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Charging Technology for Electric Aircraft: State of the Art, Trends, and Challenges

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***Abstract*— Electric aircraft technology has gained considerable attention and is rapidly developing to mitigate the environmental impact of air transportation and move toward more sustainable modes. Nevertheless, the unique characteristics of electric aircraft pose significant challenges for the charging infrastructure, which must be effectively addressed to facilitate the growth of electric aircraft. This article provides a comprehensive review of the latest developments and future trends in electric aviation, which covers electric aircraft, battery technology, and electric aircraft charging systems. This article also surveys the possible charging system architectures that can be employed for electric aircraft charging. Various power electronic converter topologies that are suitable for future electric aircraft dc fast chargers are presented. This article concludes by identifying future challenges in the path toward charging electric aircraft and discusses potential solutions to these challenges.**

***Index Terms*— Air transportation electrification, charging station, dc fast chargers, electric aircraft, extreme fast charging (XFC).**

I. INTRODUCTION

GLOBALLY, 915 million metric tons of CO_2 were released by commercial air operations in 2019 [1]. The emissions of air transport account for approximately 2% of the overall global CO_2 emissions [2]. Due to the temporary reduction caused by the COVID-19 epidemic, CO_2 emissions from international aviation in 2020 decreased significantly to 495 million metric tons [3]. However, it is anticipated by Airbus that air traffic will recover gradually by 3.6% annually in the next 20 years [4]. The corresponding growth of carbon emissions makes aviation decarbonization a vital step toward a sustainable, carbon-neutral future. To reduce CO_2 emissions and jet fuel dependency, a transition to electric aircraft is inevitable. Electrified aviation programs are evolving rapidly; most are backed up by startups, and only a few are being launched by major airframe original equipment manufacturers, such as Boeing and Airbus [5]. Between 2016 and 2022, the electric aircraft industry witnessed the emergence of over 300 projects and almost 200 startups globally [6]. Nevertheless, technological and regulatory challenges slow down the realization of air transportation electrification, including industry standards and certification, battery development, hardware technologies, and grid impacts [7]. Nowadays, the aerospace industry has made significant investments in developing and certifying electric aircraft, but less attention is paid to the corresponding charging infrastructure at airports. The absence of refueling infrastructure capable of rapidly and effectively recharging electric aircraft batteries remains a critical challenge. Thus, an urgent need is to establish a charging infrastructure that parallels the development progress of electric aircraft.

A. Related Work

The literature related to this topic can be broadly categorized into two main groups: 1) research focused on electric aircraft and 2) studies focused on charging technology.

1) Electric Aircraft: Paper [8] provided an overview of electric propulsion, which included an introduction to its fundamental concepts, the categorization, the benefits, the challenges during implementation, and research development paths for future electric aircraft operation. Barzkar and Ghassemi [9] and Schefer et al. [10] discussed the electric power systems for electric aircraft in detail, including electric propulsion, system architecture, voltage levels, semiconductor technology and topologies, electric machines, circuit breakers, and other components required in electric aircraft. Adu-Gyamfi and Good [7] gave a comprehensive review of the key enabling technologies required to make commercial electric aviation viable, including battery technology, electric machine technology, airframe design, and propulsion technologies. In addition, some conceptual designs of electric aircraft were discussed to identify the barriers to the feasible implementation of electric aircraft. In [11], energy storage technologies for electric aircraft, particularly batteries, fuel cells, and supercapacitors and the advances needed to enable the electrification of a wide range of aircraft were well surveyed. Barrera et al. [12] and Yang et al. [13] specifically identified the challenges and key performance requirements for electric aircraft batteries considering the unique mission profiles and operational needs of electric aircraft, including specific high energy density, continuous and peak discharging capability, frequent fast charging process, long cycle life, and strict safety requirement.

2) Charging Technology: The existing charging infrastructure was reviewed in [14], including different charging

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technologies for light-, medium-, and heavy-duty electric vehicles (EVs). At the same time, power electronics converters, control schemes, and structures for onboard and off-board chargers were discussed. In addition, the grid impact of large-scale deployment of current charging technology and the grid service opportunities were investigated. Tu et al. [15] and Srdic and Lukic [16] explored the state-of-the-art EV charging infrastructure and focused specifically on the extreme fast charging (XFC) technology, where the current status of dc fast chargers was discussed. Besides, design considerations of the XFC stations, such as direct connection to a medium voltage (MV) line, ac and dc local distribution networks, and power electronics converter topologies suitable for XFC, were given. The benefits, design, and adoption challenges of solid-state transformers (SSTs) in the XFC stations to replace the conventional line-frequency transformers were provided, while the paper [17] reviewed the key gaps in battery technology for XFC, focusing on both the cell level and the pack level. Furthermore, developmental needs, such as advanced electrode materials and electrode designs, better pack design, and advanced battery models, and methods to avoid lithium plating, were necessitated to accommodate XFC from the battery perspective.

After conducting a thorough literature review, it is evident that although individual studies on technical aspects of electric aircraft and charging technologies exist, an assessment that integrates all perspectives still needs to be made. This highlights the need for a comprehensive review that can provide a better understanding of the various aspects of charging technology for electric aircraft and help identify gaps and areas for future research.

B. Article Structure

This article is structured as follows. Section II covers the state-of-the-art electric aircraft and battery technology development. Section III discusses the latest development in electric aircraft charging systems. In Sections IV and V, charging station architecture and power electronic converter topology are extensively reviewed. In Section VI, challenges and future trends of the electric aircraft charging technology are identified. Finally, Section VII concludes the review and highlights the study's key findings.

II. STATUS OF ELECTRIC AIRCRAFT

A. Electric Aircraft

Electric aircraft can be defined as an aircraft that employs electric power as its primary source of propulsion, with some or all of its propulsive power derived from electrical energy. Electric aircraft can be classified according to the extent of propulsive power and energy source hybridization, with three categories: all-electric aircraft, hybrid-electric propulsion (HEP) aircraft, and turboelectric aircraft. Unlike traditional aircraft, which utilize conventional fossil fuels as their sole source of energy for propulsion, all-electric aircraft exclusively utilize electrical energy for propulsion, relying on energy storage systems, such as batteries, to power their electric motors. HEP aircraft, on the other hand, uses a combination of fuel and electrical energy storage for propulsion. Finally, turboelectric aircraft employs a fuel-based energy storage system but use electrical power transmission rather than mechanical power for propulsion. It is worth noting that hybrid-electric configurations used in HEP aircraft are comparable in some ways to hybrid EVs (HEVs), such as the fuel acts as a range extender [18]. In addition, in certain conceptual designs of hybrid electric aircraft, the gas turbine engine and electric motor can operate simultaneously during takeoff and landing missions, which can optimize energy usage and improve overall efficiency [8], [19].

Electric aircraft are currently undergoing development across a variety of aircraft types and applications. These electric aircraft programs can be classified into three main categories: small, regional, and large aircraft. These categories can further be divided into six types based on their specific use cases: pilot training, general aviation for personal or business, regional commuter, regional aircraft, light air cargo, and large commercial aircraft [20]. Table I shows the aircraft electrification development of each category, where the example electric aircraft programs for each category are listed.

In the case of small aircraft, the demands for battery energy density and capacity are relatively low due to their expected shorter ranges and lighter weights. The required cooling system is also smaller due to lower power utilization and less loss generation. Furthermore, switching to electric propulsion from internal combustion engines (e.g., $\mu_{\text{thermal}} \approx 25\%$) used in small aircraft can yield more benefits than switching from turbofans (e.g., $\mu_{\text{thermal}} \approx 50\%$) used in large aircraft because of the higher thermal efficiency differences, where μ_{thermal} denotes the thermal efficiency of respective engine [21]. By comparison, the efficiency of an electric motor is approximately 95%, and the overall system efficiency of a full battery-powered aircraft can be 73% [22]. Hence, electric aviation in pilot training, general aviation, and regional commuter will be prevalent in the near term. All-electric aircraft for pilot training has already been available on the market, including Pipistrel Velis Electro, which is the world's first electric-powered airplane to receive a Type Certificate (TC) from the European Union Aviation Safety Agency (EASA) [23]. Regional commuter or air taxi services, comprising electric vertical takeoff and landing (eVTOL) aircraft with a typical range of under 200 mi and a passenger capacity of up to four, have also gained attention from many companies in this field, such as Lilium, Archer, and Joby Aviation.

In the mid-term time frame (from 2025 to 2040), regional aircraft and light air cargo are anticipated to enter into service. The potential applications for light air cargo are expected to concentrate on personalized delivery services and military operations. For regional commuters, the service includes scheduled or unscheduled operations for air transportation of up to 19 passengers and typically around 250 mi.

In general, commercial aircraft can be classified into two categories, namely, narrow body and wide body. Narrow-body aircraft is primarily intended for short-haul flights, with a range exceeding 500 mi and a limited passenger capacity of 100–200 individuals. In the long term, large narrow-body commercial aircraft for short-haul flights with up to 150 passengers, powered partially by electricity, is projected to be available before 2050 [24]. With roughly 45% of global flights being under 500 mi, approximately half of the current flights are within the range of future electric aircraft around 2050 [20]. On the other hand, wide-body aircraft carrying 200-400 passengers and with a typical range exceeding 2000 mi are more likely to be powered by turboelectric or sustainable aviation fuel technologies due to the availability of battery technology.

Table II summarizes important statistics of the representative electric aircraft programs, such as their propulsion system, range, and expected entry into service (EIS) [8], [18], [20], [21], [23], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35]. It is worth noting that the information on the ongoing projects is only a projection and is subject to change. Besides, there are significant uncertainties regarding the timeline for electric aircraft, while the most crucial factor for both full-electric propulsion and HEP systems is the progress in battery technology.

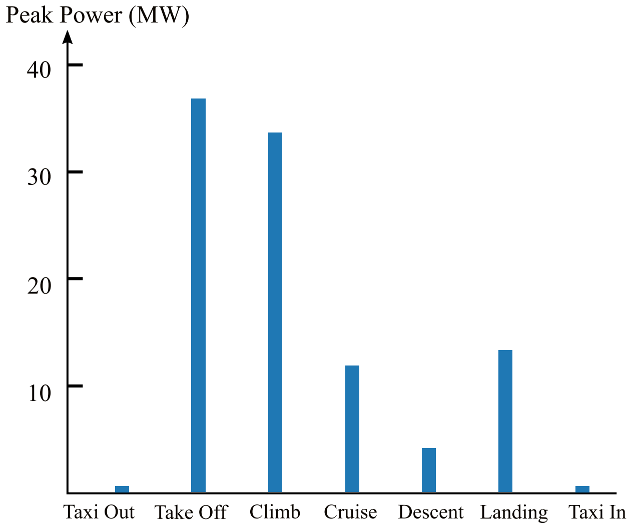


Fig. 1. Power required for a representative 150-passenger single-aisle aircraft with 3000-nmi design range flying a 1000-nmi mission [36].

B. Battery Storage System

The battery storage system plays a critical role as the energy source for electric aircraft, which must guarantee specific performance indices in terms of energy density, power density, lifetime, and safety. The gravimetric energy density ($\mathrm{W\,h\,kg^{-1}}$) is of utmost importance as it determines the range and payload of a flight, as evident from the Breguet range equation (1) for all-electric aircraft [18], [22]

$$R = \frac{L}{D}\eta_P\eta_I\eta_E\frac{e_b}{g}\frac{m_B}{m_{\mathrm{TO}}} \tag{1}$$

where L/D is the lift-to-drag ratio, η_P is the propulsive efficiency, η_I is the efficiency due to propulsion integration losses, η_E is the efficiency of electric propulsion system, e_b is the battery gravimetric energy density, g is the gravitational constant, m_B is the battery weight, and m_{TO} is the gross takeoff weight.

Likewise, power density ($\mathrm{W\,kg^{-1}}$) is the determinant of the takeoff and climb performance during the flight envelope, as these portions have higher power consumption compared with taxi-out, cruising, descent, landing, and taxi-in, as shown in Fig. 1 [11], [36]. From an eVTOL aircraft perspective, both takeoff and landing segments require high output power from the battery. During the landing segment, the output current of the battery pack is significantly higher than the takeoff segment because the battery cell and pack voltage drop throughout discharge [12], [37]. Besides, in abnormal conditions, such as battery subsystem failure, the remaining battery must be able to provide higher power density to ensure an adequate power supply. In addition, fast charging is critical to maximize aircraft utilization rates and consequently increase revenues [13]. Thus, advanced battery technology is one of the key enablers for electric aviation. Nowadays, lithium-ion battery (LIB) dominates the market for automotive applications, characterized by high power and energy density, long lifespan, and design flexibility [38]. The most popular cathode materials include lithium–iron–phosphate (LFP), lithium–nickel–manganese–cobalt (NMC) oxide, lithium–nickel–cobalt–aluminum (NCA) oxide, and lithium–manganese oxide (LMO), which can couple with a wide variety of anodes, such as graphite, lithium–titanate (LTO), and silicon-based materials [39].

1) Energy Density: Since the successful commercialization of LIBs in 1991, the advancement in the active materials (cathode and anode), inactive materials (electrolyte, separator, binder, and so on), and manufacturing accelerated the energy density rise over the past few decades [40]. To date, the highest gravimetric energy density for the LIB has reached 265 $\mathrm{W\,h\,kg^{-1}}$ at the cell level [41], [42]. Due to the integration of the thermal management system, battery management system (BMS), and packaging at the pack level, there is often a 30%–40% reduction in energy density from cell to pack [11]. By comparison, combustible fuel such as kerosene offers an energy density of around 12 000 $\mathrm{W\,h\,kg^{-1}}$, which is substantially higher than that of LIBs [43]. The volumetric energy density is another crucial parameter for aircraft performance due to the limited wing and fuselage volume. The state-of-the-art volumetric energy density achieves 730–750 $\mathrm{W\,h\,L^{-1}}$ [44], [45].

The current advancements of LIBs enable the development of all-electric small aircraft for the near-term sector. For instance, the power of Pipistrel Velis Electro is delivered by two battery packs, which consist of cylindrical LIB cells using the NMC chemistry [46]. According to the present battery technology, projections indicate that LIBs using Ni-rich NCA and NMC technology will reach an energy density of 300 $\mathrm{W\,h\,kg^{-1}}$ at the cell level by 2025 [47]. In addition, the adoption of advanced anode material (e.g., silicon or silicon-carbon) and electrolyte with higher oxidation potential can lead to higher energy density on the order of 400 $\mathrm{W\,h\,kg^{-1}}$ [11], [39]. However, for the mid-term electric aircraft, NASA has proposed a minimum energy density threshold of 750 $\mathrm{W\,h\,kg^{-1}}$ for batteries to fully enable the implementation of electric regional aircraft [48], which is beyond the theoretical limitation of LIB technology [49]. For

TABLE I
DEVELOPMENT TRAJECTORY OF AIRCRAFT ELECTRIFICATION

Timing	**Use case**	**Description**	**Model**
2020-2025 Near-term	Pilot training	– 1 pilot and 1 passenger	– Pipistrel Velis Electro – Bye Aerospace eFlyer 2 – Rolls Royce Spirit of Innovation
	General aviation: personal or business	– 1-6 passengers – Average flight time: <1 h	– Pipistrel Taurus Electro – Rhyxeon General Aircraft RX4E
	Regional commuter (eVTOL)	– Up to 1 pilot and 4 passengers – Range typically up to 200 miles	– Lilium Jet – Archer Maker – Archer Midnight – Hyundai S-A1 – Joby S4 – Beta ALIA-250 – Airbus CityAirbus
2025-2040 Mid-term	Regional aircraft	– Typical up to 19 passengers – Range typically around 250 miles	– Eviation Alice – Tecnam P-Volt – Aura Aero ERA – Heart Aerospace ES30 – Ampaire Electric EEL^{a} – Maeve 01
	Light air cargo	– Maximum payload: 7500 pounds – Custom cargo delivery	– Eviation Alice – Beta ALIA-250c – Aura Aero ERA – Ampaire Electric EEL^{a}
2040-2050 Long-term	Large commercial aircraft	– Narrow-body: typically 100-200 passengers, range more than 500 miles – Wide-body: typically 200-400 passengers, range more than 2000 miles	– Wright Spirit – Wright 1 – Boeing Sugar Volt^{a} – NASA N3-X^{b} – Airbus/Siemens/Rolls-Royce/E-Fan X^{a}

^{a} hybrid electric; ^{b} turboelectric;

TABLE II
KEY SPECIFICATIONS OF ELECTRIC AIRCRAFT

Model	**Propulsion**	**Battery nominal capacity**	**Maximum power**	**Range** **Endurance**	**Charging power** **Recharge time**	**Seats**	**EIS**
Pipistrel Velis Electro	All-electric	24.8 kW h	57.6 kW	50 min*	80 min	2	2020
Archer Maker	All-electric	75 kW h	672 kW	60 miles	133.2 kW**	2	2024
Joby S4	All-electric	200 kW h	N.A.	150 miles	N.A.	4	2024
Airbus CityAirbus	All-electric	110 kW h	N.A.	50 miles	N.A.	4	2025
Beta ALIA-250c	All-electric	N.A.	N.A.	288 miles	50 min	6	2024
Lilium Jet	All-electric	305 kW h	N.A.	162 miles	30 min	7	2024
Eviation Alice	All-electric	820 kW h	260 kW	288 miles	30 min	11	2027
Maeve 01	All-electric	2950 kW h	1.6 MW	288 miles*	4.5 MW	44	2029
Wright 1	All-electric	N.A.	N.A.	800 miles	N.A.	186	2030
Boeing Sugar Volt	Parallel Hybrid Electric	N.A.	1 MW	4028 miles	N.A.	154	2035
NASA N3-X	Turboelectric	N.A.	50 MW	8630 miles	N.A.	300	2045

* Plus VFR (Visual Flight Rules) reserve
** Estimated based on: 30% of the battery capacity is designed to be recharged in 10 min

long-term electric aircraft, the Airbus A320-class all-electric aircraft would require an energy density of $800\,\mathrm{W\,h\,kg^{-1}}$ at the pack level [21]. Bills et al. [50] corroborated these findings by specifying that commercial narrow-body and wide-body aircraft would require batteries with energy densities of 820 and $1280\,\mathrm{W\,h\,kg^{-1}}$ at the pack level, respectively. Hence, electric aviation urges the development of batteries with higher energy density.

2) Power Density: Given the short turn-around time between flights, charging power for regional aircraft can reach up to a megawatt level [20], [51]. On the other hand, from the perspective of discharging, a 300-seat electric aircraft requires a propulsive power of 60 MW [18], [29], [51]. Therefore, power density is another important parameter for battery technology. So far, the state-of-the-art LIBs' power density is between 400 and $800\,\mathrm{W\,kg^{-1}}$ [52], [53], allowing discharging rate over 2C. The variations of active materials, inactive materials, and manufacturing result in different C-rates. For instance, LTO anode-based batteries can offer a charging rate even higher than 10 C at the expense of relatively low energy density due to the low nominal cell voltage compared to graphite anode-based cells, demonstrating a tradeoff between the power and energy densities [54], [55]. Likewise, a thinner electrode allows a shorter path for ions, thereby leading to increased power density. However, a thinner electrode results in a significantly lower ratio between the weight and volume of the active and inactive parts of the battery, which means lower energy density [17], [56].

3) Thermal Management System: At the pack level, the thermal management system is crucial to adopting the XFC and discharging process since a higher current will generate more ohmic heating, which can influence the battery pack's performance and lifetime significantly [57]. In addition, thicker electrodes and decreasing amounts of electrochemical inactive material for energy-dense battery cells also deteriorate the battery cell thermal performance [58]. In principle, the thermal management system can be passive or active. A passive thermal management system relies solely on the ambient environment, whereas an active thermal management system incorporates a built-in source to provide heating and cooling. The active thermal management system can be subdivided into four categories depending on the medium: air cooling, liquid cooling, phase change materials, and a combination of the above [59]. Many thermal management strategies have been developed for the fast charging of LIBs. For instance, the elevated charging temperature in the asymmetric temperature modulation method can eliminate lithium plating, avoid solid-electrolyte-interphase (SEI) growth, and alleviate the battery cooling need significantly [41], [60]. For the battery storage system in electric aircraft, the thermal management system must be able to handle the thermal load in the worst scenario with minimum temperature variation of battery cells in the pack.

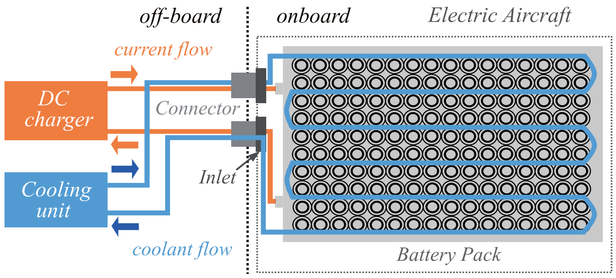


Fig. 2. Diagram illustrating the conceptual design of an off-board thermal management system for electric aircraft.

The onboard thermal management system in electric aircraft can experience reduced effectiveness during battery charging due to several factors. One reason is the lower airspeed encountered during ground operations, as the aircraft remains stationary while charging [61], [62]. In addition, the thermal load during aircraft charging is higher compared to flight operations. While the peak power demand during the takeoff and climb phases lasts very short, the high power demand during charging continues much longer. Therefore, an off-board thermal management system and charging connectors that combine the provision of electrical power and fluid for the thermal management of batteries during the charging process through charging cables can be applied in electric aircraft charging, as illustrated in Fig. 2. Such an off-board thermal management system can complement the onboard system or replace it entirely during the charging phase. It provides the flexibility to offer heating and cooling functions for the battery pack, depending on the environmental conditions and the specific battery chemistry used. Furthermore, it also offers the added benefit of weight reduction of the electric aircraft by utilizing an off-board thermal management system. Unlike ground vehicles, weight plays a critical role in electric aircraft, and reducing the overall weight enhances the energy efficiency and performance of the aircraft. The concept design of the ChargePoint 2-MW connector incorporates this off-board cooling design, while more detailed information about this connector is available in Section III-C [63].

4) Lifetime: Long battery cycle life is essential to ensure reliable, efficient, and cost-effective aircraft operation, including the ability to withstand high charge and discharge rates and frequent charging and discharging processes. Typically, the battery lifetime is represented in terms of the number of cycles to reach 80% of the rated battery capacity. However, the validity of the 80% capacity limit for aircraft is a matter of ongoing discussion, and whether this limit needs to be increased or decreased remains to be determined. The reason for this is that since the energy and power capacity of the battery pack drop over its cycle number, the aircraft will have to carry the useless weight of the aged battery pack on every mission without taking full advantage of the corresponding capacity. Therefore, finding the optimal capacity limit is crucial for ensuring the overall efficiency and performance of the aircraft. Besides, the anticipated battery lifetime for electric aircraft is significantly shorter than that of EVs. This is due to frequent fast charging processes required for revenue maximization, high discharging rate during the takeoff, and climb phase, and the battery is discharged to the maximum allowed depth after each flight. For instance, if there are five flights per day, 1000 cycles only means 200 days lifetime, which is much lower than that of EV (several years lifetime) [11].

The cycle life of commercially available NMC cathode-based LIB cells is approximately 2000–3000 cycles. On the other hand, LTO anode-based battery cells can offer a superior cycle life exceeding 5000 cycles [54]. The composition of electrodes, electrolyte, cell design, pack design, and operating conditions determines the degradation path of each specific battery cell [45]. The common degradation mechanisms can be classified into three different aging modes: loss of lithium inventory (LLI), loss of active material (LAM), and conductivity loss (CL). Another factor contributing to battery degradation is the loss of the electrolyte, which can eventually result in LAM and CL. Thus, this degradation mode is generally not considered independently. It is also worth noting that these aging modes often interact with each other, and a single degradation mechanism can trigger multiple degradation modes [64].

To extend the battery lifetime, it is important to choose the appropriate battery materials and ensure ideal operating circumstances [53], [65].

5) Safety: Safety always comes first in every operation of the aircraft. Thus, the safe and reliable operation of the battery storage system is a critical consideration in the development of electric aircraft. Battery failure can be induced by external abuse (e.g., crash, penetration, overcharge/discharge, and thermal ramp), internal mechanisms (e.g., lithium dendrite growth and stranded lithium), and safety concerns at the pack level, including overheating/nonuniform heating, inappropriate pack balancing, inadequate isolation, and arc flashing [17], [45]. These issues will ultimately lead to thermal runaway, which can cause irreversible damage to the battery cell or even an explosion.

To guarantee the safe operation of the battery storage system, protection equipment, including fuse, current interrupt device, structural frame to prevent battery deformation, vent, and BMS that monitors voltage, current, and temperature of the battery cell continuously is equipped in the battery storage system. For instance, the venting mechanism of the Pipistrel PB345V124E-L battery consists of a venting channel and exhaust located at the rear of the battery pack. This system is designed to enable the controlled release of gases in the case of a thermal runaway occurrence, which helps to reduce potential safety risks [46]. Another possible method for safety is to implement a reconfigurable modular battery system to enhance the reliability and fault-tolerance capability of electric aircraft batteries. Such a system allows for dynamic reconfiguration of the battery cell topology based on the real-time condition [66], [67], [68]. Apart from the methods mentioned above, the digital twin and novel computational modeling algorithms for battery failure prediction can help to avoid safety issues more economically and effectively [69], [70], [71]. For instance, digital twin technology can be used to simulate the behavior of the battery pack in real time, enabling accurate prediction of battery behavior and, thus, detecting and predicting potential faults in the battery pack.

According to current regulations of the International Civil Aviation Organization (ICAO), contingency fuel is required to compensate for unforeseen factors, typically 5% of the planned trip fuel [72]. Hence, the battery packs in electric aircraft need to be overdesigned by at least 5% to ensure the operation safety of electric aircraft. On top of that, electric aircraft batteries should ensure sufficient reserve energy to accommodate unplanned emergency flight operations, such as balked landings or diversion to alternative locations [12], [13]. ICAO requires long-haul aircraft to carry final reserve fuel equivalent to at least 30 min of additional cruise time [72]. Therefore, a redundant backup battery system that serves as the final reserve fuel is necessary.

6) Battery Development: Considerable attention has been devoted to the development of batteries, focusing on enhancing their performance, particularly in terms of higher energy density. As illustrated in Fig. 3, the state-of-the-art lithium-based battery technology can be classified into two main categories: LIB and post-LIB (PLIB) technologies. Among these, battery chemistries with higher potential for electric aviation applications are highlighted in bold italic formatting. As an alloying anode, the silicon-based anode is one of the most significant near-term breakthroughs in LIBs' anode chemistry. Compared with graphite (about $370\,\mathrm{mA\,h\,g^{-1}}$), Si exhibits substantially higher theoretical capacity (up to $4200\,\mathrm{mA\,h\,g^{-1}}$). However, the repetitive volume changes of nearly 300% during lithiation lead to significant capacity losses and, thus, reduced lifetime [73].

Another promising technology in lithium-based batteries is advanced PLIB chemistries, for example, solid-state batteries (SSBs), lithium–sulfur batteries (LSBs), and lithium–air batteries (LABs). Pairing the lithium metal anode with solid-state electrolytes, SSBs offer high energy density ($450\,\mathrm{W\,h\,kg^{-1}}$), improved safety performance, and a wider temperature range [74], [75], [76]. Employing nanostructured sulfur/carbon composites with conductive carbon in large quantities as cathode, which is combined with lithium metal as the anode, LSB technology can obtain enhanced safety and high gravimetric energy with low-cost sulfur ($500\,\mathrm{W\,h\,kg^{-1}}$). Theoretically, the LSB system has the potential to achieve a significantly high energy density of approximately $2600\,\mathrm{W\,h\,kg^{-1}}$ [75], [77]. However, they have a shorter cycle life than LIBs, and their material supply chain is relatively weak [33]. LABs make use of the free oxygen from the atmosphere as the positive electrode material, coupled with lithium metal as the negative active material, which offers the highest theoretical gravimetric energy density $5217\,\mathrm{W\,h\,kg^{-1}}$ [78], [79]. It is worth noting that another next-generation battery technology is based on alternative metal-ion chemistries, using sodium (Na), magnesium (Mg), calcium (Ca), potassium (K), and zinc (Zn). Compared with lithium, these elements are more abundant in resources that are more cost-effective. However, relatively low energy density makes them less attractive for electric aviation applications [80].

NMC-type LIBs are expected to dominate air transportation in the near-term future, for instance, applied in electric aircraft for general aviation [52]. This is primarily due to their well-established technology and strong battery supply chain, making them a viable choice for immediate implementation. For mid-term electric aircraft applications, LSBs present an attractive alternative due to their high theoretical energy density and low cost since sulfur is abundant and nontoxic, making this battery chemistry a highly energy-efficient and environmentally friendly option. Another potential candidate is the zinc-air battery (ZAB), which offers high energy-to-cost ratios. This chemistry is particularly attractive due to its use of the abundant element Zn and inherent safety [81]. In the long term, electric aircraft can greatly benefit from LABs, as they offer a unique advantage in terms of battery energy density, with the highest theoretical energy density among all types of batteries. Furthermore, the onboard oxygen systems that are already present in aircraft can be utilized to reduce the overall weight of the LABs. This makes LAB an ideal fit for electric aircraft applications [48]. Table III shows the key parameters of potential aviation batteries, while the maximum practical energy density is given by the highest values of the prototype cell data, as reported in [21], [33], [76], [79], [81], and [82]. Regarding the electrolyte, solid-state electrolytes show great

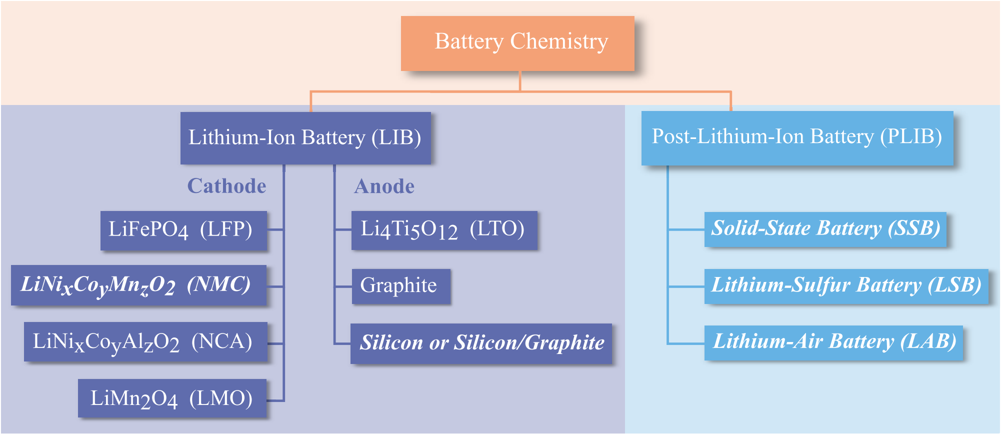


Fig. 3. Overview of lithium-based battery cell chemistries.

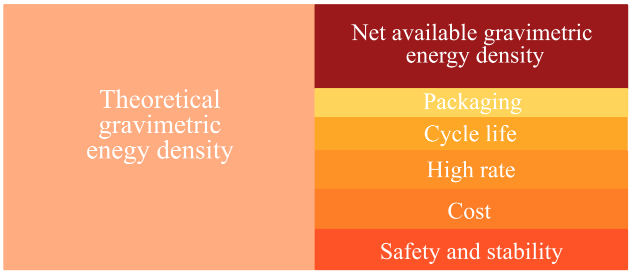


Fig. 4. Different factors that influence the practically achieved gravimetric energy density at the cell level [83].

promise for electric aircraft applications due to their potential for higher energy density and improved safety performance [21], [39].

It is important to note that compromises must be made to meet the multiple performance metrics simultaneously of practical batteries. These batteries are required to deliver sufficient power capacity, enable fast charging, operate effectively across a wide temperature range, exhibit long cycle life, ensure safety, and maintain cost competitiveness. Accomplishing all of these requisite performance metrics ultimately leads to an overall reduction in the practically achieved gravimetric energy density of the cell, as shown in Fig. 4 [83].

7) Battery Pack Voltage: What makes the all-electric aircraft unique is its full reliance on electricity as a means of propulsion, without using any combustible fuel. In other words, the high power required to propel the aircraft is supplied entirely by the electrical system. To ensure that the current in the electric propulsion system of electric aircraft stays at a manageable level, a higher battery pack voltage is necessary. Consequently, the size and weight of the power transmission cable and current stress on semiconductors are decreased [10]. Another benefit of adopting a high-voltage battery pack is that it enables fast charging by overcoming the practical cable weight limitation. Compared to the conventional EVs with 400 V, the pack voltage of the battery system in electric aircraft is expected to be 800 V and can potentially reach up to 1.5 kV [10], [14], [84], [85].

However, there are several challenges for high battery pack voltage levels, particularly under low pressure at high altitudes for aircraft applications. According to Paschen's law, the breakdown voltage is a function of the product between atmospheric pressure and air gap distance. For a 7.5-μm air gap at standard atmospheric pressure, the minimum breakdown voltage is 327 V [86]. At higher altitudes, the atmospheric pressure will decrease, and thereby, the breakdown voltage decreases. Partial discharge is one of the challenges that need to be addressed. To prevent partial discharge, the insulation, semiconducting layer, and shield layer of cables must be dimensioned carefully. Insulation materials with improved partial discharge endurance can be employed [87]. Arcing is another major hazard during aircraft operations. To mitigate the risk of electrical arcing, specialized circuit components known as combination arc fault circuit interrupters (CAFCIs) can be employed, which can protect against both series and parallel arcing by detecting current abnormalities and interrupting the current flow. Alternatively, differential relays can be utilized to prevent arcing. These relays measure the difference between sent and received current, and if this difference exceeds a predefined threshold, the transmission is then cut off [88].

C. Other Possible Energy Storage System Options

Several other energy storage technologies, such as ultracapacitors, can be considered to be candidates for electric aircraft. An ultracapacitor, also called a supercapacitor, can store energy between two conducting electrodes without chemical reactions. Because of the high power density ($10\,\mathrm{kW\,kg^{-1}}$), ultracapacitors offer high charging and discharging rates. In addition, the cycle life of ultracapacitors is quite high due to the working mechanism. However, ultracapacitors face the challenge of limited energy density, which is lower than $10\,\mathrm{W\,h\,kg^{-1}}$ at the system level [11], [89]. Given the characteristics of ultracapacitors, the ultracapacitor is a suitable candidate as an auxiliary energy storage system for electric aircraft, which supports the power required by takeoff and climbing. This approach could potentially maximize the benefits of both battery and ultracapacitor [90].

TABLE III
KEY PARAMETERS FOR POTENTIAL AVIATION BATTERY TECHNOLOGIES [21], [33], [76], [79], [81], [82]

Battery type	**Cathode**	**Anode**	**Practical gravimetric energy density** ($\mathrm{W\,h\,kg^{-1}}$)	**Practical volumetric energy Density** ($\mathrm{W\,h\,L^{-1}}$)	**Theoretical gravimetric energy density** ($\mathrm{W\,h\,kg^{-1}}$)	**Theoretical volumetric energy density** ($\mathrm{W\,h\,L^{-1}}$)
lithium-ion battery	NMC	silicon-based	265–450	730-1350	658	2126
lithium-sulfur battery	sulfur	lithium metal	185–500	170–600	2567	2843
zinc-air battery	oxygen	zinc	460–523	1389–1609	1087	3736
lithium-air battery	oxygen	lithium metal	620–1230	344-880	5217	N.A.

D. Aviation Certification

Safety must be the number one priority for air transportation. Hence, a newly developed aircraft must obtain a TC from the responsible aviation regulatory authority before entering into operation, such as the EASA or the Federal Aviation Administration (FAA). The main technical codes to be followed for the design of products for certification are set out depending on the maximum takeoff mass and the maximum number of passengers for the aircraft. Certification Standard 23 (CS-23) for Europe (EASA) and the USA (FAA) applies to aircraft with a maximum certificated takeoff weight of 8618 kg and 19 seats for passengers, also known as normal, utility, aerobatic, and commuter airplanes. Certification Standard 25 (CS-25) applies to larger aircraft [91]. For electric-powered aircraft, the majority of the CS-23 or CS-25 standards, such as flight characteristics, structure, system, and documentation, will still apply. However, there is a need for new certification requirements designed specifically for electrical propulsion, battery storage systems, and transmission of high levels of electrical power [92].

The latest amendment of CS-23 switched to performance-based rules instead of detailed prescriptive regulations, thus opening up the possibility for a new era in general aviation [93]. For the certification of electric/hybrid propulsion systems in CS-23 and CS-25 aircraft, the final version of special condition (SC) E-19 has been published by EASA. The document will play a key role in the development of eVTOL aircraft and various manned and unmanned aircraft [94]. For the certification of rechargeable lithium batteries and battery systems permanently installed on commercial passenger aircraft, the current industry standard and accepted methods of compliance are specified in RTCA DO-311A. Adhering to the requirements of this standard guarantees that the battery systems will execute the intended functions safely during aeronautical operations [12], [95]. Prepared by the Society of Automotive Engineers (SAE) AE-7D committee, which specializes in energy storage and charging of electric aircraft, two standards have been developed for rechargeable lithium battery systems used in aerospace applications. In SAE AIR6343, a basic overview of methodologies for designing and developing rechargeable lithium battery systems for aerospace applications is provided [96]. SAE AIR6897 offers basic background information and guidance for the BMSs of aerospace rechargeable lithium batteries [97]. However, given the novel components and architectures in electric aircraft, more detailed standards and regulations are needed to achieve the desired safety level. To pave the way for establishing matching regulations with technological advancement, the regulatory authorities must collaborate closely with the aviation sector [92].

III. STATE-OF-THE-ART ELECTRIC AIRCRAFT CHARGING SYSTEMS

Given the high charging power requirements for electric aircraft, onboard chargers are impractical due to the cost and volume limitations [98]. In addition, weight plays a crucial role in electric aircraft, necessitating minimal onboard charging electronics to reduce overall weight and enhance system efficiency and performance [99]. Therefore, unlike EVs, only the off-board dc charging system is considered for electric aircraft.

A. Electric Aircraft Charger

The charging power requirement for future electric aircraft will depend on several factors, such as the size and range of the aircraft, the turnaround time, and the battery technology used. For near-term applications, small electric aircraft with passenger capacities ranging from one to four seats are similar to the EVs category, and the charging power level is generally in the range of a few hundred kilowatts. Therefore, the current fast-charging technology developed for ground-based EVs is an attractive solution for the light aviation industry [20]. Aside from existing chargers for automotive applications, some companies have designed specific dc fast chargers for electric aircraft, having long cords to connect the chargers from the grid to the electric aircraft, as listed in Table IV [100], [101], [102]. For instance, Electro Aero, a company based in Australia, delivered standardized dc chargers made especially for electric aircraft, which can provide charging power at 30, 80, and 240 kW, respectively.

However, as electric aircraft continues to grow in passenger capacity and range, megawatt power levels for charging will eventually become necessary. For instance, the peak charging demand of an all-electric regional aircraft with a battery capacity of 800 kW h could potentially reach 2 MW to achieve the desired turnaround time, which exceeds current light-duty ground-based EV charging technologies and standards. To handle high-powered charging, the connector must be rugged and able to withstand the demands of repeated use. In addition, it should be simple for users to insert and remove. Heavy-duty electric trucks are anticipated to require similar charging power levels as electric aircraft. This shared power requirement creates an opportunity for electric aircraft to use the same connector as electric trucks. Some electric truck

TABLE IV
TECHNICAL SPECIFICATIONS OF THE STATE-OF-THE-ART ELECTRIC AIRCRAFT CHARGERS

Manufacturer model	**Electro Aero RAPID 240**	**Electro Aero RAPID 80**	**Beta Charge Cube**	**Pipistrel SkyCharge M20**
Maximum output power	240 kW	80 kW	350 kW	20 kW
Connector type	CCS1 / CCS2	CCS1 / CCS2	CCS 1	GB/T
Compliant standard	SAE AS6968	SAE AS6968	SAE J1772, IEC 62196-3	IEC 62196-3
Input voltage (AC)	332-528 V	332-528 V	480 V	130-400 V
Output voltage (DC)	150-1000 V	150-1000 V	max 950 V	150-440 V
Output current	max 250 A	max 200 A	350 A-500 A	max 60 A
Maximum efficiency	96%	96%	95%	92%

chargers are already available, and the technical specifications of state-of-the-art electric truck chargers are listed in Table V [103], [104], [105], [106].

Another predictable distinction is due to aircraft wingspans and the need to maintain a safe distance from the building: the charger needs to be brought into proximity of the aircraft, unlike ground-based EVs, which can be parked near the charger to avoid long charging cables with higher resistive losses. Therefore, the rapid mobile plug-in charger is a viable approach that can be moved easily next to the aircraft. Other possible solutions include aircraft gates with fixed charger installations, slow chargers at parking locations for charging overnight or during downtime, and chargers installed in indoor hangars, which are independent of weather conditions [90].

Battery swapping is another attractive approach where depleted batteries after flights can be swapped with fully charged ones at the airport apron. This method can significantly shorten the required downtime for charging and reduce instant grid power demand. However, implementing battery swapping in practice encounters several obstacles. First, the aircraft must be designed with a removable battery pack that is both flexible enough for easy swapping and reliable enough to ensure safe flight operations. Second, it is essential to standardize the physical dimensions and electrical parameters of battery interfaces for various aircraft types. Finally, the initial investment is notably high, as it requires costly robotic infrastructure for battery swapping and multiple spare batteries for uninterrupted operation [28], [92], [107], [108].

B. Standards

Currently, the standards for electric aircraft charging are evolving quickly. The SAE is actively working on the technical requirements for charging electrically powered aircraft in SAE AS6968 [109] and SAE AIR7357 [110] standards. SAE AS6968 is dedicated to addressing the conductive charging requirements of small electric aircraft, while SAE AIR7357 specifically focuses on megawatts and XFC for larger aircraft. However, despite its development, some original equipment manufacturers apply existing automotive standards for charging electric aircraft due to their immediate availability. Although these standards are not aviation-specific, they are still capable of providing reliable charging for electric aircraft with some modifications for the specific requirements of aviation applications. Nevertheless, the use of automotive standards for charging electric aircraft may not be ideal in the long run, and the industry should strive to adopt charging standards tailored for electric aviation, such as SAE AS6968, to ensure the safety and reliability of electric aircraft charging.

For EVs, several charging standards are widely used worldwide, such as CHAdeMO, CCS, GB/T, and Tesla standards. Besides, two ultrafast charging standards are under development: ChaoJi and megawatt charging system (MCS). First, CHAdeMO is a charging standard developed by CHAdeMO Organization, Japan. As a proprietary specification, CHAdeMO adheres to IEC 61851-23 and IEC 61851-24. In CHAdeMO v2.0, the possibility for bidirectional power transfer is opened up, allowing for vehicle-to-grid (V2G) functionality [111]. According to the latest published version in 2021, CHAdeMO 3.0 enables ultrafast charging over 500 kW using the next-gen plug ChaoJi [112]. ChaoJi is an ultrafast EV charging standard codeveloped by CHAdeMO and the China Electricity Council (CEC) [113]. Aiming at a harmonized future standard, ChaoJi is compatible with the existing GB/T and CHAdeMO and will also be compatible with CCS standards. "Ultra-ChaoJi," with an additional set of power pins above the standard ChaoJi pinouts, is currently under development and can be applied in future aviation [114].

Based on CCS, Charging Interface Initiative e.V. (CharIN) initiated the Task Force MCS, which aims at creating a common solution for charging heavy-duty EVs, electric aircraft, and marine vessels such as ferries [115]. As part of the preparation, standard J3271 developed by SAE is currently in progress [116]. In the meantime, the IEC began developing standard IEC/TS 63379, and the publication is planned for 2025 [117].

Another charging pathway for future electric aircraft is automatic charging, which refers to automatically charging objects without requiring any human intervention [118]. The SAE J3105 document defines the common automated conductive charging system architecture covering functional and dimensional specifications for the supply equipment and vehicle connection interfaces. To detail the connections in SAE J3105, supplemental documents are available and designated by SAE J3105/1, SAE J3105/2, and SAE J3105/3, where connection details, including connection configuration, conductor, and vehicle geometry, are covered [134].

C. Charging Plugs

As previously mentioned, the physical plugs for charging EVs are a viable solution for electric aircraft in the near term. The widely adopted plugs for EVs, including ChAdeMO, CCS Type 1, CCS Type 2, GB/T, and Tesla, are listed in

TABLE V
TECHNICAL SPECIFICATIONS OF THE STATE-OF-THE-ART ELECTRIC TRUCK CHARGERS

Manufacturer Model	**EVBox Ultroniq**	**Heliox Ultra-Fast**	**ABB HVC 680V2**	**Tritium PK350**
Power	350 kW	600 kW	640 kW	350 kW
Connector type	CCS 2	Pantograph	Pantograph	CCS 2 / CHAdeMO
Input voltage	N.A.	400 V AC	400/480 V AC	400/480 V AC
Output voltage	460 V-800 V	max 950 V	max 500 V	max 920 V
Output current	max 500 A	max 1000 A	840 A	CCS: max 500 A CHAdeMO: max 200 A
Efficiency	N.A	96%	94-96%	98.5%

TABLE VI
TECHNICAL SPECIFICATIONS OF EV PLUGS FOR DC FAST CHARGING

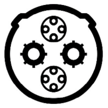
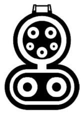
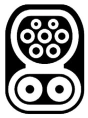
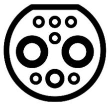
Standard	**CHAdeMO**	**CCS Type 1**	**CCS Type 2**	**GB/T**	**Tesla V3**
Connector inlet					
Maximum voltage (V)	1000	920	920	1000	500
Maximum current (A)	400	500	500	250	500
Maximum power (kW)	400	350	350	250	250
Communication protocol	CAN	PLC	PLC	CAN	PLC
V2X function	Yes	Yes (2025)	Yes (2025)	No	No
Start year	2019	2014	2013	2013	2012

TABLE VII
TECHNICAL SPECIFICATIONS OF THE CHARGING PLUGS (UNDER DEVELOPMENT)

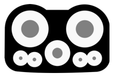
Standard	**Megawatt Charging System (MCS)**	**Chaoji**
Connector inlet		
Maximum voltage (V)	1250	1500
Maximum current(A)	3000	600
Maximum power (kW)	3750	900
Communication protocol	PLC	CAN
V2X function	Yes	Yes
Start year	2018	2020

TABLE VIII
TECHNICAL SPECIFICATIONS OF THE CHARGING CONNECTOR SPECIFICALLY FOR ELECTRIC AIRCRAFT (UNDER DEVELOPMENT)

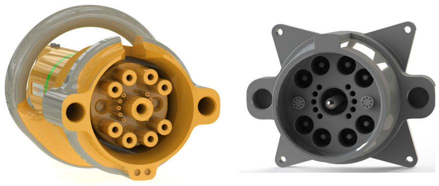
Concept design	**ChargePoint** 2 MW **charging connector**
Connector	
Output voltage	200 - 1000 V
Maximum current	4× 500 A
Maximum power	2 MW
Start year	2018

Table VI [119], [120], [121], [122], [123], [124], [125]. These connectors can handle small electric aircraft in the near term. Considering the higher charging power required by the future regional and larger commercial electric aircraft, the aforementioned emerging charging connectors can be considered: ChaoJi and MCS, as shown in Table VII [115], [126], [127]. Furthermore, at the 2018 Uber Elevate Summit, ChargePoint unveiled a new concept for a 2-MW charging connector, as illustrated in Table VIII. This is the first-ever concept design for high-powered charging of electric aircraft and semitrucks, including eVTOL aircraft. This design concept incorporates up to four BMS interfaces and 4 × 500 A delivery circuits. Each delivery circuit operates within a voltage range of 200–1000 V. To enable seamless data transfer and vehicle performance payload offload, provisions for high-speed data transfer are integrated into the design. In addition, it features an easy-to-use insertion and removal mechanism, with a motorized system facilitating the insertion process [128], [129].

For most small aircraft in the near-term category with a charging power below 350 kW, the charging cable can be manually handled, given the comparatively lower charging power requirements. However, considering the emerging dc XFC technology with charging power over 350 kW for regional and larger electric aircraft, there are limitations imposed by the weight of charging cables. Therefore, another potential solution for future larger aircraft is the implementation of automatic charging systems. As shown in Table IX [130], [131], [132], [133], [134], there are two pantograph options: pantograph down and pantograph up. The first method involves mounting the pantograph on the vehicle roof, while the second method incorporates the pantograph as part of the charging infrastructure [135]. For instance, the ABB pantograph down system is able to charge electric buses efficiently and quickly. The battery system is connected to the pantograph via rails on the roof of the electric bus, while the charging power can reach up to 600 kW [132]. In addition to the pantograph, the high-power charging system, quick charging connector (QCC), enables a universal solution for automatic charging. Because of the high level of safety, increased efficiency, and enclosed design, the automated connection device (ACD) can transfer 1500-V dc and 670 A continuously, maximum of 1440 A in several minutes [130]. This connector makes it possible to transfer high power to electric aircraft.

D. Charging Cable

To support charge times comparable to filling up the fuel tank on a conventional aircraft, cables are being developed to accommodate the new types of inlets and standards [107]. Due to the cable resistance and the associated heating issue, charging cables with greater diameters are necessary to realize fast charging currents. According to the Occupational Safety and Health Administration (OSHA), the maximum lifting capacity for an average human adult is 22.7 kg [136]. To charge a 400-V battery pack at 50 kW, the weight of the cable and connector is 10.4 kg, assuming a typical cable length of 3.7 m [137]. However, the cable weight for charging a battery pack at the same voltage level with 200 kW exceeds the safe lifting limit by OSHA, which is too bulky and cumbersome to handle [138].

To reduce the cable weight, a battery pack operating at the 800-V level is one of the promising alternatives. Aside from the benefit of higher charging capability, the 800-V powertrain yields a higher power density of the motor due to the improved motor electromagnetic performance. In addition, the 800-V inverter paired with an 800-V motor exhibits higher inverter efficiency and smaller filter capacitor size. From the perspective of the auxiliary power unit (APU), the 800-V APU features slightly higher efficiency at higher power levels [85]. However, the 800-V battery pack still requires a wire gauge of 350 MCM (thousand circular mils), which corresponds to over 11.8 kg m^{-1}, and the total cable mass does not satisfy the OSHA safety requirements. Thus, to achieve XFC, battery pack voltage over 1000 V is the future trend, which is within the voltage range of MCS (1250 V), ChaoJi (1500 V), pantograph (1000 V), and QCC (1000 V) [137].

E. Communication Protocol

Given the high charging power, the coordination and communication between electric aircraft, the charge point, and the charge point operator (CPO) are increasingly necessary for power management at the airport. For example, the BMS updates the battery characteristics, e.g., battery state of charge (SOC), with the charge point during communication. In addition, information including desired reference charging current and voltage is exchanged [139]. Therefore, the communication protocol, including a collection of rules and guidelines to assist data communication and exchange, is needed to ensure successful charging demand management and grid integration of electric aircraft.

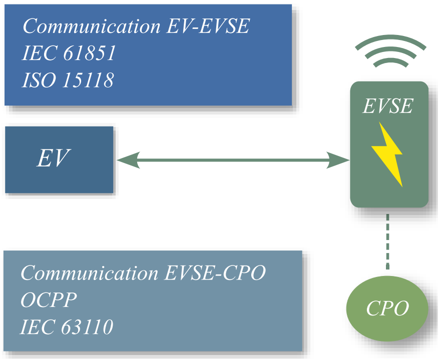


Fig. 5. Communication protocols for EV charging.

Up until now, no specific communication protocol related to electric aircraft charging is commercially available. Therefore, the subsequent discussion will focus on the communication protocols for EVs with some level of compatibility for electric aircraft. There are two categories of communication protocols between entities: front- and back-end protocols. The front-end protocol is responsible for the communication between EVs and the EV supply equipment (EVSE), which defines the plugs, charging topologies, communication, security, and safety requirements. IEC 61851-24 standard defines the basic digital communication between the EV and the dc EV charging station [140]. On top of IEC 61851, ISO 15118, developed by the International Organization for Standardization (ISO), defines a more advanced communication protocol, including ac and dc charging, wireless charging, and pantograph charging for heavy-duty vehicles [141].

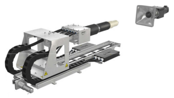
On the other hand, the back-end protocol handles the communication between the EVSE and the CPO, including open charge point protocol (OCPP) and IEC 63110 [139], [142]. OCPP is a widely used standard open protocol enabling EVSE to communicate with various central management systems. This protocol includes a variety of features, such as smart charging functionality, transaction handling, and security communication [143], [144]. IEC 63110 is an international standard defining a communication protocol between EVSE and CPO, which covers the management of energy transfer, asset management of EVSE, authentication/authorization/payment of charging sessions, the provision of other e-mobility services, and cybersecurity [145]. The overview of the communication protocols is presented in Fig. 5.

F. Charging Strategy

The commercialization of electric aircraft heavily depends on the development of fast charging techniques for aircraft batteries. However, fast charging typically deteriorates the

TABLE IX

STANDARD FOR EV POWER TRANSFER SYSTEM USING CONDUCTIVE ACDS

Standard	**SAE J1305**		
	SAE J3105/1	SAE J3105/2	SAE J3105/3
Implementation	Pantograph Down	Pantograph Up	QCC
Connector inlet	 [ABB]	 [Schunk]	 [Stäubli]
Maximum voltage (V)	1000	1000	1000
Maximum current (A)	1200	1200	2000
Maximum power (kW)	1200	1200	2000
Communications link	WiFi	PLC	WiFi
Standards compliance	IEC 61851-23 OppCharge	IEC 61851-23 DIN 70121 ISO 15118	IEC 61851-23

battery performance and accelerates its lifetime reduction [146]. Hence, the optimal charging strategy plays an important role in the fast charging development field [147], [148], [149], [150], [151], [152], [153], [154]. A desirable charging strategy can realize shorter charging time, higher charging efficiency, minimization of performance deterioration, and guarantee safe operation.

As mentioned before, the relatively higher energy and power density help to make the LIB the most popular battery technology in automotive applications. Thus, the following discussion focuses on LIB as a typical case study. In general, there are two categories of available charging strategies for LIBs: passive charging and active charging. The passive charging strategy is a model-free method based on predefined charging instructions and fixed battery constraints, i.e., current, battery, and power. The constant-current constant-voltage (CC-CV) charging is one of the typical passive charging strategies, as illustrated in Fig. 6. The CV phase starts when the battery voltage reaches the preset upper cell voltage limit. In addition, there are variants of the CC-CV strategy and pulse charging technique that belong to passive charging. For the active charging strategy, it can be further categorized into two different charging strategies that use empirical battery models and electrochemical battery models, respectively. Compared with the passive charging strategy, the active charging strategy is closer to the actual battery state at the expense of higher computing complexity [155].

The CC-CV charging strategy is the most widely adopted passive charging technique due to its simplicity and low implementation cost. However, it can be observed that the conventional CC-CV charging strategy is not suitable for high charging rates. First, the high charging rate during the CC part can put significant stress on the thermal management system of the battery [54]. In addition, due to the metallic lithium plating and SEI growth during the fast charging process, the combined losses of primary active material (Li^+), secondary active material, and the rate capability losses on both positive and negative electrodes occur, which result in the battery capacity deterioration [156], [157]. Moreover, in the case of electric aircraft, it is crucial to charge the battery system as fully as possible, as flying with limited SOC windows can raise multiple safety concerns, such as inadequate power for takeoff or climb. However, to fully charge the battery, the remained 20% SOC results in a long CV period, which is comparable to the CC period. Consequently, the total charging time is significantly prolonged, as shown in Fig. 6 [13], [158], [159].

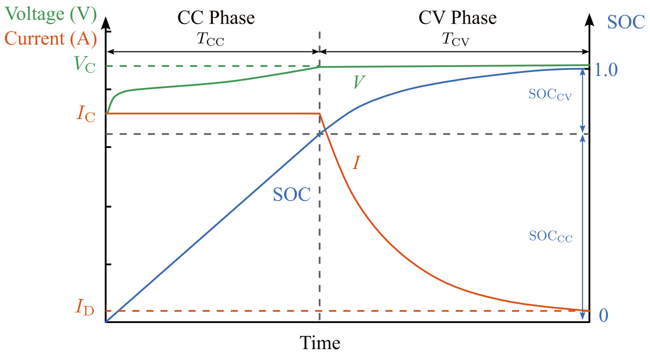
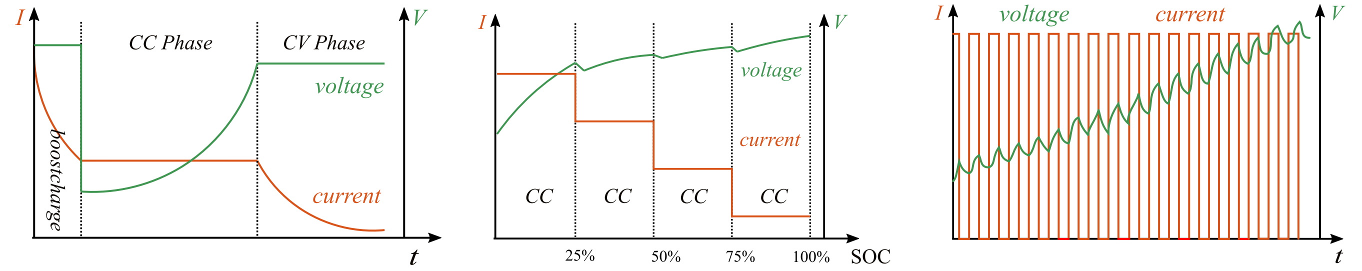


Fig. 6. Conventional CC-CV charging strategy.

Hence, proposing an appropriate optimal charging strategy is essential for electric aircraft development to ensure battery performance and lifetime. A variant of the CC-CV strategy for ultrafast charging is introduced in [149]: boost-charging strategy, as shown in Fig. 7(a). The boost-charging strategy, where the basic principle can be characterized as CV-CCCV charging, is able to accelerate the charging process without introducing any extra degradation effect compared with the conventional CC-CV strategy. Paper [160] gives a comprehensive review of the effects of the pulse charging technique, as illustrated in Fig. 7(c) [161], while improvements in charging efficiency, reduced charging time, and decreased capacity fade can be observed. In [151], an active charging strategy based on the multistage CC (MCC) method with the integration of the Taguchi method and SOC estimation is proposed, as shown in Fig. 7(b). The proposed charging strategy offers moderate temperature rise, slightly improved energy



(a) (b) (c)

Fig. 7. Schematic representation of other common charging strategies. (a) Basic principle of boost-charging strategy. (b) MCC charging strategy proposed in [151]. (c) Pulse charging strategy.

efficiency, and shorter charging time by 22.5% compared with the CC-CV charging strategy. Liu et al. [148] applied heuristic methods to design an optimal charging strategy that can optimize charging time, energy efficiency, and thermal performance based on a coupled thermoelectric battery model. Hu et al. [154] designed an optimal charging strategy with objectives of reduced charging time and fewer energy losses based on the first-order RC model.

G. Aviation-to-Grid Flexibility

Similar to the V2G functionality in EV charging, a novel concept of aviation-to-grid (A2G) is proposed in [162], which utilizes electric aircraft charging with the battery swap method to provide grid flexibility, such as frequency response services. According to the flight schedules, there is a significant decrease in flight activity between 00:00 and 07:00. During this period, A2G was proven to be more effective due to the availability of fully charged electric aircraft batteries and the weaker inertia of the power system. Besides, the centrally managed and highly scheduled operations of electric aircraft can help to ensure the availability of A2G capacity. However, this capacity is significantly influenced by flight schedules. During peak flight scheduling periods, the primary focus of electric aircraft batteries is to fulfill aviation requirements, resulting in lower power response capacity. In addition, it is crucial to acknowledge that the more frequent charging and discharging cycles due to A2G can impact the lifetime of electric aircraft batteries. Besides, the energy losses during the conversion process involved in A2G operations cannot be neglected.

IV. ELECTRIC AIRCRAFT CHARGING STATION DESIGN: ARCHITECTURE

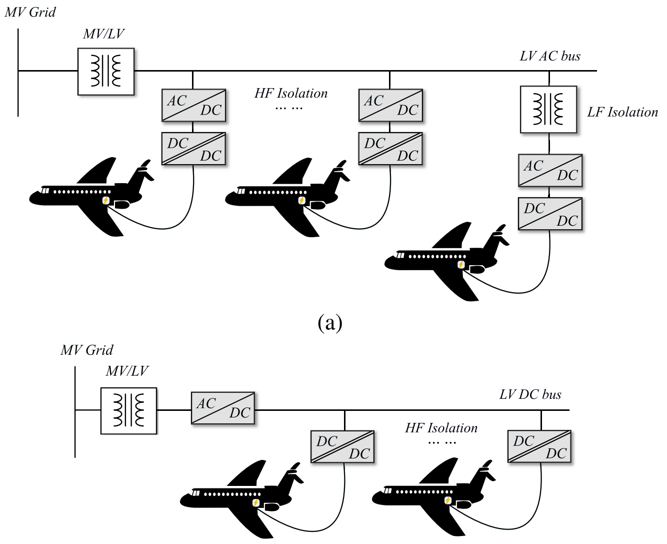
A. AC and DC Architectures

Currently, EV charging facilities are typically powered by low-voltage (LV) distribution networks. However, considering the increasing charging demands of various electric aircraft types, the direct connection to the MV distribution network will occur [15], [16], [122], [163], [164], [165]. Inside the charging station, the local LV distribution network can be ac or dc, as shown in Fig. 8. As illustrated in Fig. 8(a), a three-phase step-down transformer is applied to interface the MV grid supply and provide the LV ac power to all chargers. The LV ac bus line-to-line voltage operates at 250–480 V. In Fig. 8(b), the MV distribution system is linked with multiple charger ports via a service transformer and an LV rectifier, while the dc bus voltage is normally less than 1000 V. Whether ac or dc LV distribution network, all the subsystems are connected to the LV bus through switchgear cabinets that contain breakers and disconnect switches to control, protect, and isolate the charging subsystems [15].

Nowadays, compared with the dc-coupled system, the fast charging station with an ac power distribution network is much more popular because of the mature switchgear, protection devices, converter technology, and the availability of well-established standards, which is particularly suitable for near-term small aircraft applications. However, it can be anticipated that the dc-connected system will be the future solution due to the increasing integration of renewable energy resources, battery energy storage systems, higher penetration of electric transportation, and the growing charging power levels of mid-/long-term electric aircraft. The ac-connected system requires more conversion stages to interface dc components, leading to lower energy efficiency, higher system complexity, and hardware cost, and a complicated control system dealing with reactive power control, inverter synchronization, and voltage and frequency control during islanded operation mode. On the contrary, the dc-distribution concept is able to eliminate the repetitive ac/dc conversion stages: not only the power flow from the grid to the individual charger but also the conversion stages deliver power from renewable resources or battery storage systems to the charger [16]. Despite these advantages of the dc-couple system, the protection presents the main barrier to successful implementation due to the lack of guidelines and standards for dc microgrid protection and relatively higher costs for dc protection devices, such as dc breakers [166]. Furthermore, the absence of established accuracy, calibration, and testing guidelines for the commercially available dc meters presents another challenge for the energy generation and consumption measurement among the charging station [15].

B. MV Local Distribution Network

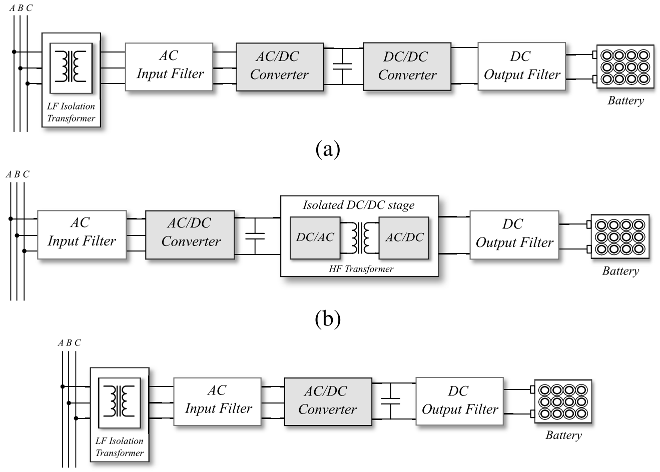
Given the higher battery pack voltage and megawatt charging power levels of future regional and large electric aircraft, it is possible that future local distribution networks will need to operate at MV levels, potentially in the range of 1.5–3 kV. This shift in voltage level can greatly improve efficiency in



(a)

(b)

Fig. 8. System architecture for the electric aircraft charging station. (a) AC-connected system. (b) DC-connected system.



(a)

(b)

(c)

Fig. 9. Simplified block diagrams of a dc fast charger. (a) DC fast charger with LF isolation. (b) DC fast charger with HF isolation. (c) Single-stage dc fast charger.

the distribution network, as higher voltages can lead to lower power losses and greater transmission efficiency. However, it should be noted that implementing MV local distribution networks may also require additional infrastructure upgrades and investments, as well as increased safety considerations. Nevertheless, the trend toward electrification in the aviation industry makes the design of distribution networks a critical area for further research and development.

C. DC Fast Charger Configuration

The power electronics configuration of a typical dc fast charger is designed as a two-stage system, as illustrated in Fig. 9(a) and (b): an ac/dc rectification stage with power factor correction (PFC), which converts the input ac voltage into an intermediate dc voltage, and a dc/dc stage, which performs the battery voltage and current regulation [14], [15]. To attenuate the leakage current, galvanic isolation inserting a high common mode impedance between the grid and charging objects is required according to standards IEC 61851-23, JEVS G105-1993, SAE J1772, and UL 2231. This guarantees the safety of user and system operation [14], [167], [168]. For the system configuration, the isolation can be deployed on either the high-frequency (HF) or low-frequency (LF) side. As shown in Fig. 9(a), the LF isolation in terms of the line-frequency transformer is put at the input side of the ac input filter. On the other hand, the HF isolation is realized inside the dc/dc stage, as shown in Fig. 9(b) [16]. The HF isolation eliminates bulky LF transformers. Thus the overall system size and weight are reduced significantly [16], [169]. However, the power losses of the HF transformer are higher than the LF one [170], [171]. Therefore, there is a tradeoff between weight/size and efficiency for isolation design.

The installation and operating cost of an XFC station is high considering the necessary electrical service upgrades, special equipment, installation permits and administration, and costly maintenance warranties [164], [172]. Therefore, there are usually multiple chargers inside an XFC charging station, which can reduce the capital investment and operating cost per charger [15], [164]. However, for the future megawatt charging power requirement from regional and larger commercial electric aircraft, one potential solution is the individual single-stage charger system, which has the advantage of eliminating the need for a dc/dc converter, thus improving efficiency and reducing costs, as illustrated in Fig. 9(c). Nonetheless, since there is no dc/dc converter, careful consideration must be given to the design of the transformer turns ratio, which transforms the MV voltage to the level required by the ac/dc rectifier. If there is a significant difference between the peak ac voltage and the load side voltage, it can result in efficiency losses in the ac/dc rectifier. Therefore, the appropriate turns ratio should be chosen to ensure that the charging system operates within the desired voltage range and achieves efficient power transfer.

D. Multiplug Charging System

Given the future megawatt charging power requirement, the concept of multiplug charging system arises. In future electric aircraft, the large battery pack can be divided into multiple smaller packs, each charged independently using separate plugs, as illustrated in Fig. 10. This multiplug structure enables simultaneous charging of multiple batteries in a single electric aircraft, which is similar to concepts presented in [163]. This approach removes the need for a single high-power plug to handle the megawatt charging power requirement. Instead, the power is divided among several charging plugs, which can improve overall efficiency and address the limitation of charging cable weight. However, using a multiplug charging system for electric aircraft can be operationally complex, which makes it more challenging. Besides, charging standards would need to be adapted to accommodate this approach.

E. Solid-State Transformer

In the state-of-the-art fast-charging station, step-down transformers are connected to the MV grid to provide a three-phase

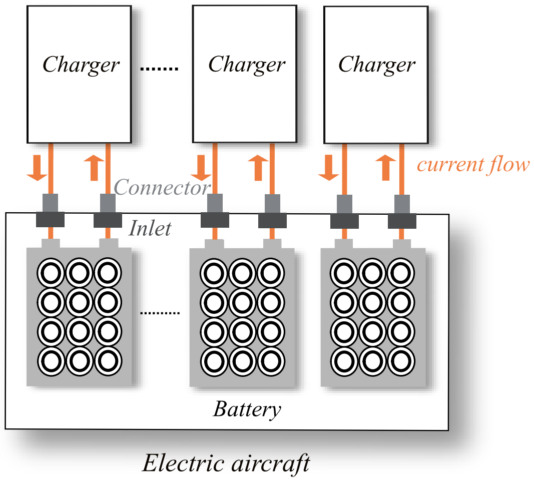


Fig. 10. Conceptual multiplug charging system.

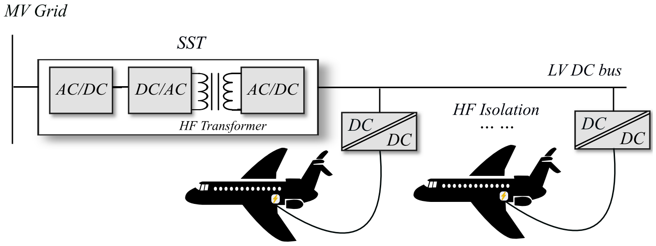


Fig. 11. SST-based electric aircraft charging station.

power supply to the charging station. However, the bulky MV-to-LV service transformer complicates the system installation and increases the size and cost of charging stations. To solve these issues, the line-frequency service transformer can be replaced by a power electronics-based SST, which provides galvanic isolation by an HF transformer, as shown in Fig. 11.

Compared with the traditional line-frequency transformer, the key benefits of SSTs are better controllability and reduced system size [173]. In addition, SSTs have the potential to facilitate multiple isolated output windings, which can be rectified directly to dc and connected to the battery. In the context of charging electric aircraft, the compact footprint of the SST-based charging system can optimize site utilization in airports. However, there are still some challenges to the SST-based charger adoption, including degraded efficiency due to more power conversion stages, the lack of fast-acting protection devices, the absence of well-established standardization and certification of the charging equipment with direct MV connection, concerns regarding reliability and economics, and the requirement of additional layers of control and communication system [16], [173].

F. Battery Buffered Charging System and Onsite Renewable Generation

Due to the substantial charging power required when multiple electric aircraft are charged simultaneously, the peak demand on the grid becomes very high. To mitigate stress on grid infrastructure, stationary local energy storage can be integrated into the electric aircraft charging station, which can act as a power buffer between the grid and electric aircraft [16], [159], [174]. Two different energy management strategies can be applied to the charging station with an energy storage system: load leveling and load shifting strategies. In the first scenario, the energy storage system provides the peak power, while the grid supplies the average charging demand. For the second case, energy is stored during the off-peak hours and released during heavily loaded periods [55], [175]. If the grid-interfaced converter is bidirectional and time-of-use rates are used, it also opens up a possibility for energy arbitrage and grid support services [164]. However, suppose that the SOC of the battery buffer falls below a critical level. In that case, it cannot discharge to provide charging power, and part of the grid capacity is unavailable since it is used to charge the battery buffer. Moreover, the wear and tear on batteries and efficiency losses are additional drawbacks compared to traditional charging [176].

Aside from the energy storage system, the onsite renewable energy generation system can also be integrated to avoid excess power charges. Among various renewable energy technologies, solar photovoltaic (PV) plants are particularly well-suited for airport premises. Airports often have ample ground and rooftop space, which are available for PV panels' installation. In addition, solar systems can operate more efficiently in airport areas since there are no or negligible shading factors. A notable example is the Cochin airport in India, which has been operating fully on solar power since 2016. The total installed solar capacity is $50\,\mathrm{MW}_P$ [177], [178]. In The Netherlands, the solar park in the Rotterdam The Hague Airport is located parallel to the airport's runway. This solar park, operational since 2022, generates approximately $14\,\mathrm{GW\,h}$ of green energy annually, which is three times more than the energy consumed by the airport itself [179]. Although PV systems can generate a significant amount of energy, the key challenge of PV systems is the diurnal and seasonal variation in solar generation and the corresponding variation in the airport load.

V. ELECTRIC AIRCRAFT CHARGING STATION DESIGN: CONVERTER TOPOLOGY

Power electronics converters play a crucial role in charging systems as they are responsible for converting the input ac voltage into the required output dc voltage. Up until now, the requirements of power converter topology for electric aircraft chargers are aligned with EV charging. These converters need to handle the wide and assorted range of battery voltages and charging profiles across different electric aircraft models while ensuring safety, reliability, efficiency, compactness, and compliance with grid harmonic standards [14]. The desired conversion stages should guarantee reliable and efficient operation at low component cost [180]. In principle, most of the topologies have already been applied for EV solutions and can be readily extended for electric aircraft operation.

A. AC/DC Converter

The front-end high-power ac/dc converter rectifies the input ac voltage into a regulated dc voltage, while its desired features

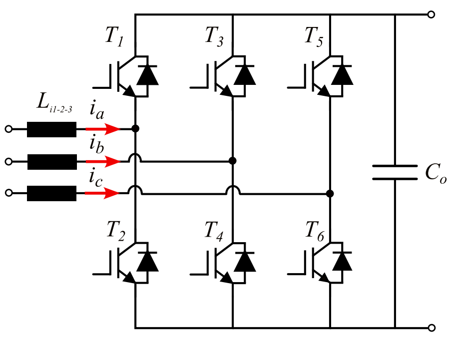


Fig. 12. Front-end ac/dc converter: PWM rectifier.

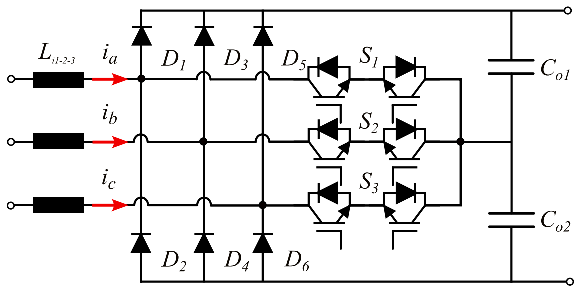


Fig. 13. Front-end ac/dc converter: Vienna rectifier.

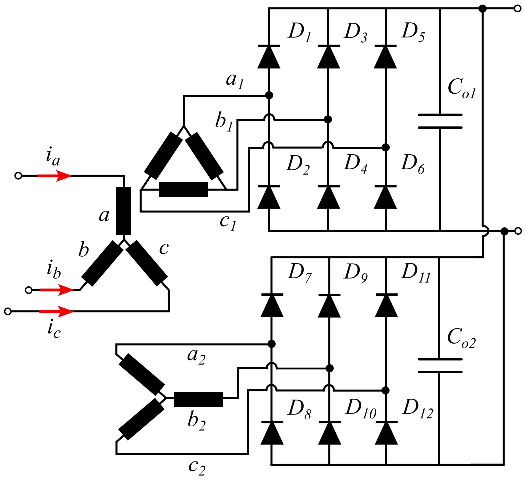


Fig. 14. Front-end ac/dc converter: multipulse rectifier.

include PFC, distortion-free operation, high efficiency, and high power density, which is achieved by eliminating bulky input filters and having fewer active and passive components [53], [98], [181].

Due to the simple circuit topology, well-developed modulation and control schemes, and the availability of high-voltage SiC devices, the traditional three-phase six-switch voltage-source-inverter (VSI)-based bidirectional boost rectifier is the most popular candidate for the ac/dc conversion stage of dc fast chargers in the power range of 50 kW or higher. The topology, also known as a pulsewidth-modulated (PWM) rectifier, is illustrated in Fig. 12. Utilizing boost inductors, this topology can shape the input ac, while the output dc voltage is regulated to a higher level than the input peak-to-peak voltage [181], [182]. One drawback of this topology is the need for a bulky filter inductor to achieve low-harmonic input current generation. Hence, the power density of this topology is relatively low compared to other three-level topologies [183].

Another popular ac/dc front-end stage implementation is the Vienna rectifier, as illustrated in Fig. 13. Compared with the PWM rectifier, the main advantage enabled by the three-level switching implementation of the Vienna rectifier is the higher power density, as only half of the inductance for the input boost inductors is required. Besides, the Vienna rectifier is characterized by high efficiency and reduced voltage stress on power devices [184], [185]. Despite having all the advantages of three-level converters, this topology also faces the same challenges of three-level converters, including the requirement for dc-link capacitor voltage balancing. Furthermore, the Vienna rectifier only allows unidirectional power flow and has limited reactive power control. The narrow range of achievable reactive power depends on the output voltage due to the constrained modulation vector [15].

In high-power-rating applications, the multipulse rectifier is very competitive because of its high reliability and simplicity [182]. Furthermore, the utilization of a multipulse rectifier, which does not require HF switching devices, presents the advantage of achieving higher efficiency at a reduced cost. This makes it particularly suitable for megawatt power level charging. However, this topology faces challenges such as high input current harmonics and unregulated output voltage [186]. To accomplish harmonic cancellation, different configurations, such as star, delta, and zigzag connections, can be utilized in primary and secondary in the transformers [187]. As shown in Fig. 14, a single transformer with star primary, one star secondary, and one delta secondary is used to interface the 12-pulse diode rectifier. In paper [186], a 12-pulse diode rectifier along with a harmonic reduction method is proposed as the ac/dc conversion stage for a 1.1-MW charging station.

The neutral-point-clamped (NPC) converter is also a promising candidate for the implementation of the front-end AC/DC converter, as illustrated in Fig. 15. Due to its inherent three-level characteristics, this topology features lower voltage stress on devices and reduced input current harmonics. In addition, as a multilevel converter, the NPC converter allows operations at higher dc-link voltage levels for high-power applications [188], [189]. Besides, the NPC converter offers the advantage of lower ripple in the output current and half of the transient in the output voltage. This enables the achievement of high-power density with less inductance [183]. In paper [190], a dc EV charging station at the megawatt level with a bipolar dc bus is proposed by using a single grid-tied NPC converter as the rectifier stage. In this structure, the subsequent dc/dc converter is allowed to connect to half of the dc-bus voltage so that the power capacity of the station is increased. A significant drawback of the NPC topology is the high number of power semiconductor switches. Even though lower voltage-rated switches can be used, the gate drive circuit for each switch leads to complex control. In addition, the utilization of both active semiconductor switches and diodes results in an asymmetrical distribution of losses across the power stage, making thermal management a challenging task [183].

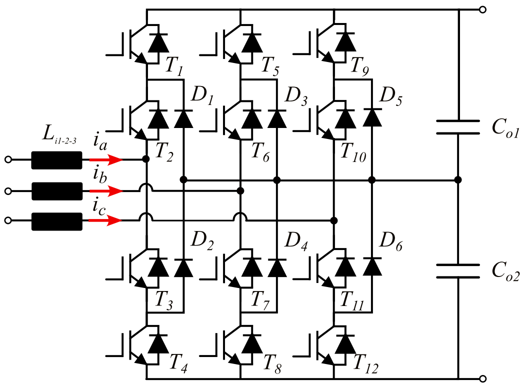


Fig. 15. Front-end ac/dc converter: NPC converter.

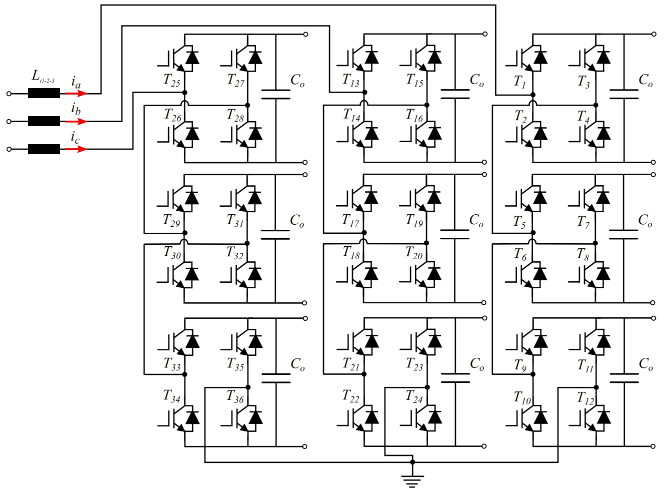
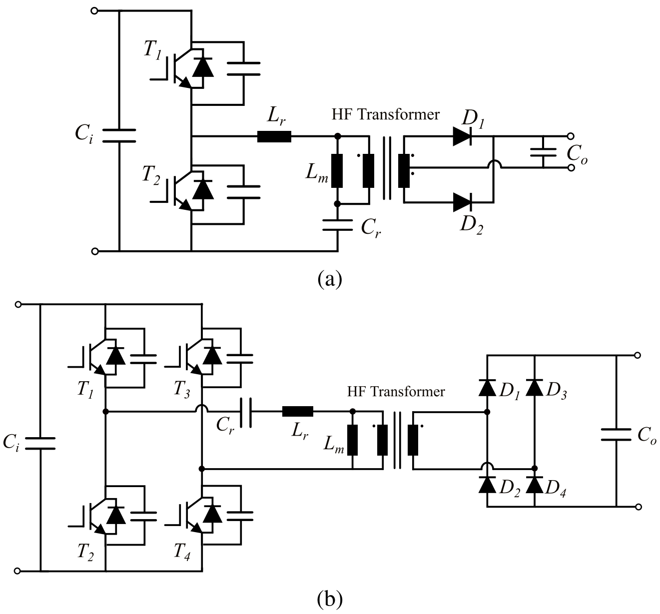


Fig. 16. Front-end ac/dc converter: CHB converter.

Due to its inherent modularity and scalability, the cascaded H-bridge (CHB) converter is well-suited for MV and high-power applications, as shown in Fig. 16. The power rating can be increased by incorporating more modules with the same architecture and control strategy, which enables the integration of redundant modules [191]. In [163], the CHB converter is employed as the ac/dc conversion stage for megawatt-scale charging. In addition, the utilization of the CHB converter allows for a notable reduction in filtering components on the grid side, as the injected currents exhibit minimal harmonic content [174]. Nevertheless, implementing CHB converters requires an isolated dc supply or a specialized transformer with multiple secondary windings per submodule [165].

Table X presents a comprehensive overview of various ac/dc converter topologies, highlighting their respective advantages and disadvantages. When selecting a converter topology, it is preferable to use converter topologies that offer higher efficiency, reduced peak voltage stress, improved modularity, and lower cost. Among these factors, cost is particularly critical as long as the converter topology meets the required harmonics standards and demonstrates comparable high efficiency and reliability.



(a)

(b)

Fig. 17. Isolated dc/dc converter: *LLC* resonant converter. (a) Half-bridge *LLC* resonant converter. (b) Full-bridge *LLC* resonant converter.

B. Isolated DC/DC Converter

After the front-end ac/dc stage, the dc/dc conversion stage is required to regulate the dc voltage and interface the electric aircraft battery directly. It also serves as the interface to onsite battery storage systems and renewable energy sources. Similar to the ac/dc converter, there are various topology options for the dc/dc conversion stage.

One popular topology is the half-bridge *LLC* resonant converter because of its high efficiency and power density, as shown in Fig. 17(a). There are several advantages of this topology, including the zero-voltage switching (ZVS) ability for switching losses reduction, high efficiency at high input voltage, the LV stress on the secondary rectifier diode, galvanic isolation capability, and eliminating the use of inductor in the output filter [192]. Aside from the half-bridge *LLC* resonant converter, there are multiple variants of the *LLC* topology, such as the full-bridge *LLC* topology, as shown in Fig. 17(b), which provides current stress reduction and magnetic core utilization improvement. However, one limitation of this topology is its narrow operating range. This is because its optimal performance is achieved when operating near the resonance frequency, and the output voltage regulation relies on varying the switching frequency. In addition, paralleling and synchronizing multiple *LLC* converter modules are challenging and typically demand external control logic for safety [183].

Advantages including simple control, wide load range, and LV/current stress on power devices make the phase-shifted full-bridge (PSFB) converter an alternative solution for fast charging applications, as illustrated in Fig. 18. In addition, this converter is modular and can be paralleled to achieve higher power [183]. With the phase-shifted PWM technique, ZVS turn-on conditions for the active switches are achieved by the parasitic capacitances of semiconductors and leakage inductance of the transformer [193]. However, one drawback

TABLE X
SUMMARY OF DIFFERENT AC/DC CONVERTER TOPOLOGIES FOR ELECTRIC AIRCRAFT CHARGING

Converter topology	Advantages	Disadvantages	Bidirectional
PWM rectifier (Fig. 12)	Low cost Simple control Reduced input current harmonics	Low power density High peak voltage stress Low efficiency	Yes
Vienna rectifier (Fig. 13)	Low peak voltage stress Reduced input current harmonics High power density High efficiency	DC-link capacitor voltage balancing Limited range of reactive power	No
Multi-pulse rectifier (Fig. 14)	Lowest cost High reliability Very high efficiency	High input current harmonics Unregulated output voltage	No
NPC rectifier (Fig. 15)	Low peak voltage stress Reduced input current harmonics Higher power density Very high efficiency	Complex control High cost Difficult thermal management	Yes
CHB converter (Fig. 16)	Simple control Low peak voltage stress Reduced input current harmonics High efficiency High power density Improved modularity	High cost Isolated DC-link for each sub-module	Yes

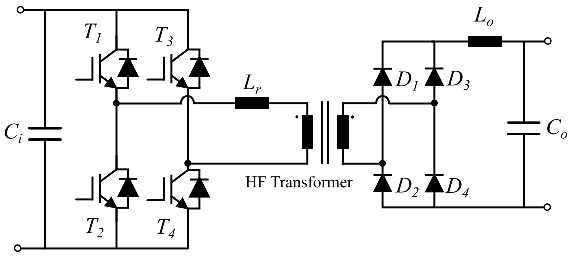


Fig. 18. Isolated dc/dc converter: PSFB converter.

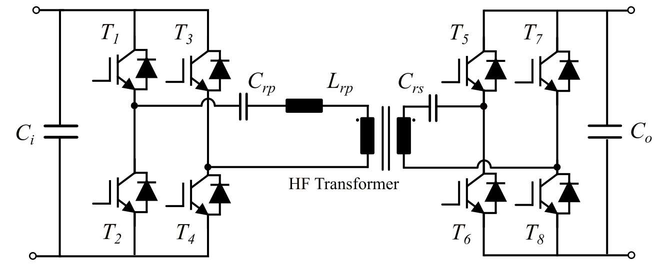


Fig. 19. Isolated dc/dc converter: full-bridge $CLLC$ resonant converter.

of this topology is its high turn-off switching losses in primary switches and the losses in the output diode, leading to reduced efficiency [15]. A number of variants of the phase-shifted ZVS full-bridge converter are proposed to resolve voltage overshoot, ringing, and high losses issues [194], [195], [196]. In [196], a symmetric auxiliary circuit is employed, which guarantees the ZVZCS operation over all load conditions and eliminates the voltage overshoot across the output diode. In [195], the secondary diode bridge of the ZVS full-bridge converter is directly connected to the output capacitor, and the trailing edge PWM gating scheme is applied. Such a novel topology without extra components can achieve high efficiency due to the reduction of the reverse recovery losses in secondary diodes.

For the bidirectional isolated dc/dc converter, the full-bridge $CLLC$ resonant converter is a viable candidate, as shown in Fig. 19. The $CLLC$ converter features ZVS for the primary active switches and ZCS for the secondary side, which can offer high efficiency. In addition, the voltage stress on switching devices is limited to the input and output voltages without the use of clamp circuits. Due to its symmetrical structure, the switch control algorithm is simplified for bidirectional operation [197], [198]. However, the $CLLC$ converter exhibits the tradeoff between efficiency degradation and wide load operation [199]. With a fixed bus voltage, this topology has a very limited output voltage range. In addition, scaling to higher power levels can be challenging, which requires a highly symmetrical tank structure and synchronization of multiple modules [183].

Another option in the isolated category is the dual active bridge (DAB) converter, as shown in Fig. 20. As introduced in [200], the DAB converter can provide ZVS conditions for all active power switches to offer high efficiency. Besides, high power density is achieved due to the controlled action of two active bridges. In addition, the DAB converter features favorable characteristics, including minimum power devices stress, low VA rating of the HF transformer, the capability of a buck–boost operation, and inherent bidirectional power flow. In paper [201], an efficiency-optimized modulation scheme for the DAB is developed, which determines the respective duty cycle for two active bridges and the phase shift angle between two bridges. Table XI provides a summary of various isolated dc/dc converter topologies for electric aircraft charging. $CLLC$ and DAB topologies may not be necessary

TABLE XI

SUMMARY OF DIFFERENT ISOLATED DC/DC CONVERTER TOPOLOGIES FOR ELECTRIC AIRCRAFT CHARGING

Converter topology	**Advantages**	**Disadvantages**	**Bidirectional**
LLC resonant converter (Fig. 17)	High power density High efficiency	Limited modularity Complex control Limited output voltage High peak voltage stress	No
PSFB converter (Fig. 18)	Simple control Wide output voltage Improved modularity Low peak voltage stress	Low efficiency	No
Full-bridge $CLLC$ resonant converter (Fig. 19)	High efficiency Moderate control Low peak voltage stress	Limited output voltage Limited modularity	Yes
DAB converter (Fig. 20)	Wide output voltage Improved modularity Lowest peak voltage stress High efficiency High power density	Inherent reactive current	Yes

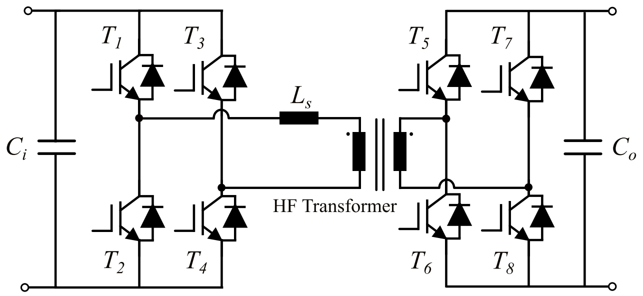


Fig. 20. Isolated dc/dc converter: DAB converter.

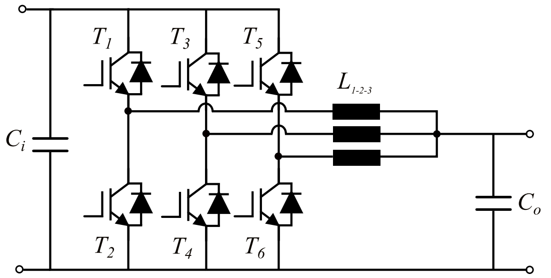


Fig. 21. Nonisolated dc/dc converter: three-phase interleaved buck converter.

due to the limited use case of bidirectional operation. Instead, their corresponding unidirectional versions, LLC and PSFB topologies, can be more suitable and important in future electric aviation applications.

C. Nonisolated dc/dc Converter

As mentioned before, the line-frequency transformer can realize the isolation requirements before the front-end ac/dc conversion stage rather than the dc/dc stage. Thus, the dc/dc conversion stage in the dc fast charger can be nonisolated.

The three-phase interleaved buck converter is an attractive solution for the nonisolated dc/dc topology, as illustrated in Fig. 21. This topology offers better performance in current ripple reduction and exhibits reduced output filter size. Besides, its modularity allows it to be scaled to higher power levels. Moreover, the load-sharing across phases characteristics of the three-phase interleaved converter improve the current-carrying capability at the cost of extra hardware [182]. In [202], the three-phase interleaved buck converter unit is applied in the 125-kW recharging infrastructure operating at the 2-kHz switching frequency, which has advantages including simple topology, low output current ripple, and easy implementation of the phase-shifted gate signal.

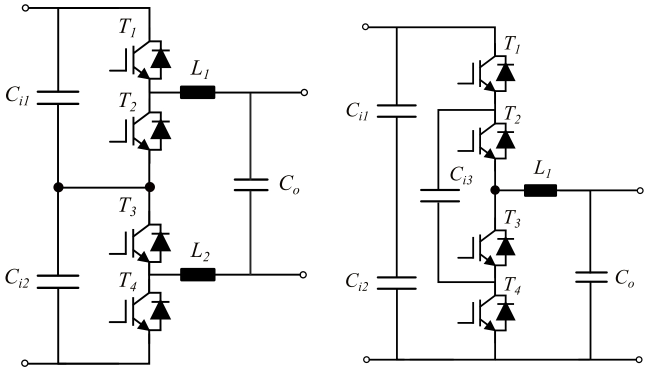
To deal with the high power rating, multilevel power converters receive considerable attention. One of the popular multilevel power converters is the three-level buck converter, as illustrated in Fig. 22(a). The voltage stress on the switches is halved, which opens up the possibility of using active switches in lower voltage ratings with better switching and conduction performance. Therefore, the working efficiency is improved [203]. In addition, the required size of the magnetic component is smaller compared with the two-level buck converter [204]. However, the EMI issue is severe for the three-level buck converter from the perspective of common-mode noise, which is harmful to the battery pack and aircraft avionics [205]. Besides, this topology cannot be paralleled easily. If there is a phase shift between the parallel three-level phase legs, it can lead to significant circulating currents unless interphase inductors are employed [206].

A flying capacitor can be integrated into the three-level buck converter to achieve a reduced size of the inductor by decreasing the volt-second across the output inductor, as illustrated in Fig. 22(b) [207]. In contrast to the three-level buck converter, the three-level flying capacitor converter has a lower EMI and better scalability and interleaving capability due to its structure. However, the drawback of this topology is the long loop for switching communication of devices between the dc bus capacitor and the flying capacitor. In addition, the design of short-circuit protection is difficult due to the existence of the flying capacitor [205]. Table XII provides

TABLE XII

Summary of Different Nonisolated DC/DC Converter Topologies for Electric Aircraft Charging

Converter topology	**Advantages**	**Disadvantages**
Three-phase interleaved buck converter (Fig. 21)	Simple control Improved modularity Low current ripple Increased current-carrying capability	High peak voltage stress Higher cost
Three-level buck converter (Fig. 22a)	Low peak voltage stress Reduced current ripple Lower cost	Limited modularity High EMI
Three-level flying capacitor converter (Fig. 22b)	Low peak voltage stress Improved modularity Lower cost Lower EMI	Difficult short-circuit protection



(a) (b)

Fig. 22. Nonisolated dc/dc converter: three-level converter. (a) Buck converter. (b) Flying capacitor converter.

an overview of various nonisolated dc/dc converter topologies for electric aircraft charging.

It is important to note that although dc/dc converters with buck capability are widely employed in EV chargers, their applicability to electric aircraft batteries is limited due to the growing trend toward higher battery pack voltages, such as 800 V or higher. Considering the existing LV local distribution networks, the battery pack voltage may be higher than the output voltage of the front-end rectifier. As a result, using a dc/dc converter with boost or buck/boost capability becomes necessary to achieve the desired output voltage for battery charging. Alternatively, a reconfigurable dc/dc converter could be employed to achieve a wide output voltage operating range, with the output voltage of the converter being twice that of a single secondary side via the series connection. This approach could offer greater flexibility in adapting to different charging requirements while also maintaining high system efficiency [208].

VI. Electric Aircraft Charging Stations: Challenges and Future Trends

Despite the lower fuel cost, quieter operation, and reduced environmental impact, there are still challenges associated with aviation electrification. The charging infrastructure is one of the major obstacles to electric aircraft adoption. As outlined in the previous discussion, the implementation of electric aircraft charging infrastructure, particularly in the context of XFC, presents several significant challenges that must be addressed.

A. Battery Technology Development

1) Advanced Battery Chemistry: Key gaps in battery technology need to be overcome to enable XFC. First, advancements in battery chemistry are crucial. At the cell level, developing advanced negative electrode materials with both fast reaction kinetics to prevent lithium plating and low potential to enable high energy content is essential. In addition, better positive electrode materials that are more resistant to stress-induced failure and improved electrode designs that facilitate fast diffusion in and out of the electrodes are necessary. Furthermore, future research on the XFC impact on advanced battery cell materials should be undertaken, such as silicon negative electrodes and lithium metal negative electrodes, which is crucial for optimizing battery design and improving their overall performance [17]. Aside from the solutions mentioned above, the nanoelectrofuel flow battery technology is also a viable solution, while the charging is realized by battery fluids replacement [209].

2) Thermal Management: Second, thermal management will be challenging for the battery packs during XFC. To address thermal issues, the future thermal management system needs to enable improved heat transfer from cell to liquid coolant to ensure a uniform temperature within the pack and cell while adhering to the volume constraint. In addition, the best technique for heat rejection outside the pack needs to be determined [17]. Novel thermal management strategies, such as jet impingement or immersion of the battery in a dielectric fluid, may be necessary to maintain the battery temperature below the maximum operational limit. In addition, the improvement of the thermal efficiency of positive and negative electrode materials, as well as the optimization of the cell thermal design, is necessitated to meet the performance requirement, safety, and lifetime expectations [58]. Moreover, there is a possibility of utilizing an off-board thermal management system to provide cooling for electric aircraft batteries during the charging process.

3) Safety: Higher pack voltage and charging rate necessitate additional safety measures. First, specific protection components, such as the CAFCI and different relays, are needed to avoid dielectric breakdown. In addition, advanced BMSs are needed to continuously monitor the battery pack status to detect abnormal behavior and prevent catastrophic failures. Moreover, the use of digital twin technology can significantly improve battery performance by providing a virtual replica of the physical battery pack.

4) Advanced Charging Strategy: From the charging strategy perspective, advanced charging strategies should be investigated to optimize battery performance and minimize lifetime degradation, which can potentially be model-based and closed-loop. Two critical components are necessary to achieve this: first, a high fidelity, simplified, and controllable battery model; second, an optimal control strategy that is both computationally efficient and well-suited to the battery model [155].

B. Cables' Weight Limitation

To achieve XFC, a higher charging current is required. However, for a typical 400-V battery pack, the charging current is constrained by the practical charging cable size. There are several solutions to overcome this cable weight limitation.

1) Higher Battery Pack Voltage: The first promising approach is moving toward a higher battery pack voltage level, such as 800 or over 1000 V [84]. However, moving toward a higher voltage battery pack creates difficulties for electrical safety, including arc hazards and partial discharge. Hence, it is necessary to develop cables that can prevent the potential of dielectric breakdown and the ensuing leakage current. In addition, more advanced and robust control and management algorithms of battery packs are required because of the increased number of cells in the series string [17].

2) Liquid Cooling Cable: The second option to solve the cable weight limit is using the liquid cooling cable, which can achieve a thinner and lighter cable. Liquid coolant is circulated via the charging cable and between the charger and connector [210]. The load of the cooling system is determined by the battery pack size, chemistry, design, and maximum allowable temperature deviation during the charging process for specific charging power [137]. However, it is important to note that thin liquid cooling cables result in lower efficiency due to higher cable resistance and losses in the cable.

3) Automated and Inductive Charging: To handle the bulky charging cable, the third solution is automated charging, which can start the charging process without human interaction, including pantograph, QCC, and robotic arm. With the use of a charging robotic arm carrying the charging connector and cable, the insertion and disconnection of charging plugs into charging inlets can be performed intelligently and autonomously [118], [211], [212]. Another approach to address the issue of heavy cables is inductive charging, such as wireless power transfer. Inherent galvanic isolation is provided by the inductive charging method. In parallel, removing mechanical contact allows for improved safety, higher reliability, and better utilization of turnaround time. To date, a high-power inductive charging system exceeding 1 MW has been demonstrated in the laboratory for the marine sector [213]. However, both pantographs and wireless power transfer systems pose challenges to cost, package, and efficiency [107]. Furthermore, wireless charging presents potential EMI issues that could affect sensitive aviation and lightning arrest systems [20].

C. Power Conversion Design Considerations

1) Power Electronic Building Blocks: In an effort to accept the increasing charging powers required by electric aircraft and supply the whole range of dc chargers, modular power electronics technologies with features such as "power electronic building blocks (PEBBs)" are adopted by several manufacturers. Typically, the subunit ranges between 10 and 75 kW. Modular design streamlines the power expansion, increases the system reliability, and improves efficiency at different load conditions, which paves the way for charging electric aircraft [14], [182]. However, intricate interactions among multiple modules increase the complexity of the control system [214].

2) Wide Bandgap Devices: From the voltage perspective, the utilization of silicon devices is limited by higher voltage and prices, as well as a rise in switching losses. The status quo for mass market equipment is 1.2 kV [107]. To overcome the limitation of Si power devices, wide bandgap (WBG) devices, such as SiC, are preferred as they can operate at higher voltage, switching frequency, and temperature [215], [216]. Currently, SiC MOSFETs have commercially available devices with blocking voltages of 650 and 900 V and 1.2, 1.7, and 3.3 kV. Samples of 10-kV SiC MOSFET products are already available for purchase from various suppliers [217]. However, efforts are needed for mass deployment. The high cost of SiC devices is one of the serious concerns, which makes this technology less competitive [218]. Besides, the design of gate drivers, as well as other sensing and control components, would require modifications to accommodate the higher isolation requirements associated with the higher voltage levels [219].

D. Grid Impact Mitigation

Large penetration of electric aircraft also brings challenges to the grid since the charging power drawn from the power system is very high. The issues induced by the overload distribution equipment can be summarized as peak demand, voltage fluctuation, and harmonic distortion [122], [181], [220], [221], [222], [223]. It is obvious that the grid infrastructure can be upgraded to solve these problems. However, this approach can turn out to be very costly [224].

1) Integration of Local Energy Storage and Renewable Generation: To avoid expensive upgrades in the power system, local energy storage systems and onsite renewable energy generation sources can be integrated into the charging station to supply the large pulsating load. Consequently, the charging power drawn from the power system is reduced, which avoids the heavy power lines installation for the station.

2) Smart Charging: Another option to mitigate the grid impact is smart charging, which is widely studied for EVs [225], [226], [227], [228], [229], [230], [231]. Similarly, in the context of electric aircraft, the smart charging technique can help in two ways. First, since the aircraft operation is typically schedule-based, there are moments when the parking time exceeds the required charging time, such as during nights or periods of reduced flight demand. In such situations, using smart charging, i.e., controlling the charging power or scheduling based on local renewables generation or grid congestion, can effectively manage the charging load, thereby reducing the grid impact associated with electric aircraft charging. In [232], a smart charging algorithm is proposed for hybrid-electric aircraft, which can reduce the peak power demand significantly with slight alterations of flight schedules. Second, controlling the charging power intelligently based on the battery SOC, battery chemistry, thermal management system, and environmental conditions can significantly help reduce charging times and extend the battery lifetime. Besides, the battery-swapping concept allows for more flexibility in applying smart charging techniques. However, during periods of peak traffic and limited charging time, the priority is to charge the aircraft as quickly as possible.

VII. CONCLUSION

With growing concern over the effects of climate change, there is rapid development in the electrification of the transport section, including aviation. Despite the increasing interest in electrifying air transport, the lack of charging infrastructure is one of the stumbling blocks that hinder the mass deployment of electric aircraft. Therefore, it is imperative to establish charging infrastructures with performance on par with the existing fuel-refueling infrastructure to guarantee the high utilization rates of electric aircraft and, thus, maximize revenues.

In conclusion, this article has provided a comprehensive review of the charging technologies for electric aircraft. It has highlighted the importance of advanced battery chemistry at the cell level to meet the demands of frequent fast charging without compromising battery lifetime and incurring safety issues. At the battery pack level, proper thermal management and safety considerations are crucial. Besides, advanced charging strategies are required to enable short turnaround time without deteriorating battery performance. To facilitate electric aircraft charging, an emerging trend is higher onboard battery pack voltage, such as 800 or over 1000 V, which are beneficial for both onboard electric propulsion power transmission and off-board charging cabling. Several other potential solutions to address the cable-related issue include liquid cooling cables, automated charging, and inductive charging. By exploiting the state-of-the-art chargers for electric aircraft, emerging charging standards tailored to electric aircraft and specialized charging plugs capable of delivering megawatt charging are discussed.

This article has also explored charging infrastructure design, including different architectures, such as ac and dc local distribution networks. It has emphasized the suitability of dc distribution for future electric aircraft charging infrastructure. Besides, the potential of individual single-stage chargers and multiplug charging systems in aviation applications is investigated. The discussion on power electronic converter topologies highlights the critical parameters relevant to electric aircraft charging applications. Furthermore, in addition to conventional converter topologies, using nonisolated dc/dc converters with boost or buck/boost capability is envisioned for electric aircraft chargers. From the grid perspective, the importance of grid upgrades and investment in local grids, including onsite energy storage and renewable energy sources' integration and smart charging techniques, has been emphasized. It is evident that the success of electric aircraft charging relies on complete standardization, enhanced battery technologies, efficient charging systems, and grid infrastructure upgrades to meet the demanding power requirements.

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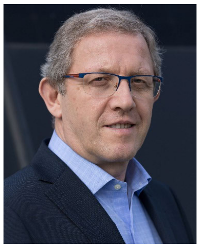

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