the literature. This paper presents two main architectures of such converters. Architecture-I employs individual two-port DC-DC converters to link each source to the DC bus, and Architecture-II uses a single multiport converter to connect all the sources to the DC bus. Architecture-I categorizes the two-port DC-DC converter topologies into unidirectional and bidirectional converters, followed by further classifications based on isolation and control schemes. Multiport DC-DC converters for Architecture-II are categorized based on port numbers and then source connection methods. This review investigates multiple topologies within each category or classification, highlighting selected circuit diagrams and their features and shortcomings. The paper presents several insightful comparisons, among various bidirectional converters for Architecture-I, and multiport converters for Architecture-II, for a designer to choose a proper converter. In terms of converter characteristics, this paper focuses on DC voltage gain, power density, efficiency, and reliability, as these qualities are of utmost importance in an aviation application.**

***Index Terms*—DC-DC converters, high-conversion high-voltage, unidirectional, bidirectional, multiport converters, more electric aircraft (MEA), unmanned aerial vehicles (UAV)**

I. Introduction

In recent years, the aviation industry is experiencing tremendous growth in air traffic, including passenger or cargo flights and unmanned aerial vehicles (UAVs). Environmental concerns and fossil fuel depletion, among other factors, drive the development of more electric power distribution systems (EPDS) in aircraft [1]–[3]. More electric aircraft (MEA) have replaced hydraulic and pneumatic systems with electric counterparts, resulting in increased efficiency and reduced fuel burn rate, maintenance cost, and system weight [3], [4]. Boeing 787 is one notable MEA [5]–[7]. The future trend is all-electric aircraft, where all the aircraft loads (e.g., propulsion, avionics, cabin environmental control system, in-flight entertainments, lights, deicing, etc.) are powered entirely from the electrical system [5], [8]. The all-electric drivetrain technology is already in the market for road transportation. MEA and all-electric aircraft designs have led to innovation in transportation markets such as flying taxis and air package delivery [9]. Some of these are expected to enter the market in the US by 2023 [10], [11]. The emerging research in electrified aerial vehicles is the EPDS as the present electrical system has a limitation in achieving the required specific power density for large passenger aircraft [5], [12].

Niraja Swaminathan and Yue Cao are with the School of Electrical Engineering and Computer science, Oregon State University, Corvallis, OR 97331, USA. E-mails: Niraja.Swaminathan@ieee.org, Yue.Cao@oregonstate.edu

Fig. 1 shows one sample EPDS of MEA, which consists of a possible hybrid source of generators, fuel cells, batteries, and supercapacitors [1], [6], [7], [13], [14]. On the other hand, all-electric UAVs beyond hobbyist drones, becoming heavy-duty such as those for package delivery [9], possess a less complicated power system and may include a fuel cell and/or a battery pack. Different electrical sources perform unique functions in an EPDS. Some sources provide inrush currents during transients, while some provide the required base power. The purposes of each source are as follows [4]:

- AC generators provide most of the power required by the load.
- Supercapacitors supply short-term peak power to the load transients.
- Fuel cells, as secondary power sources, supply power to the load.
- Batteries supply or sink excess power in the system. Batteries also store regenerative power.

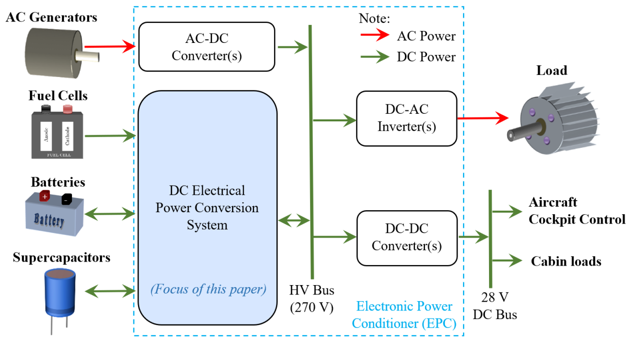

Fig. 1: Sample electrical power distribution architecture in MEA

Note in Fig. 1 and remaining discussions that 270 V and 28 V are selected as high-voltage (HV) and low-voltage representatives. However, throughout this paper, the reviewed converters are abstractable to a variety of voltage levels for future electrical architecture development.

Current MEAs prefer a 270 V or higher DC bus to reduce the conductor/machine size, weight, and cost [3], [4], [7], [13], [15], [16]. Joint Strike Fighter is one example that uses a 270 V DC electrical power system [12]. In addition to the 270 V DC bus, other DC buses such as 28 V, 12 V, and 5 V exist in the modern aerial vehicles, which generally feed the low power loads and control system [13], [16].

The above-discussed energy sources are of different voltage levels and require an electronic power conditioner (EPC) to link to the HV DC bus, as shown in Fig. 1. In existing MEAs, batteries and fuel cells are rated at 28 V to 48 V but require high-conversion high-voltage (HCHV) DC-DC converters to transfer power to or from the HV DC bus [1], [4], [15], [16]. In existing UAVs, batteries and fuel cells are rated between 24 V and 48 V DC that directly powers low-voltage motor systems, but a future HV ($>$200 V) motor is possible and desirable [9], [17]. Such future UAVs require similar HCHV DC-DC converters. Recent research activities target these converters for efficient, lightweight, reliable, and low-cost concerns [13]. Desirable requirements of these DC-DC converters, when used in modern aerial vehicles, include:

- High-conversion ratio of 10 or more to step-up different energy source voltages;
- Bidirectional power flow – depending on the type of source;
- High power density concerning volume and weight, and often associated with high switching frequency to reduce the filter and magnetics sizing;
- High conversion efficiency thereby reduced cooling system;
- Reduced Electromagnetic Interference (EMI);
- Reliability – redundancy to ensure safe operation even during failures;
- MIL-STD-704F compliant for specified voltage regulation on 270 V DC bus.

For aircraft electrification, EMI, especially common-mode (CM) noise will be an important concern as input and output terminals of HCHV converters are placed on the same chassis [18]. CM noise is caused by a high dv/dt due to switching of devices. Using a CM choke at the input side, providing an inductor (with a low Q value) at the ground path, or directly shorting the input and output grounds possibly reduces the CM noise [19]–[21]. These two grounding-related methods are to be reconsidered when isolated converters are employed. The CM noise can also be minimized with the choice of topology. For example, if the topology operates with soft-switching, particularly zero-voltage switching (ZVS), dv/dt is drastically reduced [22].

HCHV DC-DC converters for aircraft electrification is an emerging research direction, but a detailed study of these converters is limited in the literature. There are existing reviews of other electrical aspects of MEA reported, such as [4], [6], [23]. Ref [6] presents the high-level review of major subsystems of the aircraft power system, such as the main engine start, auxiliary power units, environmental control system, on-board inert gas generation system, and future propulsion system. In [4], the overview of individual subsystems of on-board microgrids in MEA is the focus. A brief discussion on power electronic converter topologies is presented, including AC-AC, DC-AC, AC-DC, and DC-DC converters. Ref [23] summarizes MEA electrical machines and power electronics development on the aspects of their materials, architecture, control, power quality, reliability, and thermal management. Also, the overall system stability and reliability are discussed. A more DC-DC conversion oriented review from [17] presents isolated bidirectional converters for an avionic onboard DC microgrid, with a focus on system efficiency improvement.

This paper presents a state-of-the-art review of existing HCHV DC-DC converters suitable for modern aerial vehicles, aiming to help designers choose the converter among many possibilities. Insights of HCHV converters from the telecommunication, electric vehicles, and solar PV applications are also obtained, as HCHV converters for MEA are still emerging. Nevertheless, key features such as reliability, safety, and power density preferred for MEA are taken into account.

This work discusses two main architectures of HCHV DC-DC converters for aircraft electrification – two-port converters and multiport converters (MPCs). Within each architecture, there are several classification approaches, such as unidirectional or bidirectional, non-isolated and isolated, control mechanisms, and physical constructions. As the discussion proceeds, the paper provides circuit diagrams of the selected topology in each converter category, along with their merits and limitations. Potential converter topologies for MEA and UAV systems are compared based on figures of merit such as DC voltage gain, efficiency, isolation, number of components, filter requirements, and control complexity.

Although this paper focuses mainly on the HCHV conversion on the energy source to DC bus side, most of the topologies discussed here have equal potentials for the high conversion from the DC bus to low voltage loads, such as the 28 V supply in MEA and UAVs. Feasibility for such topologies is also included in this paper.

The organization of the rest of the paper is as follows: Section II explains the architectures of the HCHV DC electrical power conversion system. Section III discusses two-port converters for MEA and UAV systems, followed by families of three-port and MPC topologies in Section IV. Section V concludes the review.

II. HCHV DC Electrical Power Conversion System Architectures

This section describes two architectures of the DC-DC converter implementation in an EPDS with an HV DC bus, as shown in Fig. 2. In Architecture-I, individual two-port converters link each energy source to the HV bus; and in Architecture-II, a single MPC links all DC sources [24]–[27]. As shown in Fig. 2, some DC-DC converters require bidirectional conduction while others suffice from unidirectional. Among these converters, there are isolated or non-isolated. Non-isolated converters have high power density due to the absence of the transformer. However, the achievable gain is limited. In contrast, isolated topologies have the advantage of a higher conversion ratio in addition to the safety of humans and equipment. However, the effects of leakage inductance, parasitic capacitance, additional conduction, and transformer core losses must be considered during the design stage.

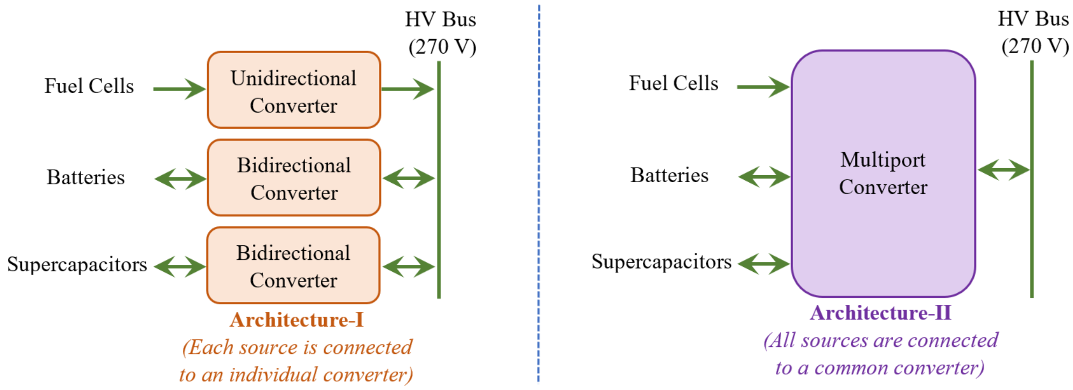

Fig. 2: Architectures of HCHV DC electrical power conversion system for modern aerial vehicles

For aviation applications, the power converters in EPDS must be reliable and resilient [4], [28]. The general method of improving the reliability is to have redundant power converters [4], [28]. However, this introduces additional weight and reduces the overall power density. Work is reported in the literature to achieve reliability with increased power density. One such work is the fault-tolerant circuit presented in [28], which uses a few extra diodes to reduce the number of redundant converters. Another way of achieving reliability is through different power system architectures. In Architecture-I, each source uses separate power converters so that failure of one does not affect the other, thereby having a more reliable system operation. However, it requires intricate coordination among various sources. MPCs in Architecture-II, in general, have fewer components and higher efficiency than two-port converters. However, the reliability is lower as one failure point of MPC tends to collapse the whole power system.

The following sections will present various HCHV DC-DC converter topologies under each main architecture. The discussion will particularly consider the DC voltage gain, power density, efficiency, and reliability aspects.

III. Two-port DC-DC Converters for Architecture-I

In this architecture, two-port DC-DC converters are classified in several layers, as given in Fig. 3.

A. *Unidirectional two-port converters*

Unidirectional converters, in general, have fewer active devices and therefore, are economical with simple control. However, these converters cannot handle any regeneration from the DC bus due to bidirectional power flow incapability [17]. This subsection discusses unidirectional converters, such as those link fuel cells to the HV DC bus, and can be either non-isolated or isolated.

1) Non-isolated unidirectional two-port converters: The basic Boost converter is a well-known high DC voltage gain non-isolated converter, but the DC voltage gain drops with a duty ratio above 0.6 at high power [29]. The drop in the DC voltage gain is due to the voltage drop across the winding resistance of the boost inductor [29]. This leads to predominant conduction loss in the inductor, reducing the overall efficiency of the converter [29], [30]. Therefore, Boost converters are used mostly as front-end converters to improve, usually double, the achievable DC voltage gain [2], and hence hardly qualify as high-conversion step-down converters. For an indirect usage, on the other hand, these converters can perform a front-end power factor correction with a suitable control when fed from a diode bridge rectified DC source, as part of the overall DC-DC conversion.

There are other non-isolated two-port converters such as Buck-Boost, Buck, and Cuk converters [29] that are of less interest for aerial vehicles due to limited achievable DC voltage gain and low power handling capabilities.

2) Isolated unidirectional two-port converters: In contrast to non-isolated converters, isolated converters provide high DC voltage gain and prevent electric shocks or equipment damages [31]. Isolated converters are further classified as duty-controlled and phase-shift controlled converters based on their control technique, as given in Fig. 3.

a) Duty-controlled isolated unidirectional converters: The duty-controlled converters regulate the output voltage by controlling the duty ratio of the active switches while keeping the switching frequency constant. Flyback, single-switch forward, two-switch forward, push-pull, half-bridge, and full-bridge (FB) converters are commonly known duty-controlled unidirectional isolated converters [29]. Among these, flyback, forward, and push-pull converters have a low transformer utilization factor and require a large transformer turns ratio to achieve a high DC voltage gain. The high leakage inductance of such a transformer results in a reduced efficiency [30]. Therefore, these converters are not suitable for high power applications.

Among other duty-controlled converters, FB converters are popular because of better transformer core utilization, simple circuitry for flux resetting, low-voltage stress on devices, and high power capability [2], [29], [31]–[38]. Traditional FB [29] and Boost FB [39]–[44] are well-known families of FB duty-controlled converters. The traditional FB converter, as shown in Fig. 4, consists of an active-bridge at the primary side and a diode bridge at the secondary side. In this topology, the diagonal switches are switched simultaneously using a symmetrical duty control technique (i.e., all devices have the same duty ratio) with the duty ratio restricted to 0.5 (theoretically), as shown in Fig. 5. The working principle of this converter is similar to the basic Buck converter. The advantage of this converter is that the voltage and current stresses of the active switches are the same as the input voltage and reflected load current,

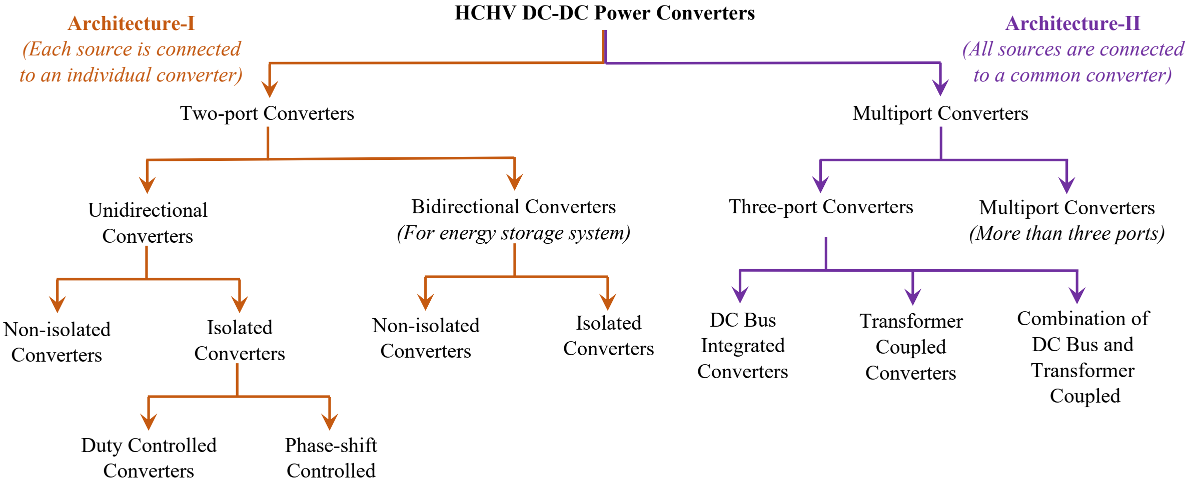

Fig. 3: Broad classification of HCHV DC-DC converters for electrified aviation power supply

respectively. As this topology being buck in nature, it is suitable for a HC step-down converter.

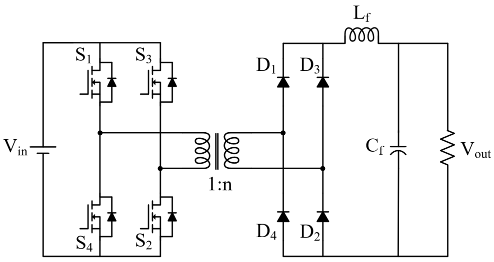

Fig. 4: Traditional full bridge converter [29]

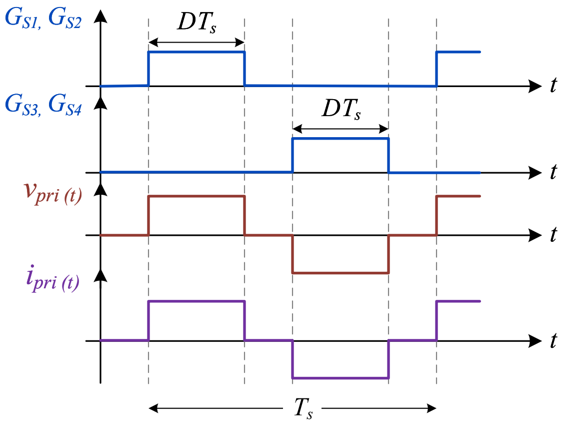

Fig. 5: Characteristic waveforms of FB converter [29]

Boost FB converter circuit, as shown in Fig. 6, is similar to the traditional FB converter, except that the inductor is tied to the source rather than the load. Therefore, it is a current-controlled converter [40], [44], [45]. The Boost FB converter uses a similar control pattern as the traditional FB converter, but with the minimum duty ratio limit of 0.5 (theoretically) to ensure uninterrupted inductor current. This converter works with the principle similar to the basic non-isolated Boost converter. Therefore, it has a high DC voltage gain of $\frac{n}{(1-D)}$ than a traditional FB converter's nD, where n is the transformer turns ratio, and D is the duty ratio of the transformer primary voltage. Furthermore, the Boost FB converter, shown in Fig. 6, has continuous input current as the inductor (L_b) is tied to the source, which reduces the input filter requirement. Additionally, since this converter has an output capacitive filter (C_o), the voltage stress on the HV side diodes is just the output voltage (V_{out}), unlike nV_{in} (always $> V_{out}$) as in the case of traditional FB converter [39], [40]. However, the output capacitor (C_o) must supply a large load current at high power. This filter increases the size and weight of the Boost FB converter. Both traditional FB and Boost FB converters require an auxiliary circuit to achieve soft-switching to reduce the switching loss and CM noise while operating at a high switching frequency for high power density [2], [42], [44], [46].

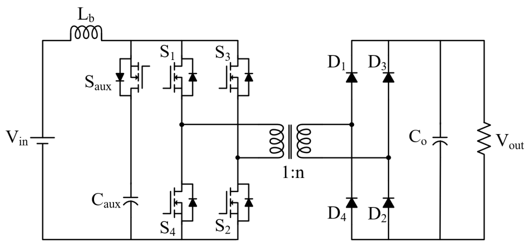

Fig. 6: Boost full-bridge topology with active-clamp [44]

Another variant of the FB converter is presented in [30] that has the potential for aerial vehicles. In this converter, two of the output diodes are replaced by active switches to improve efficiency. Additionally, the output filter inductor from the traditional Boost is eliminated in this topology, improving the power density and reducing the voltage stress on the HV diodes. Soft-switching of the devices is achieved, which further enhances the efficiency at the high switching frequency and reduces the EMI.

b) Phase-shift controlled isolated unidirectional converters: This family of converters uses a phase-shift modulation technique, where the duty ratio of all the switching devices is fixed at 0.5, but the phase difference among the switch PWMs is varied to control the output. Family of phase-shift converters, specifically FB Resonant Transition converter [33], [35], [36], [46] and Buck-Boost FB converter, [2], [47], [48] have gained attention over duty-controlled FB converters due to the advantages: (i) inherent soft-switching by utilizing the leakage inductance of the transformer and parasitic capacitance of the semiconductor devices without additional circuitry; (ii) constant switching frequency despite being a resonant converter; (iii) low-voltage stress on the input devices; (iv) simple to control, as the phase-shift and output voltage have almost linear relationship at the operating zone; and (v) high power capability [2], [33], [46], [49].

FB Resonant Transition converter is a load resonant converter, and the circuit is the same as the traditional FB converter, as shown in Fig. 4, but with the characteristic waveforms given in Fig. 7, as this converter uses the phase-shift modulation technique. In this converter, phase-shift between the PWM of switches S_1 and S_2 is varied to adjust the duty ratio D of the transformer voltage v_{pri} (see Fig. 7), thereby controlling the output voltage V_{out}. The DC voltage gain of this converter is a function of load R_o, switching frequency f_s, and turns ratio n as given in eq. (1) [33]. This converter has high power capability and has been widely used in telecommunications for 400 V to 48 V conversion [50]. As this converter operates with ZVS, the CM noise is relatively reduced. However, when used in modern aerial vehicles, this converter exhibits a high duty loss (i.e., reduction in the DC voltage gain) due to a larger turns ratio n (from high conversion ratio requirement), as observed from eq. (1). As a result, to achieve the required DC voltage gain, switching frequency is limited (in the range of a few tens of kilohertz) when used for aerial vehicle applications [2], [50].

$$\frac{V_o}{V_{in}} = \frac{nD}{1 + \frac{4n^2 f_s L_{lk}}{R_o}} \tag{1}$$

where,
f_s - Switching frequency, Hz
L_{lk} - Leakage inductance of the transformer, H
n - Turns ratio of the transformer
D - Duty ratio of the transformer primary voltage
R_o - Load resistance, Ω

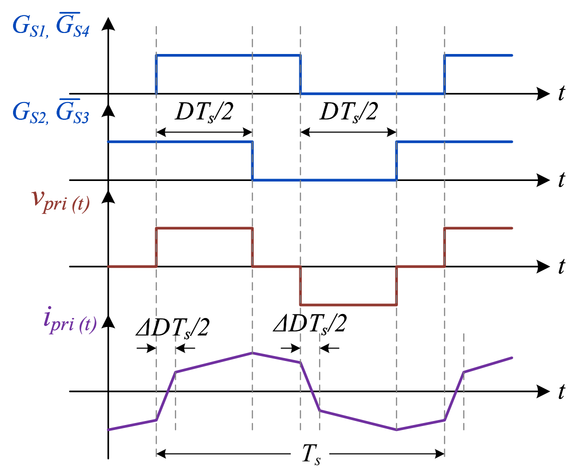

Fig. 7: Characteristic waveforms of FB resonant transition converter [33]

Current-controlled Buck-Boost FB converter families have improved on the switching frequency limit issue and provide twice the DC voltage gain at a given switching frequency compared to the FB Resonant Transition converter [2], [47], [48]. The primary side of the Buck-Boost FB converter performs the basic Boost operation at a 0.5 duty ratio, and the rest behaves similar to the FB Resonant Transition converter, which is the reason for twice the DC voltage gain. This converter inherits the advantages of FB Resonant Transition converter along with the reduced filter requirements, continuous input, and output currents. Nevertheless, the Buck-Boost FB converter exhibits a DC-current in the transformer and requires a unique control scheme to mitigate, as presented in the literature [2], [51].

Both FB Resonant Transition and Buck-Boost FB converters use an LC filter at the output, and thus require HV rated output diodes (due to high-voltage stress nV_{in} as compared to V_o with just capacitor output filter). Besides, the ZVS range in these converters is limited. Also, the circulating current caused by the free-wheeling output inductor current in the interval $\frac{(1-D)T_s}{2}$ (see Fig. 7) adds to the conduction loss [37], [52]–[54].

Modified FB topologies [37], [52]–[56] report extended ZVS ranges with reduced leakage/circulating current, conduction loss, and EMI. Some circuits [52], [56] use coupled inductors in the FB converter to minimize leakage current, while [37], [53]–[55] use an auxiliary circuit as indicated in blue in Fig. 8. An adaptive control method is used in topologies shown in Fig. 8(a) and Fig. 8(b) to achieve an extended ZVS range in both legs. However, the auxiliary circuit in Fig. 8(b) features a narrower operating frequency range than the circuit in Fig. 8(a). A phase-shift modulation scheme is used for the topology in Fig. 8(c). These modified FB topologies are popular for electric vehicles in the literature; nevertheless, they also have potentials for MEA.

B. Bidirectional two-port converters

This subsection discusses bidirectional converters that are possibly used for battery charging or discharging [58], [59]. The control of these converters is reported to be more complicated than unidirectional converters due to bidirectional energy flow, more active switches, and separate source or load requirements [60]. Bidirectional converters have the capability of handling DC bus regeneration. Similar to unidirectional converters, bidirectional converters are classified into non-isolated and isolated, as shown in Fig. 3. Topologies discussed in this section can also be used as HC DC bus to load step-down converters due to the bidirectional nature.

1) Non-isolated bidirectional two-port converters: Bidirectional DC-DC converters [58], [61], [62] have potentials for high-conversion ratio, high efficiency, and soft-switching, as desired for EPDS in aerial vehicles. The power density of non-isolated bidirectional converters is usually high due to the absence of a power transformer, similar to other non-isolated converters. One such non-isolated current-controlled bidirectional converter [61] is shown in Fig. 9. This converter features two auxiliary resonant networks (as highlighted in blue), each consisting of an active switch ($S_{rx,\ x=1\ or\ 2}$), an inductor ($L_{rx,\ x=1\ or\ 2}$), and a capacitor ($C_{rx,\ x=1\ or\ 2}$) to achieve soft-switching [61]. Additionally, the active switches of auxiliary networks (S_{r1} and S_{r2}) are also soft-switched to minimize the overall

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TTE.2020.3009152, IEEE Transactions on Transportation Electrification

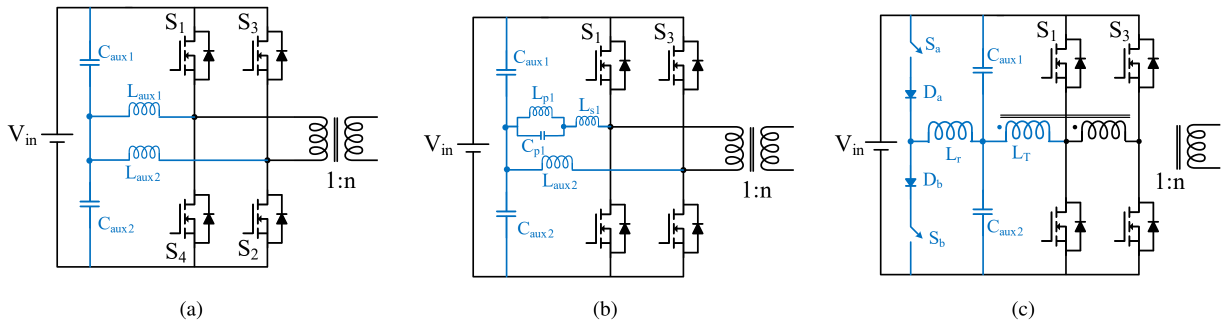

Fig. 8: FB converters showing the primary side with an auxiliary circuit indicated in blue: (a) as presented in [37], (b) as presented in [57], and (c) as presented in [55]

switching loss in this converter. This converter operates with the DC voltage gains of $\frac{1-\frac{D}{3}}{(1-D)^2}$ and $1.5D^2$ in boost and buck modes, and experimentally achieved gains of 17.8 and 6.67, respectively. The limitation of this converter is the use of more components, as given in Table I.

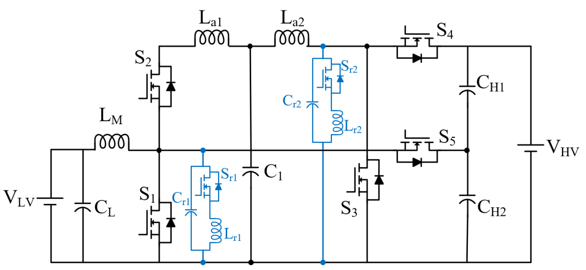

Fig. 9: High gain bidirectional converter with two auxiliary circuits [61]

Ref [58] presents another non-isolated bidirectional converter with the conversion gain of $\frac{2}{(1-D_{eff})}$, which is approximately twice that of a basic Boost converter. This converter uses an optimized PWM control to ensure a smooth transition between the boost and buck modes [58]. This topology [58] in a 5 kW experimental prototype achieves maximum efficiency of about 98% at 30 kHz. However, this converter consists of a bulky series capacitor, as highlighted in the Table I.

In general, the use of non-isolated converters in the aircraft application would benefit in terms of power density, weight, and efficiency. Still, the reliability will be affected as the fault in the system impairs the rest of the system. In contrast, isolated converters provide high reliability, and several isolated bidirectional converters are discussed next.

2) Isolated bidirectional two-port converters: Reconfiguring isolated unidirectional converters such as flyback, forward, and full-bridge converters by replacing diodes with active switches enables bidirectional operations [1], [63]–[66]. Bidirectional flyback converters [63] have fewer switches but are only suitable for low power applications because of the low transformer core utilization. The family of half-bridge bidirectional converters presented in [64], [65] claims to be ideal for medium-high power (a few kilowatts) applications. However, high output capacitance requirements result in low power density for aerial vehicle applications. Ref [67] presents a bidirectional converter based on the combination of half-bridge and current-fed push-pull converter specially constructed for battery charging/discharging. However, it is not suitable for modern aerial vehicles due to low power capability.

The well-known isolated bidirectional converter in aircraft applications is the dual active bridge (DAB) due to its simple structure, high transformer utilization factor, and good power handling capability [1], [68]–[71]. These converters are most commonly investigated for aircraft applications [4]. The DAB converter consists of active-bridges in the primary and secondary sides, as shown in Fig. 10, and uses a phase-shift modulation technique to control the power flow between input and output ports. In the DAB phase-shift modulation, the duty ratio of all the active devices is fixed at 0.5; also, diagonal switches are switched simultaneously unlike the FB Resonant Transition converter, but the phase-shift ϕ between the primary and secondary side devices is varied, as shown in Fig. 11. The modeling and control of DABs are well established in the literature for electric vehicle application, which provide a valuable insight for MEA applications.

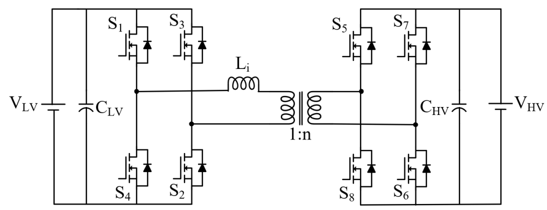

Fig. 10: Dual active bridge converter [68]

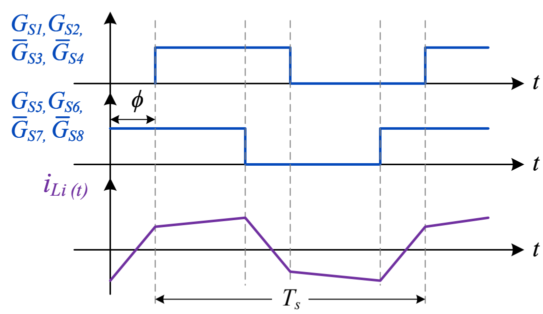

Fig. 11: Characteristic waveforms of DAB with phase-modulation scheme [68]

Apart from the phase-modulation scheme, several other schemes are available in the literature with improved

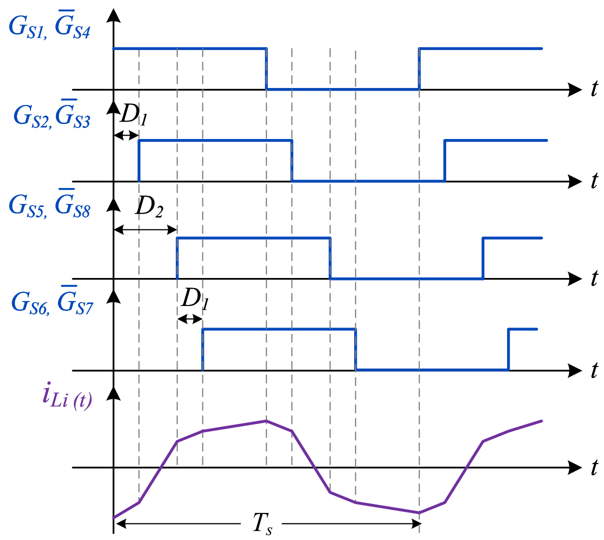

Fig. 12: Characteristic waveforms of DAB with dual phase-shift scheme [72], [73]

performance. Ref [72], [73] present a dual phase-shift (DPS) control scheme for the DAB shown in Fig. 10. The characteristic waveforms of the DAB with DPS are given in Fig. 12. With DPS control, the input device's voltage stress and peak-peak current magnitude are reduced, thereby increasing the overall efficiency [72], [73]. The additional phase control in DPS regulates the inductor peak current to reduce the conduction loss and devices' current stress [74]. Furthermore, a triple phase-shift control having three degrees of freedom is presented in [75]. This scheme prevents the DC current from flowing back to the source at both DAB ports, resulting in reduced conduction loss and improved efficiency.

Variants of the DAB topology are reported in the literature for aircraft applications to achieve high efficiency [74], [76]–[79]. A series resonant tank is used in DAB to improve the efficiency, yet retaining the advantages of DAB in [17], [76]. This topology is inspired from the unidirectional series resonant FB converter. Reliability study on the series resonant DAB is presented in [76]. This converter also features soft-switching for both input and output devices with reduced EMI emissions [17]. However, the input current peak is higher than that of a regular DAB's. Ref [74], [79] present a current-controlled Boost DAB converter. An active clamp circuit is used to achieve soft-commutation [79]. This is a bidirectional version of the Boost FB converter shown in Fig. 6. In [79], the primary and secondary side bridges are switched with a symmetrical duty control, and the converter achieves a DC voltage gain of 29 with 88% peak efficiency. The Boost DAB, on the other hand, requires an active/passive snubber circuit at the input side to reduce the input devices' voltage stress, EMI and to achieve soft-switching. In general, despite several advantages, DAB variants have a limitation in achievable power density due to a high number of active switches, large input/output capacitance, and considerable input/output current ripples [4].

Ref [80], [81] presents active-bridge active-clamp (ABAC) bidirectional converters specifically constructed for aircraft applications. The operating behavior of the converter in [80] is similar to that of DAB. The difference is the continuous output current due to the presence of output inductor, reducing the burden on the output capacitor. As a result, ABAC converter weight and volume are reduced compared to DAB, as mentioned in Table I. Ref [81] presents another ABAC converter with a dual secondary structure. This converter also uses a phase-shift modulation scheme to control the power and features high power capability and reduced current ripple on the low-voltage side. However, this converter has many controllable switches, as given in Table I, that reduce power density and increase the control complexity.

Families of the bidirectional converter with fewer switches than DAB and ABACs exist [60], [82]. The bidirectional converter in [82] features high efficiency and simple circuit due to a lower number of active and passive components, as provided in Table I. This converter employs a series capacitor to prevent DC-current in the transformer, but this capacitor must be large enough to provide the sufficient RMS current demanded by the load. As a result, this converter becomes bulky and expensive for high power applications. Another converter with fewer active switches is presented in [60]. This converter consists of a basic Boost converter and a half-bridge circuit on both the primary and secondary sides. The primary and secondary structure of this converter is identical, making it more flexible and easy to implement. Additionally, when employed in aerial vehicles, this converter reduces the requirement of some redundant converters for achieving reliability due to identical input/output structures. This topology [60] is experimentally evaluated for the DC voltage gain of only 2.4 at 1 kW, on the other hand. Thus the feasibility of this converter for DC voltage gain over ten and at high power levels is questionable.

Ref [83] presents a two-stage isolated bidirectional converter demonstrated at a 10 kW power level. This topology employs both IGBTs and MOSFETs to exploit their advantages, thereby reducing the switching loss and achieving high efficiency to fit in the aerial vehicle applications. However, the rise-time and fall-time of the MOSFETs and IGBTs must be considered to avoid shoot-through or open-circuit at the low-voltage side.

Similar to unidirectional converters, bidirectional converters also use duty-controlled and phase-shift modulation techniques to control the output voltage, and several topologies use both these techniques to benefit their advantages. Table I provides the comparison of selected unidirectional and bidirectional converters with potentials for modern aerial vehicles.

As a summary, Section III has investigated unidirectional and bidirectional two-port HCHV DC-DC converters. The converters are possibly non-isolated or isolated, and isolated converters are further categorized as duty-controlled or phase-shift controlled to understand the nature and features of the converters. Several non-isolated and isolated bidirectional are discussed above, and a comparison table is provided highlighting the device count, achievable DC voltage gain, efficiency, and features.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TTE.2020.3009152, IEEE Transactions on Transportation Electrification

TABLE I: Comparison of HCHV DC-DC converters for Architecture-I

Conv.	Unidir./ Bidir.	Electrical Isolation	Components Count S	L	C	Voltage Gain #	Max. Efficiency#	Rated Power	Switching Frequency	Features
[2]	Unidir.	Yes	4 + 4 (diodes)	2	2	15	87%	500 W	100 kHz	Provides DC voltage gain with reduced EMI. Increased output diodes' voltage stress.
[41]	Unidir.	Yes	4 + 2 (diodes)	1	2	13.33	98%	1.5 kW	45 kHz	Provides high DC voltage gain. Requires auxiliary circuit to achieve soft-switching
[84]	Unidir.	Yes	4 + 4 (diodes)	1	1	8.5	91%	1 kW	100 kHz	Switching voltage is limited by the DC voltage gain. Increased output diodes' voltage stress.
[58]	Bidir.	No	4	4	4	5.5	97.9%	5 kW	30 kHz	Series capacitor RMS current rating needs to be high leading to reduced power density
[61]	Bidir.	No	7	5	6	17.8	97%	200 W	100 kHz	Continuous current from the low-voltage source and capacitive filter at high-voltage side. More number of components.
[80]	Bidir.	Yes	8	3	4	9.64	NA	8.4 kW	100 kHz	Weight and volume of the converter are less compared to the DAB
[81]	Bidir.	Yes	12	4	5	9.64	NA	10 kW	100 kHz	More number of active devices increase the complexity in control
[82]	Bidir.	Yes	4 + 2 (diodes)	1 + 2 (coupled)	1	25	96%	2 kW	20 kHz	Power density of the converter needs to be evaluated.

S-Switches; L-Inductor; C-Capacitor; Unidir-Unidirectional; Bidir-Bidirectional; Conv-Converter topology; NA-Not available in the reference; #Experimentally achieved value in the reference; Red-colored text indicates disadvantages

IV. Multiport DC-DC Converters for Architecture-II

DC-DC converters for Architecture-II shown in Fig. 2 have multiple input/output terminals and are capable of bidirectional power flow as they need to integrate different sources. MPCs are gaining popularity in more electric aerial vehicles as they combine multiple sources and energy storage elements within one frame [1], [24], [85]–[87]. MPCs use a combination of various basic converter circuits, often active-bridge circuits, with common active switches (i.e., different converter circuits share some active switches). This results in a lower number of components leading to improved efficiency, power density, and reduced size, weight, and cost of EPDS [1], [24]. Besides, MPCs alleviate complex communication or coordination among various sources. However, challenges in MPCs are the control of multiple source connections and to minimize or nullify their circulating currents [24]. Reliability is another major drawback in these converters, particularly when used in aerial vehicles, as a fault in the MPC tends to down the complete power system. Research on the fault-tolerant circuits in aircraft application is emerging to eliminate the use of redundant power converters to improve the power density of EPDS [23], [28], [88].

In general, sources in MPCs can be integrated either at the DC bus or through a high-frequency transformer, or a combination of both. Based on the source integration mechanism and the number of available ports, MPCs are classified as shown in Fig. 3. Table II presents the comparison of different multiport converters based on the number of ports, circuity principles, number of components, source voltage levels, and filter requirement. The red-colored text in the table indicates the limitations of the circuit. Note that although experimentally achieved DC voltage gains in [1], [89] are 1, a much higher gain can be achieved by adjusting the transformer turns ratio. Similarly, voltage gains in [25], [90] can be increased by cascading more stages. More details are covered in the subsections below.

A. Three-port converters with DC bus integration

In this three-port converter family, integration of the sources occurs at the DC bus without any magnetic coupling. The sources are of similar DC voltage levels [24], [25] and are mostly non-isolated [24], [25], [92]–[94]. Fig. 13 shows a simple three-port converter constructed using two synchronous Boost converters at a common output DC bus similar to the interleaved Boost converter [24].

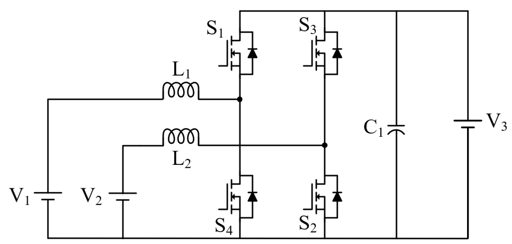

Fig. 13: Three-port converter with DC bus integration [24]

Ref [25] presents two non-isolated three-port converters constructed using basic circuitries such as Boost and phase-shift switched-capacitor circuits for one converter, and Boost and non-isolated DAB for the other converter. These topologies have common active switches shared by both the basic circuitries, reducing the overall device count. These converters exploit both phase-shifted and duty-controlled techniques to control the output voltage and power flow. The phase-shift switched-capacitor based three-port converter provides DC voltage gain of 2, while the non-isolated DAB based three-port converter offers the DC voltage gain of 1, theoretically. Additionally, these converters require significant input and output filters due to pulsed currents, as given in Table II. Since there is a limitation in the achievable DC voltage gain in the above-discussed converters, they are not suitable for the high-conversion needs. Nevertheless, the DC voltage gain can be increased by adding LC circuits and switches [25], but this reduces the power density. For example, a high DC voltage gain is achieved in a non-isolated three-port converter using switched capacitor and voltage lift circuits [94].

A boost converter based three-port converter is presented in [92], which employs two boost converters and four voltage multipliers to provide a high DC voltage gain. This converter provides a DC voltage gain of $\frac{n+1}{(1-D)}$ and is regulated using a duty-controlled scheme. The authors have experimentally achieved a DC voltage gain of 20. Even at a high DC voltage gain, this converter employs only two active switches, which simplify the control. However, this converter consists of more diodes and capacitors, which reduce the power density of the EPDS.

A standard limitation with the three-port converters with DC bus integration is that the fault in any of the sources propagates to the other sources causing a shutdown of the system. Other three-port converters with magnetic coupling, which improves reliability, are discussed next.

B. Three-port converters with high-frequency transformer integration

This subsection discusses three-port converters in which sources are coupled together magnetically. For the discussion, the inputs are low-voltage sources, and output is the HV DC bus. Sources of different voltage levels can be integrated by adjusting the number of turns of the transformer winding.

Triple Active Bridge (TAB) based three-port converters are available, which consist of three active-bridges connected through a high-frequency transformer [15], [24], [86], [95]–[99]. The TAB is an extension of DAB. Fig. 14 shows the TAB converter, where one of the three ports is taken as an output port (HV DC bus), while the other two ports are inputs. The number of turns of the transformer windings is designed based on the source voltages. TABs have the advantage of integrating multiple sources with different voltage levels allowing flexibility. Additionally, TABs have relatively high reliability due to the transformer coupling, as each source can be isolated individually during a fault. Ref [86] presents an equivalent circuit model and control analysis of the converter shown in Fig. 14. The TAB topology exhibits inherent soft-switching, although the soft-switching operating range is limited, as given in Table II. However, with the use of an asymmetrical duty control, this range can be extended [24]. Ref [86], [96] proposes the energy management method and validates various scenarios of power-sharing between multiple sources. Overall, TAB three-port converters can be employed in modern aerial vehicles to integrate battery and fuel cells to the HV DC bus.

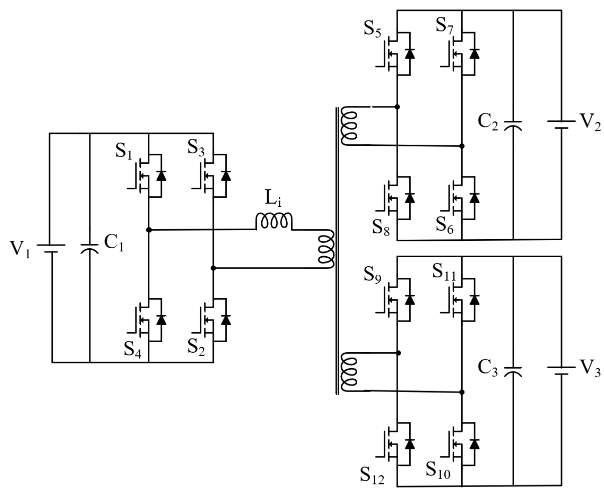

Fig. 14: Three-port converter with magnetic coupling [86]

There are other variants of three-port converters presented in the literature apart from the TAB. Ref [24] presents a family of transformer-coupled converters. These converters have half-bridge and full-bridge on the primary side and boost-half-bridge switching circuit on the secondary side.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TTE.2020.3009152, IEEE Transactions on Transportation Electrification

TABLE II: Comparison of HCHV DC-DC converters for Architecture-II

Conv.	No. of Ports	Basic Circuitry	Electrical Isolation	Components Count S	Components Count L	Components Count C	Voltage Gain$^{\#}$	Eff.$^{\#}$	Source Voltages	Filter Requirement	Features and Limitations
[25]	3	Bidirectional PWM and DAB or switched capacitor circuit	No	5 (incl. 1 diode)	2	4	1.6*	95.7%	Large difference voltage sources cannot be integrated	Large input and output filter required due to pulsed currents	Less component count. Lower DC voltage gain.
[24]	3	Half-bridge	Yes	6	0	6	9.5	90%	Sources with different voltages could be integrated	Large input and output filter required due to pulsed currents	Extended soft-switching range. Presence of circulating current.
[86]	3	Active bridge	Yes	12	0	3	8.33	NA	Sources with different voltages could be integrated	Large input and output filter required due to pulsed currents	Inherent soft-switching, high reliability, but for a limited operating range.
[91]	3	Interleaved	Yes	6 (incl. 2 diodes)	3	2	5.83	90%	Large difference voltage sources cannot be integrated	Large input filter at one of the source terminals	Isolated converter with less component count. Chances of DC-current in the transformer.
[1]	4	Active bridge	Yes	16	0	4	1*	96.5%	Sources with different voltages could be integrated	Large input and output filter required due to pulsed currents	High reliability. High switch count.
[90]	>4	Cascaded multiport	No	6 (for 4-port)	3	1	2*	NA	Large difference voltage sources cannot be integrated	Input and output currents are continuous reducing filter requirement	Less switch count for four-port converter, but more inductor count.
[89]	>4	QAB	Yes	16 (for 4-port)	0	4 (for 4-port)	1*	NA	Sources with different voltages could be integrated	Large input and output filter required due to pulsed currents	High reliability. High component count.

S-Switches; L-Inductor; C-Capacitor; Eff-Efficiency; Conv-Converter topology; NA-Not available in the reference; $^{\#}$Experimentally achieved value in the reference; *Higher gain can be achieved by modifying the transformer turns ratio or adding cascaded stage to the converter; Red-colored text indicates disadvantages

These converters use the duty ratio of the switches to control the DC bus voltage, and the phase-shift of the transformer voltage to control the power flow. Either a simple PI controller [86] or a PID controller [24] is used to implement the feedback control. The transformer equivalent circuit and power loss model are derived in [96]. The observed limitation in these topologies [24], [86] is the presence of circulating current, which adds to the conduction loss, as mentioned in the Table II.

C. Three-port converters with the combination of DC bus integration and magnetic coupling

Three-port converters with multiple sources integrated both at a common DC bus and through magnetic coupling are presented in [24], [26], [91], [100]–[105]. In these converters, some sources are interconnected at the DC bus,

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TTE.2020.3009152, IEEE Transactions on Transportation Electrification

while the transformer couples the rest. The source voltages are required to be similar when integrated at the DC bus or can be different when coupled through the transformer. As some sources are integrated at the DC bus, the number of transformer windings is reduced, at the same time, some sources are magnetically coupled, improving reliability than three-port converters with DC bus integration. Thus, this category inherits the advantages of both the other categories discussed earlier.

Fig. 15 shows one such three-port converter, where source V_1 is magnetically coupled with V_2, V_3, while V_2 and V_3 are integrated at the DC bus indirectly. This converter has isolation due to magnetic coupling, overcoming the downside of the solely DC bus integrated approach [24], [26], [91], [100]–[103]. At the same time, this converter requires less magnetics overall so that the power density is higher than the solely magnetic coupled approach.

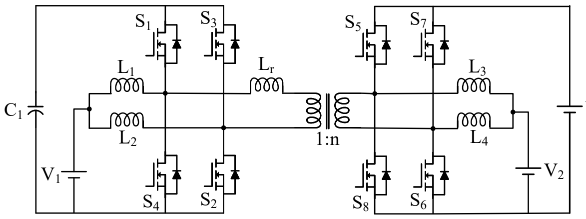

Fig. 15: Three-port converter with the combination of DC bus integration and magnetic coupling [100]

The power flow control in most of these converters utilizes a phase-shift technique [24], [100], [101], although some topologies [26] use a duty-controlled technique. The converter in [91] uses phase-shift control for power flow and duty ratio control for voltage regulation. In general, converters with active-bridge circuits mostly use the phase-shift technique to benefit from soft-switching. In some of these converters [91], the operation can cause a DC-offset in the transformer current leading to saturation as given in Table II. The transformer must be rated sufficiently to avoid saturation but at the cost of extra weight and size.

D. Other multiport converters (four ports or more)

This subsection is mainly an extension of the three-port converters. Family of Quadruple Active Bridge (QAB) converters and Multiple Active Bridge (MAB) converters consist of four or more ports [1], [85], [89], [106]–[108]. Some of the three-port converters such as TAB can be extended to four- or more-port by adding the appropriate active-bridges [24], [86]. A QAB converter shown in Fig. 16 consists of four active-bridges connected through a coupled transformer [1], [89], [108]. QABs are suitable four-port converters interfacing fuel cells, batteries, supercapacitors, and high-voltage bus for modern aerial vehicles [1], [85], [89], [106], [107]. QABs use a phase-shift technique for power flow control. Similar to TABs, QABs also have high reliability as the fault in one source does not propagate to the other sources due to transformer isolation, as mentioned in Table II.

QABs have the modularity feature so that MABs of an increasing number of ports can be formed by adding active bridges [89], [109]. More ports integrate more sources into

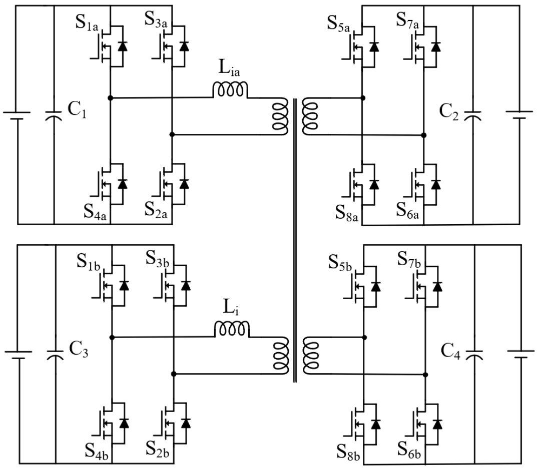

Fig. 16: Quadruple active bridge converter [1]

one frame in MABs; however, control of all the sources becomes challenging. Ref [1] presents the equivalent model of the feedback control loop with a PI controller. This model is used for controlling the power flow in MABs.

On a side literature search, a non-isolated switched-capacitor based MPC is presented in [27], [90]. The work in [27] presents operating modes and power flow among multiple sources. However, this topology involves excessive switches, diodes, and capacitors. Additionally, for applications where isolation is required, these non-isolated MPCs cannot be employed, as discussed earlier.

As a summary, multiport DC-DC converters such as three-port converters with the DC Bus link, magnetic coupling, and a combination of both, and other multiport converters are investigated in this section. The features and limitations of each category of converters are analyzed. A table is provided comparing several MPCs based on the component count, basic circuitry used, source voltage levels, filter requirement, and features and limitations.

V. Conclusion and Outlook

This paper reviews the state-of-the-art of HCHV DC-DC converters suitable for modern aerial vehicles, including MEAs and UAVs. Such DC-DC converters serve to connect multiple low-voltage sources to the HV DC bus within an electrical power distribution system. This work provides an insight into various classifications of HCHV DC-DC converters and their representative literature. In Architecture-I, individual converters link each source to the DC bus using two-port converters; and in Architecture-II, a centralized converter links all the sources together to the DC bus, also known as a multiport converter. Architecture-I endures system-level reliability because of separate converters but involves more circuits and components. Architecture-II improves the power density but encounters reliability concerns as one failure point is prone to shut down the entire DC-DC system. Architecture-I is first categorized by unidirectional and bidirectional conversions, under which isolation and control classifications are further developed. Architecture-II is all bidirectional so that it is categorized by circuit construction types, i.e., DC bus integration and magnetic coupling, although similar to non-isolated and isolated classifications. A multiple-port (more than three)

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TTE.2020.3009152, IEEE Transactions on Transportation Electrification

converter is viewed as an extension of a three-port converter, which is discussed in detail. For each well-known topology, circuit topologies and characteristic waveforms are explicitly presented. In particular, this paper compares various two-port converters and multiport converters, in two separate tables, highlighting the achievable DC voltage gains, power levels, switching frequencies, number of components, device stress, isolation, efficiency, and advantages and disadvantages.

Presently the 270 V DC bus is common, and related industry standards have been developed, while research on the 540 V DC bus is ongoing. Due to numerous benefits of a HV bus and development in the power semiconductor device technology, future aircraft electrification will consider a DC bus voltage above 1000 V [110]. For such an electrical system, power electronic converters, specifically HCHV DC-DC converters will be key. Consequently, safety and reliability become a primary concern in such a power system. Therefore, a proper converter topology choice is critical. For safety, HCHV DC-DC converters prefer to have an electrical isolation such that a fault does not propagate through the system. For reliability, modularity in converters improves the redundancy. Considering these features, and the desires for high power density, high efficiency, high power capability, and low EMI, selected topologies from both Architectures I and II are listed and compared in Table III. Note that although the DC voltage gains for DAB and QAB topologies in Table III are <2.5 in the respective literature, a high conversion is possible by adjusting the transformer turns ratio. Other isolated topologies discussed in this review have potentials for feeding secondary loads, such as avionics, cabin electronics, etc., and non-isolated topologies can be used for low power loads or as front-end converters. Overall, authors deem Architecture-II a higher potential for adoption for its high efficiency and high power density, even though Architecture-I has better reliability in nature. Features such as modularity, individual port isolation, and port number flexibility in MPCs may address the reliability concern. In case of any source failure in the aircraft power supply, MPCs can still maintain stability and performance by disconnecting the respective port.

REFERENCES

[1] G. Buticchi, L. F. Costa, D. Barater, M. Liserre, and E. D. Amarillo, “A Quadruple Active Bridge Converter for the Storage Integration on the More Electric Aircraft,” *IEEE Transactions on Power Electronics*, vol. 33, no. 9, pp. 8174–8186, Sep. 2018.

[2] N. Swaminathan and N. Lakshminarasamma, “Hybrid control scheme for mitigating the inherent DC-current in the transformer in buck-boost full-bridge converter for an all-electric motor drive system,” *IET Power Electronics*, vol. 11, no. 8, pp. 1452–1462, 2018.

[3] M. Tariq, A. I. Maswood, C. J. Gajanayake, and A. K. Gupta, “Modeling and Integration of a Lithium-Ion Battery Energy Storage System With the More Electric Aircraft 270 V DC Power Distribution Architecture,” *IEEE Access*, vol. 6, pp. 41 785–41 802, 2018.

[4] G. Buticchi, S. Bozhko, M. Liserre, P. Wheeler, and K. Al-Haddad, “On-Board Microgrids for the More Electric Aircraft—Technology Review,” *IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5588–5599, July 2019.

[5] P. Wheeler, “Technology for the more and all electric aircraft of the future,” in *2016 IEEE International Conference on Automatica (ICA-ACCA)*, Oct 2016, pp. 1–5.

[6] B. Sarlioglu and C. T. Morris, “More Electric Aircraft: Review, Challenges, and Opportunities for Commercial Transport Aircraft,” *IEEE Transactions on Transportation Electrification*, vol. 1, no. 1, pp. 54–64, June 2015.

[7] J. Chen, C. Wang, and J. Chen, “Investigation on the Selection of Electric Power System Architecture for Future More Electric Aircraft,” *IEEE Transactions on Transportation Electrification*, vol. 4, no. 2, pp. 563–576, June 2018.

[8] P. Wheeler and S. Bozhko, “The More Electric Aircraft: Technology and challenges.” *IEEE Electrification Magazine*, vol. 2, no. 4, pp. 6–12, Dec 2014.

[9] A. P. Thurlbeck and Y. Cao, “Analysis and Modeling of UAV Power System Architectures,” in *2019 IEEE Transportation Electrification Conference and Expo (ITEC)*, June 2019, pp. 1–8.

[10] “AEROMOBIL - Flying Car,” $https://www.aeromobil.com/aeromobil-4_0-stol/$, accessed: 03.03.2020.

[11] “Possibility or pipe dream: How close are we to seeing flying cars?” $https://www.usatoday.com/story/tech/2019/11/04/flying-cars-uber-boeing-and-others-say-theyre-almost-ready/4069983002/$, published: 11.04.2019, Accessed: 03.03.2020.

[12] P. Wheeler, “The more electric aircraft: Why aerospace needs power electronics?” in *2009 13th European Conference on Power Electronics and Applications*, Sep. 2009, pp. 1–30.

[13] J. Brombach, T. Schröter, A. Lücken, and D. Schulz, “Optimized cabin power supply with a $+/-$ 270 V DC grid on a modern aircraft,” in *2011 7th International Conference-Workshop Compatibility and Power Electronics (CPE)*, June 2011, pp. 425–428.

[14] F. Gao, X. Zheng, S. Bozhko, C. I. Hill, and G. Asher, “Modal Analysis of a PMSG-Based DC Electrical Power System in the More Electric Aircraft Using Eigenvalues Sensitivity,” *IEEE Transactions on Transportation Electrification*, vol. 1, no. 1, pp. 65–76, June 2015.

[15] J. S. Ngoua Teu Magambo, R. Bakri, X. Margueron, P. Le Moigne, A. Mahe, S. Guguen, and T. Bensalah, “Planar Magnetic Components in More Electric Aircraft: Review of Technology and Key Parameters for DC–DC Power Electronic Converter,” *IEEE Transactions on Transportation Electrification*, vol. 3, no. 4, pp. 831–842, Dec 2017.

[16] S. Günter, G. Buticchi, G. De Carne, C. Gu, M. Liserre, H. Zhang, and C. Gerada, “Load control for the dc electrical power distribution system of the more electric aircraft,” *IEEE Transactions on Power Electronics*, vol. 34, no. 4, pp. 3937–3947, April 2019.

[17] G. Buticchi, L. Costa, and M. Liserre, “Improving system efficiency for the more electric aircraft: A look at dcdc converters for the avionic onboard dc microgrid,” *IEEE Industrial Electronics Magazine*, vol. 11, no. 3, pp. 26–36, 2017.

[18] T. Ninomiya and K. Harada, “Common-mode noise generation in a dc-to-dc converter,” *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-16, no. 2, pp. 130–137, 1980.

[19] “Commom Mode Noise Considerations,” $http://www.apowerdesign.com/pdf/common_mode_noise.pdf$, accessed: 05.25.2020.

[20] L. Xie, X. Ruan, H. Zhu, and Y. Lo, “Common-mode voltage cancellation for reducing the common-mode noise in dc-dc converters,” *IEEE Transactions on Industrial Electronics*, pp. 1–1, 2020.

[21] M. Laour and R. Tahmi, “Effective filtering solution with low cost small size for common-mode reduction in dc–dc converters,” *Electronics Letters*, vol. 52, no. 5, pp. 388–390, 2016.

[22] P. Caldeira, R. Liu, D. Dalal, and W. J. Gu, “Comparison of emi performance of pwm and resonant power converters,” in *Proceedings of IEEE Power Electronics Specialist Conference - PESC ’93*, 1993, pp. 134–140.

[23] K. Ni, Y. Liu, Z. Mei, T. Wu, Y. Hu, H. Wen, and Y. Wang, “Electrical and Electronic Technologies in More-Electric Aircraft: A Review,” *IEEE Access*, vol. 7, pp. 76 145–76 166, 2019.

[24] H. Tao, A. Kotsopoulos, J. L. Duarte, and M. A. M. Hendrix, “Family of multiport bidirectional DC-DC converters,” *IEE Proceedings - Electric Power Applications*, vol. 153, no. 3, pp. 451–458, May 2006.

[25] Y. Sato, M. Uno, and H. Nagata, “Nonisolated Multiport Converters Based on Integration of PWM Converter and Phase-Shift-Switched Capacitor Converter,” *IEEE Transactions on Power Electronics*, vol. 35, no. 1, pp. 455–470, Jan 2020.

[26] M. Uno, R. Oyama, and K. Sugiyama, “Partially isolated single-magnetic multiport converter based on integration of series-resonant converter and bidirectional pwm converter,” *IEEE Transactions on Power Electronics*, vol. 33, no. 11, pp. 9575–9587, Nov 2018.

[27] M. Uno and K. Sugiyama, “Switched capacitor converter based multiport converter integrating bidirectional pwm and series-resonant converters for standalone photovoltaic systems,” *IEEE Transactions on Power Electronics*, vol. 34, no. 2, pp. 1394–1406, Feb 2019.

TABLE III: Potential HCHV DC-DC converter topologies for electrified aviation power supply

Topology	Category	Remarks
Boost-FB [41]	Isolated unidirectional two-port	High DC-voltage gain. Input current is non-pulsating. Requires auxiliary circuit for achieving soft-switching.
DAB [70]	Isolated bidirectional two-port	Requires fewer redundant converters due to modularity nature. Well established in the EV application. High component count.
TAB [15]	Isolated bidirectional three-port	Requires fewer redundant converters due to modularity nature. Can operate as DAB without losing stability. Can integrate sources of different voltage levels. High component count.
QAB [1], [109]	Isolated bidirectional four-port	Requires fewer redundant converters due to modularity nature. Can operate as DAB, TAB or MAB without losing stability. Can integrate sources of different voltage levels. High component count.

Red-colored text indicates disadvantages

[28] G. Chen, L. Chen, Y. Deng, K. Wang, and X. Qing, "Topology-Reconfigurable Fault-Tolerant LLC Converter With High Reliability and Low Cost for More Electric Aircraft," *IEEE Transactions on Power Electronics*, vol. 34, no. 3, pp. 2479–2493, March 2019.

[29] R. W. Erickson and D. Maksimovic, *Fundamentals of Power Electronics*. Springer International Edition, 2011.

[30] R. Sharma and Hongwei Gao, "Low cost high efficiency DC-DC converter for fuel cell powered auxiliary power unit of a heavy vehicle," *IEEE Transactions on Power Electronics*, vol. 21, no. 3, pp. 587–591, May 2006.

[31] M. Taheri, J. Milimonfared, B. A. Arand, and S. S. Dobakhshari, "High step-up dual full-bridge ZVS DC-DC converter with improved integrated magnetics and new resonant switched capacitor cell," *IET Power Electronics*, vol. 10, no. 6, pp. 606–618, 2017.

[32] C. Li, Y. Zhang, Z. Cao, and D. XU, "Single-Phase Single-Stage Isolated ZCS Current-Fed Full-Bridge Converter for High-Power AC/DC Applications," *IEEE Transactions on Power Electronics*, vol. 32, no. 9, pp. 6800–6812, Sept 2017.

[33] J. A. Sabate, V. Vlatkovic, R. B. Ridley, F. C. Lee, and B. H. Cho, "Design considerations for high-voltage high-power full-bridge zero-voltage-switched PWM converter," in *Fifth Annual Proceedings on Applied Power Electronics Conference and Exposition*, March 1990, pp. 275–284.

[34] L. Zhao, H. Li, Y. Hou, and Y. Yu, "Operation analysis of a phase-shifted full-bridge converter during the dead-time interval," *IET Power Electronics*, vol. 9, no. 9, pp. 1777–1783, 2016.

[35] J. H. Cho, H. W. Seong, S. M. Jung, J. S. Park, G. W. Moon, and M. J. Youn, "Implementation of digitally controlled phase shift full bridge converter for server power supply," in *2010 IEEE Energy Conversion Congress and Exposition*, Sept 2010, pp. 802–809.

[36] M. J. Schutten and D. A. Torrey, "Improved small-signal analysis for the phase-shifted PWM power converter," *IEEE Transactions on Power Electronics*, vol. 18, no. 2, pp. 659–669, Mar 2003.

[37] A. Safaee, P. K. Jain, and A. Bakhshai, "An Adaptive ZVS Full-Bridge DC–DC Converter With Reduced Conduction Losses and Frequency Variation Range," *IEEE Transactions on Power Electronics*, vol. 30, no. 8, pp. 4107–4118, Aug 2015.

[38] C. Woo-Young, "High-efficiency duty-cycle controlled full-bridge converter for ultracapacitor chargers," *IET Power Electronics*, vol. 9, no. 6, pp. 1111–1119, 2016.

[39] C.-T. Tsai and S.-H. Chen, "PV Power-Generation System with a Phase-Shift PWM Technique for High Step-Up Voltage Applications ," *IEEE International Journal of Photoenergy*, vol. 2012, 2012.

[40] S. Jalbrzykowski and T. Citko, "Current-Fed Resonant Full-Bridge Boost DC/AC/DC Converter," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 3, pp. 1198–1205, March 2008.

[41] M. Nymand and M. A. E. Andersen, "High-Efficiency Isolated Boost DC-DC Converter for High-Power Low-Voltage Fuel-Cell Applications," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 2, pp. 505–514, Feb 2010.

[42] A. Mousavi, P. Das, and G. Moschopoulos, "A Comparative Study of a New ZCS DC-DC Full-Bridge Boost Converter With a ZVS Active-Clamp Converter," *IEEE Transactions on Power Electronics*, vol. 27, no. 3, pp. 1347–1358, March 2012.

[43] M. Baei and G. Moschopoulos, "A ZVS-PWM full-bridge boost converter for applications needing high step-up voltage ratio," in *2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Feb 2012, pp. 2213–2217.

[44] V. Yakushev, V. Meleshin, and S. Fraidlin, "Full-bridge isolated current fed converter with active clamp," in *APEC '99. Fourteenth Annual Applied Power Electronics Conference and Exposition. 1999 Conference Proceedings (Cat. No.99CH36285)*, vol. 1, March 1999, pp. 560–566 vol.1.

[45] P. U R and A. K. Rathore, "Extended range zvs active-clamped current-fed full-bridge isolated dc/dc converter for fuel cell applications: Analysis, design, and experimental results," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 7, pp. 2661–2672, 2013.

[46] K. Shi, D. Zhang, Z. Zhou, M. Zhang, and Y. Gu, "A Novel Phase-Shift Dual Full-Bridge Converter With Full Soft-Switching Range and Wide Conversion Range," *IEEE Transactions on Power Electronics*, vol. 31, no. 11, pp. 7747–7760, Nov 2016.

[47] E. F. R. Romaneli and N. Barbi, "New isolated phase-shift controlled non-pulsating input and output converter," in *2001 IEEE 32nd Annual Power Electronics Specialists Conference (IEEE Cat. No.01CH37230)*, vol. 1, 2001, pp. 237–242 vol. 1.

[48] E. F. R. Romaneli and I. Barbi, "A new DC-DC converter with low current ripple characteristics," in *INTELEC. Twenty-Second International Telecommunications Energy Conference (Cat. No.00CH37131)*, 2000, pp. 560–566.

[49] R. Redl, N. O. Sokal, and L. Balogh, "A novel soft-switching full-bridge DC/DC converter: analysis, design considerations, and experimental results at 1.5 kW, 100 kHz," *IEEE Transactions on Power Electronics*, vol. 6, no. 3, pp. 408–418, July 1991.

[50] N. Swaminathan and N. Lakshminarasamma, "Investigation of Resonant Transition Converter Performance for Step-up/Step-down Operation," in *2020 IEEE International conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE 2020)*, 2020, pp. 1–6.

[51] ——, "A Control Scheme for Mitigating the Impact of Variations in Device Parameters for Phase-Modulated Converters," in *2018 IEEE International Telecommunications Energy Conference (INTELEC)*, Oct 2018, pp. 1–6.

[52] Y. Jang and M. M. Jovanovic, "A new family of full-bridge ZVS converters," *IEEE Transactions on Power Electronics*, vol. 19, no. 3, pp. 701–708, May 2004.

[53] X. Wu, X. Xie, J. Zhang, R. Zhao, and Z. Qian, "Soft switched full bridge dc–dc converter with reduced circulating loss and filter requirement," *IEEE Transactions on Power Electronics*, vol. 22, no. 5, pp. 1949–1955, 2007.

[54] M. Borage, S. Tiwari, and S. Kotaiah, "A passive auxiliary circuit achieves zero-voltage-switching in full-bridge converter over entire conversion range," *IEEE Power Electronics Letters*, vol. 3, no. 4, pp. 141–143, 2005.

[55] G. N. B. Yadav and N. L. Narasamma, "An Active Soft Switched Phase-Shifted Full-Bridge DC-DC Converter: Analysis, Modeling, Design, and Implementation," *IEEE Transactions on Power Electronics*, vol. 29, no. 9, pp. 4538–4550, Sept 2014.

[56] Yungtack Jang, M. M. Jovanovic, and Yu-Ming Chang, "A new zvs-pwm full-bridge converter," *IEEE Transactions on Power Electronics*, vol. 18, no. 5, pp. 1122–1129, 2003.

[57] M. Pahlevaninezhad, P. Das, J. Drobnik, P. K. Jain, and A. Bakhshai, "A novel zvzcs full-bridge dc/dc converter used for electric vehicles," *IEEE Transactions on Power Electronics*, vol. 27, no. 6, pp. 2752–2769, 2012.

[58] M. Kwon, S. Oh, and S. Choi, "High Gain Soft-Switching Bidirectional DC–DC Converter for Eco-Friendly Vehicles," *IEEE Transactions on Power Electronics*, vol. 29, no. 4, pp. 1659–1666, April 2014.

[59] A. Diab-Marzouk and O. Trescases, "SiC-Based Bidirectional Ćuk Converter With Differential Power Processing and MPPT for a Solar Powered Aircraft," *IEEE Transactions on Transportation Electrification*, vol. 1, no. 4, pp. 369–381, Dec 2015.

[60] G. Ma, W. Qu, G. Yu, Y. Liu, N. Liang, and W. Li, "A Zero-Voltage-Switching Bidirectional DC–DC Converter With State Analysis and Soft-Switching-Oriented Design Consideration," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 6, pp. 2174–2184, June 2009.

[61] R. H. Ashique and Z. Salam, "A High-Gain, High-Efficiency Nonisolated Bidirectional DC–DC Converter With Sustained ZVS Operation," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 10, pp. 7829–7840, Oct 2018.

[62] S. Dusmez, A. Khaligh, and A. Hasanzadeh, "A Zero-Voltage-Transition Bidirectional DC/DC Converter," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 5, pp. 3152–3162, May 2015.

[63] Gang Chen, Yim-Shu Lee, S. Y. R. Hui, Dehong Xu, and Yousheng Wang, "Actively clamped bidirectional flyback converter," *IEEE Transactions on Industrial Electronics*, vol. 47, no. 4, pp. 770–779, Aug 2000.

[64] Hui Li, Fang Zheng Peng, and J. S. Lawler, "A natural ZVS medium-power bidirectional DC-DC converter with minimum number of devices," *IEEE Transactions on Industry Applications*, vol. 39, no. 2, pp. 525–535, March 2003.

[65] F. Z. Peng, Hui Li, Gui-Jia Su, and J. S. Lawler, "A new ZVS bidirectional DC-DC converter for fuel cell and battery application," *IEEE Transactions on Power Electronics*, vol. 19, no. 1, pp. 54–65, Jan 2004.

[66] L. Zhu, "A Novel Soft-Commutating Isolated Boost Full-Bridge ZVS-PWM DC-DC Converter for Bidirectional High Power Applications," *IEEE Transactions on Power Electronics*, vol. 21, no. 2, pp. 422–429, March 2006.

[67] M. Jain, M. Daniele, and P. K. Jain, "A bidirectional DC-DC converter topology for low power application," *IEEE Transactions on Power Electronics*, vol. 15, no. 4, pp. 595–606, July 2000.

[68] V. Raveendran, M. Andresen, and M. Liserre, "Improving onboard converter reliability for more electric aircraft with lifetime-based control," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5787–5796, July 2019.

[69] H. L. Chan, K. W. E. Cheng, and D. Sutanto, "Bidirectional phase-shifted DC-DC converter," *Electronics Letters*, vol. 35, no. 7, pp. 523–524, April 1999.

[70] R. T. Naayagi, A. J. Forsyth, and R. Shuttleworth, "High-power bidirectional dc–dc converter for aerospace applications," *IEEE Transactions on Power Electronics*, vol. 27, no. 11, pp. 4366–4379, 2012.

[71] B. Zhao, Q. Song, W. Liu, and Y. Sun, "Overview of dual-active-bridge isolated bidirectional dc–dc converter for high-frequency-link power-conversion system," *IEEE Transactions on Power Electronics*, vol. 29, no. 8, pp. 4091–4106, 2014.

[72] B. M. Kumar, A. Kumar, A. H. Bhat, and P. Agarwal, "Comparative study of dual active bridge isolated dc to dc converter with single phase shift and dual phase shift control techniques," in *2017 Recent Developments in Control, Automation Power Engineering (RDCAPE)*, 2017, pp. 453–458.

[73] S. Chi, P. Liu, X. Li, M. Xu, and S. Li, "A novel dual phase shift modulation for dual-active- bridge converter," in *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2019, pp. 1556–1561.

[74] S. Bal, D. B. Yelaverthi, A. K. Rathore, and D. Srinivasan, "Improved modulation strategy using dual phase shift modulation for active commutated current-fed dual active bridge," *IEEE Transactions on Power Electronics*, vol. 33, no. 9, pp. 7359–7375, 2018.

[75] J. Su, S. Luo, and F. Wu, "Improvement on transient performance of cooperative triple-phase-shift control for dual active bridge dc-dc converter," in *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2019, pp. 1296–1301.

[76] L. F. Costa, G. Buticchi, and M. Liserre, "Highly efficient and reliable sic-based dc–dc converter for smart transformer," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 10, pp. 8383–8392, 2017.

[77] B. X. Nguyen, D. M. Vilathgamuwa, G. H. B. Foo, P. Wang, A. Ong, U. K. Madawala, and T. D. Nguyen, "An efficiency optimization scheme for bidirectional inductive power transfer systems," *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6310–6319, 2015.

[78] N. Liu and T. G. Habetler, "Design of a universal inductive charger for multiple electric vehicle models," *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6378–6390, 2015.

[79] L. Zhu, "A novel soft-commutating isolated boost full-bridge zvs-pwm dc-dc converter for bidirectional high power applications," *IEEE Transactions on Power Electronics*, vol. 21, no. 2, pp. 422–429, 2006.

[80] L. Tarisciotti, A. Costabeber, L. Chen, A. Walker, and M. Galea, "Current-Fed Isolated DC/DC Converter for Future Aerospace Microgrids," *IEEE Transactions on Industry Applications*, vol. 55, no. 3, pp. 2823–2832, May 2019.

[81] L. Chen, L. Tarisciotti, A. Costabeber, Q. Guan, P. Wheeler, and P. Zanchetta, "Phase-Shift Modulation for a Current-Fed Isolated DC–DC Converter in More Electric Aircrafts," *IEEE Transactions on Power Electronics*, vol. 34, no. 9, pp. 8528–8543, Sep. 2019.

[82] H. Chiu and L. Lin, "A bidirectional dc–dc converter for fuel cell electric vehicle driving system," *IEEE Transactions on Power Electronics*, vol. 21, no. 4, pp. 950–958, July 2006.

[83] K. Yoo and J. Lee, "A 10-kW Two-Stage Isolated/Bidirectional DC/DC Converter With Hybrid-Switching Technique," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 6, pp. 2205–2213, June 2013.

[84] N. Swaminathan and N. Lakshminarasamma, "The Steady-State DC Gain Loss Model, Efficiency Model, and the Design Guidelines for High-Power, High-Gain, Low-Input Voltage DC–DC Converter," *IEEE Transactions on Industry Applications*, vol. 54, no. 2, pp. 1542–1554, March 2018.

[85] S. Falcones, R. Ayyanar, and X. Mao, "A DC–DC Multiport-Converter-Based Solid-State Transformer Integrating Distributed Generation and Storage," *IEEE Transactions on Power Electronics*, vol. 28, no. 5, pp. 2192–2203, May 2013.

[86] J. L. Duarte, M. Hendrix, and M. G. Simoes, "Three-Port Bidirectional Converter for Hybrid Fuel Cell Systems," *IEEE Transactions on Power Electronics*, vol. 22, no. 2, pp. 480–487, March 2007.

[87] M. C. Mira, Z. Zhang, A. Knott, and M. A. E. Andersen, "Analysis, Design, Modeling, and Control of an Interleaved-Boost Full-Bridge Three-Port Converter for Hybrid Renewable Energy Systems," *IEEE Transactions on Power Electronics*, vol. 32, no. 2, pp. 1138–1155, Feb 2017.

[88] Q. Li, X. Jiang, W. Huang, and R. Cao, "Fault-tolerant drive system based on the redundancy bridge arm for aerospace applications," *IET Electric Power Applications*, vol. 12, no. 6, pp. 780–786, 2018.

[89] G. Buticchi, M. Andresen, M. Wutti, and M. Liserre, "Lifetime-Based Power Routing of a Quadruple Active Bridge DC/DC Converter," *IEEE Transactions on Power Electronics*, vol. 32, no. 11, pp. 8892–8903, Nov 2017.

[90] B. Wang, Y. Wang, Y. Xu, X. Zhang, H. B. Gooi, A. Ukil, and X. Tan, "Consensus-based control of hybrid energy storage system with a cascaded multiport converter in dc microgrids," *IEEE Transactions on Sustainable Energy*, pp. 1–1, 2019.

[91] W. Li, J. Xiao, Y. Zhao, and X. He, "PWM Plus Phase Angle Shift (PPAS) Control Scheme for Combined Multiport DC/DC Converters," *IEEE Transactions on Power Electronics*, vol. 27, no. 3, pp. 1479–1489, March 2012.

[92] V. A. K. Prabhala, P. Fajri, V. S. P. Gouribhatla, B. P. Baddipadiga, and M. Ferdowsi, "A DC–DC Converter With High Voltage Gain and Two Input Boost Stages," *IEEE Transactions on Power Electronics*, vol. 31, no. 6, pp. 4206–4215, June 2016.

[93] J. Zhao, H. H. C. Iu, T. Fernando, L. An, and D. Dah-Chuan Lu, "Design of a non-isolated single-switch three-port DC-DC converter for standalone PV-battery power system," in *2015 IEEE International Symposium on Circuits and Systems (ISCAS)*, May 2015, pp. 2493–2496.

[94] B. Honarjoo, S. M. Madani, M. Niroomand, and E. Adib, "Non-isolated high step-up three-port converter with single magnetic element for photovoltaic systems," *IET Power Electronics*, vol. 11, no. 13, pp. 2151–2160, 2018.

[95] H. Pinheiro and P. K. Jain, "Series-parallel resonant UPS with capacitive output DC bus filter for powering HFC networks," *IEEE Transactions on Power Electronics*, vol. 17, no. 6, pp. 971–979, Nov 2002.

[96] C. Zhao, S. D. Round, and J. W. Kolar, "An Isolated Three-Port Bidirectional DC-DC Converter With Decoupled Power Flow Management," *IEEE Transactions on Power Electronics*, vol. 23, no. 5, pp. 2443–2453, Sep. 2008.

[97] H. Krishnaswami and N. Mohan, "Three-Port Series-Resonant DC–DC Converter to Interface Renewable Energy Sources With Bidirectional Load and Energy Storage Ports," *IEEE Transactions on Power Electronics*, vol. 24, no. 10, pp. 2289–2297, Oct 2009.

[98] H. Tao, A. Kotsopoulos, J. L. Duarte, and M. A. M. Hendrix, "Transformer-Coupled Multiport ZVS Bidirectional DC–DC Converter With Wide Input Range," *IEEE Transactions on Power Electronics*, vol. 23, no. 2, pp. 771–781, March 2008.

[99] H. Tao, J. L. Duarte, and M. A. M. Hendrix, "Three-Port Triple-Half-Bridge Bidirectional Converter With Zero-Voltage Switching," *IEEE Transactions on Power Electronics*, vol. 23, no. 2, pp. 782–792, March 2008.

[100] Z. Ding, C. Yang, Z. Zhang, C. Wang, and S. Xie, "A novel soft-switching multiport bidirectional dc–dc converter for hybrid energy

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TTE.2020.3009152, IEEE Transactions on Transportation Electrification

storage system," *IEEE Transactions on Power Electronics*, vol. 29, no. 4, pp. 1595–1609, April 2014.

[101] M. C. Mira, Z. Zhang, A. Knott, and M. A. E. Andersen, "Analysis, Design, Modeling, and Control of an Interleaved-Boost Full-Bridge Three-Port Converter for Hybrid Renewable Energy Systems," *IEEE Transactions on Power Electronics*, vol. 32, no. 2, pp. 1138–1155, Feb 2017.

[102] J. Zeng, Z. Yu, J. Liu, and F. Liu, "Triple-Compound-Full-Bridge-Based Multi-Input Converter (TCF-MIC) with Wide ZVS Range and Wide Conversion Gain," *IEEE Transactions on Industrial Electronics*, pp. 1–1, 2019.

[103] Z. Qian, O. Abdel-Rahman, H. Al-Atrash, and I. Batarseh, "Modeling and Control of Three-Port DC/DC Converter Interface for Satellite Applications," *IEEE Transactions on Power Electronics*, vol. 25, no. 3, pp. 637–649, March 2010.

[104] Z. Wang and H. Li, "An Integrated Three-Port Bidirectional DC–DC Converter for PV Application on a DC Distribution System," *IEEE Transactions on Power Electronics*, vol. 28, no. 10, pp. 4612–4624, Oct 2013.

[105] Y. Shi, R. Li, Y. Xue, and H. Li, "Optimized Operation of Current-Fed Dual Active Bridge DC–DC Converter for PV Applications," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 11, pp. 6986–6995, Nov 2015.

[106] L. F. Costa, G. Buticchi, and M. Liserre, "Quad-Active-Bridge DC–DC Converter as Cross-Link for Medium-Voltage Modular Inverters," *IEEE Transactions on Industry Applications*, vol. 53, no. 2, pp. 1243–1253, March 2017.

[107] L. F. Costa, F. Hoffmann, G. Buticchi, and M. Liserre, "Comparative Analysis of Multiple Active Bridge Converters Configurations in Modular Smart Transformer," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 1, pp. 191–202, Jan 2019.

[108] S. Falcones, R. Ayyanar, and X. Mao, "A DC–DC Multiport-Converter-Based Solid-State Transformer Integrating Distributed Generation and Storage," *IEEE Transactions on Power Electronics*, vol. 28, no. 5, pp. 2192–2203, May 2013.

[109] L. F. Costa, G. Buticchi, and M. Liserre, "Optimum Design of a Multiple-Active-Bridge DC–DC Converter for Smart Transformer," *IEEE Transactions on Power Electronics*, vol. 33, no. 12, pp. 10 112–10 121, Dec 2018.

[110] Advanced Research Projects Agency – Energy (ARPA-E) , U.S. Department of Energy, "Aviation-class synergistically cooled electric-motors with integrated drives (ASCEND) - DE-FOA-0002238," $https://arpa-e-foa.energy.gov/$, 2019, accessed: 06.03.2020.

Niraja Swaminathan (S'14-M'18) received the B.E. degree in electrical and electronics engineering from Anna University affiliated college, Chennai, TN, India, in 2012, and the M.S. and Ph.D. degrees in electrical engineering from the Indian Institute of Technology Madras (IITM), Chennai, TN, India, in 2019.

Dr. Swaminathan is currently a Post-Doctoral Scholar with the Energy Systems Group at Oregon State University (OSU), Corvallis, OR, USA. Before joining Ph.D., she was a Project Associate with the Decentralized Solar PV system team at IITM. Her current research interests include power converters for renewable energy and aviation applications, digital control for power converters, maximum power point tracking for solar PV, and energy-efficient green buildings.

Dr. Swaminathan was a recipient of a SERIIUS - MAGEEP award to pursue collaborative work with a SERIIUS partner organization, in 2014, and was awarded the Thirteenth rank among 5418 candidates graduated B.E in 2012. She has been an invited reviewer for several IEEE and IET Transactions. She helped establish a joint IEEE PES/PELS Chapter at OSU, in 2020.

Yue Cao (S'08-M'17) received the B.S. (Hons.) degree in electrical engineering with a second major in mathematics from the University of Tennessee, Knoxville, TN, USA, in 2011, and the M.S. and Ph.D. degrees in electrical engineering from the University of Illinois at Urbana–Champaign (UIUC), Champaign, IL, USA, in 2013 and 2017, respectively.

Dr. Cao is currently an Assistant Professor with the Energy Systems Group at Oregon State University (OSU), Corvallis, OR, USA. Before joining OSU, he was a research scientist with the propulsions team at Amazon Prime Air in Seattle, WA, USA. He was a power electronics engineer intern with special projects group at Apple Inc., Cupertino, CA, USA; Halliburton Company, Houston, TX, USA; Flanders Electric, Evansville, IN, USA; and Oak Ridge National Laboratory, Oak Ridge, TN, USA. His research interests include power electronics, motor drives, and energy storage with applications in transportation electrification, renewable energy integration, and energy-efficient buildings.

Dr. Cao received the Myron Zucker award from the IEEE Industry Applications Society (IAS) in 2010. He was a Sundaram Seshu Fellow at UIUC in 2016, where he was a James M. Henderson Fellow in 2012. He is a recipient of Oregon State Learning Innovation Award for transformative education in 2020. Dr. Cao is the Tutorials Chair of 2021 IEEE Energy Conversion Congress Expo (ECCE), and he was a Local and Industry co-Chair of ECCE 2018. He was a Panel Chair on More Electric Aircraft at 2019 IEEE International Transportation Electrification Conference (ITEC). He was the Corresponding Technical Programs Chair of 2016 IEEE Power and Energy Conference at Illinois (PECI). In 2020, he helped establish a joint IEEE PES/PELS Chapter at OSU. He is currently an Associate Editor for IEEE Transactions on Transportation Electrification.