Overview of electric aircraft and charging infrastructure: current development and EMC standards

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Abbreviations

ASTM	American Society for Testing and Materials
CAAC	Civil Aviation Administration of China
DLR	German Aerospace Center
EASA	European Union Aviation Safety Agency
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
eVTOL	Electrical Vertical Take-off and Landing
FAA	Federal Aviation Administration
IATA	International Air Transport Association
ICSA	International Coalition for Sustainable Aviation
NASA	National Aeronautics and Space Administration
SAE	Society of Automotive Engineers

1. Introduction

The environmental effects of aviation on climate change have become a major driving force for the development of electric aircraft. According to the International Air Transport Association (IATA), aviation makes up 2.4% of the total global carbon dioxide emissions from fossil fuels and this number has increased by 32% from 2013 to 2018 [1]. The International Coalition for Sustainable Aviation (ICSA) warns that without serious action, aviation could account for more than a fifth of global carbon emissions by 2050 [1]. The UN predicts global "human-caused" carbon emissions need to fall by about 45% from 2010 levels by 2030 and reach net zero by around 2050. In order to achieve this objective, the development of fossil free aircraft is a key part. Besides zero emission, another benefit of electric aircraft is the potential for noise reduction. A study published by magniX indicates that the noise level of an electric airplane could be 100 times lower than that of a traditional plane [2].

So far, most research regarding electric aircraft focuses on safety and battery durability. Electromagnetic compatibility (EMC), however, is not at present in focus. There are currently no global standards about EMC requirements specifically for electric aircraft and their accessories. Electric aircraft, as well as their charging infrastructure which contain powerful electronics and high voltage up to a few hundreds of volts, are subjected to EMC problems just like any other electronic equipment. On one hand, they might be affected by interference from equipment in the vicinity; on the other hand, they might become an interference to surrounding equipment, for example, communication systems at an airport. Previous study suggests that charging stations for electric vehicles might produce radiated emission that exceeds the limits for class B equipment in IEC 61851-21-2 [3]. Another study shows that they might generate harmonic currents that exceeds the limits in IEC 61000-3-2 [4]. Therefore, it is reasonable to assume that the same problems might occur to charging stations for electric aircraft and it is significant to take EMC into account when designing charging stations and installing them at airports.

This report is one part in a project which investigates interactions between charging stations and other electronic equipment in an airport environment. The task is to determine the level of interference produced by charging stations for electric aircraft and then quantify the influence of the interference. As a starting point, tThis report provides an overview of the current developments of electric aircraft and their charging stations with an emphasis on EMC. In chapter 2, an introduction of electric aircraft is presented. In chapter 3, techniques for charging electric aircraft are provided. In chapter 4, the key points of IEC 61851-21-2, EMC requirements for off-board electric vehicle charging systems, is summarized and chapter 5 is the conclusion.

2. Electric aircraft

An electric aircraft is an aircraft powered by electric motors. It can be either fully electric or hybrid electric. Two major types of energy storage technologies for electric airplanes dominate the field: battery electric and hydrogen fuel cell electric. This chapter will not go into depth regarding technological details, only an overview of current situation will be reviewed. There are over 100 electric aircraft, most of which are prototypes, that are under development in more than 10 countries and a list of them can be found in [5]. In addition, a summation of the current status of electric aviation can be found in [6], from which most of the contents in this chapter are quoted.

2.1 Battery electric aircraft

A battery electric aircraft is an electric aircraft that stores its energy in batteries. Some electric aircraft are described in this section.

The Slovenian company Pipistrel has developed three electric aircraft. Pipistrel's Taurus Electro model was the first two-seat electric airplane in serial production available on the market in 2007. The airplane was powered by a 40 kW Li-based battery technology [7]. Today, the Pipistrel Alpha Electro is the world's first electric airplane intended for flight training. It has a flight time of 1 hour plus a 30-minute reserve. The theoretical range is 600 km. The electric motor is 60+ kW and weighs 20 kg. The 21 kWh battery pack can either be replaced in minutes or recharged in less than an hour [8]. The aircraft is certified in accordance with Federal Aviation Administration (FAA) regulations [9]. Pipistrel has a third model, the Pipistrel Velis Electro, which in June 2020 became the world's first EASA-type certified electric airplane. It is fully approved for pilot training. The Velis Electro has an entirely liquid-cooled powertrain, including the batteries. This is next generation technology that enables about a doubling of the powertrain lifetime. Flight training is the main purpose for the Velis Electro. The commercial range is around 100 km or 50 minutes [10].

Pure flight is a Czech company that has developed the electric airplane Phinix or ΦNIX. Its first flight was in 2018, and the airplane is certified in accordance with ELSA (Experimental Light-Sport Aircraft) regulations [11]. The two-seat plane is powered by a 60 kW battery and the flight range is 2.5 hours [12]. In 2019, the company performed winter-climate test flights in northern Sweden [13].

Bye Aerospace is an American company located in Denver. They started in 2014 to develop the eFlyer 2 and eFlyer 4. The eFlyer 2 will be used for pilot training and is equipped with 90 kW electric power [14]. The eFlyer 2 had its first test flight in 2018, and the goal is FAA and EASA certified during 2021. Its flight time is three hours [15]. The eFlyer 4 is aiming for air taxi, cargo and advanced training uses. In April 2021, Bye Aerospace announced the eight-seat eFlyer 800. This electric aircraft will be equipped with two wing-mounted electric motors. The eFlyer 800 is powered by solid state lithium-sulphur batteries being developed by Oxis Energy, a U.K. startup. The power needed in the battery cells is 550 kWh/kg. The Li-sulphur batteries are 60% lighter than Li-ion batteries, because there is less shielding required to prevent thermal runaway when the cells are assembled into packs. Sulphur is effective as a fire retardant for the highly flammable lithium in the battery. The eFlyer 800 will have a maximum range of 930 km at a cruising speed of 520 km/h. According to Bye Aerospace, operating costs will be one fifth of conventional twin turboprop aircraft. Market introduction is planned for between 2024 and 2026 [16].

RX1E aircraft is China's first electrical two-seat aircraft developed by Liaoning Ruixiang General Aircraft Manufacture Co., Ltd in 2016 [17]. It has a certificate from the Civil Aviation Administration of China (CAAC) and under the American Society for Testing and Materials (ASTM) standard. It has also a mass producer license. Its power is 30 kW. The RX1E is similar to Pipstrel Alpha Electro with six Kokam battery packs that can be removed for recharging [18]. Another two-seat model, the Ruixiang Extended Range Electric Aircraft (RX1E-A), had its first test flight in 2018 [19].

MagniX is a company founded in Australia in 2009 and now located in Seattle. It creates electrical motors designed to replace conventional engines [20]. The electrical motor magni250 produces 375 horsepower (280 kW) for smaller airplanes, such as the nine-seat Eviation Alice aircraft. The magni500 is a 750-horsepower (560 kW) electrical motor designed to fit in models like the de Havilland Beaver, Cessna Caravan and Beechcraft King Air. The range will be around 160 km [15]. In 2019, the Havilland Beaver, retrofitted with the magni500 system, made its first flight in Vancouver, Canada. It is operated by Harbour Air and is intended for short flights (30 minutes plus 30 minutes back-up) to the nearby villages from Vancouver. A certification process was started after the demonstration flight and will take around two years [21] [22]. The first 30-minute test flight with a turboprop aircraft, the nine-seat MagniX's 208B Cessna Grand Caravan, took place in 2020 in partnership with AeroTec. The aircraft was equipped with the magni500 engine [23]. The MagniX electrical engines has a lifetime of around 30,000 hours, which is a lot more compared to conventional engines used today [6].

Heart Aerospace is a Swedish start-up developing a 19-seat electric aircraft, the Heart ES-19. Its range is 400 km, and it has a cruising speed of around 300 km/h for aluminium aircraft. The aircraft will be equipped with 4 engines of 400 kW each, which means a total power of around 1600 kW. The engines will be powered by 4 batteries of 180 kWh each [24]. The goal is to have the aircraft certified and ready for commercial flights in 2026. The plane should be able to use short runways, 750 m, and focuses on regional travel [25]. The company is working a lot with simulations to develop the aircraft. In late 2020, the electric propulsion system was ready, and real tests have started [26].

Eviation is an Israeli start-up developing the electric aircraft Alice. It is a nine-seat plane (plus 2 crew) with a range of 1000 km, a cruising speed of 410 km/h and a Li-ion battery with usable 920 kWh [27]. The aircraft will use the electric motor from MagniX [28]. In 2019, the company announced that American-based Cape Air will include Alice in their 92 plane fleet. The goal is to be EASA and FAA certified in 2022, but the project might suffer from delays since the prototype caught on fire in January 2020 [29]. However, the goal is to perform the first test flight in 2021 [30].

Wright Electric is an American company developing the aircraft model Wright 1 in cooperation with Easyjet. Wright 1 has 186 seats and multiple electric propulsion systems under each wing. The plan is to be ready in 2030. The range will be 500 km to start with, but the goal is to attain a range of 1280 km [31].

2.2 Fuel cell electric aircraft

Aircraft powered by fuel cells store their energy for the engines in the form of hydrogen, which is converted into electricity through the fuel cells. In this section, a number of hydrogen-based aircraft are introduced.

ZeroAvia is located both in United Kingdom and the United States. In June 2020, ZeroAvia held the first test flight of the six-seat Piper M-class equipped with an electrical motor. In September 2020, the first test flight with the Piper M-class aircraft powered with hydrogen and fuel cells was done in Cranfield, UK [32]. It was equipped with a system from the Swedish company Powercell [33]. The next step is a 400 km zero emission flight. ZeroAvia is also working towards having a 19-seat aircraft that uses fuel cells instead of batteries ready for the market by 2023. It will have a range of 560 km and be equipped with a 600 kW hydrogen-electric powertrain [34]. The company also hopes to have an aircraft for 50 to 100 passengers in 2030 and for around 200 passengers in 2040 [35].

H2FLY is a German spin-off from the German Aerospace Center (DLR). The company operates the HY4, which was developed by DLR, H2FLY, Pipistrel, Stuttgart Airport, Hydrogenics and the University of Ulm [36]. HY4 is a four-seat aircraft powered by a hydrogen fuel cell system with electrical propulsion. The 80 kW motor has a cruising speed of 145 km/h and a range of 750 to 1500 km. The HY4 has a special design with two fuselages, each with room for two passengers. In 2016, the HY4 made a successful test flight. A lithium battery was covering peak power loads during take-off and when climbing [37]. In November 2020, the HY4 made 35 take-offs, flying up to 2 hours per flight using a hydrogen powertrain within the EU project Modular Approach to Hybrid-Electric Propulsion Architecture (MAHEPA). H2FLY has also announced two additional aircraft: a six to 19 seater for 2027 and a 40 seater for 2030. The six to 19 seater will be powered by a 300 kW hydrogen propulsion system (peak power 425 kW). Range will be up to 1500 km and it will have a maximum cruise speed of 370 km/h. For the 40 seater, a 1.4 MW hydrogen power system (3 MW peak power) will enable a maximum range of 1850 km and a cruise speed of 520 km/h [38].

Pipistrel not only works with battery electrical aircraft but also with a model called Miniliner, which has a hydrogen based propulsion system. It is a 19-seat aircraft, with a range of 200 to 1000 km and capable of operating quietly from runways shorter than 1 km, including grass airstrips at small aerodromes. The airplane is being developed within the EU-funded project Community Friendly Miniliner (UNIFIER19), and the first step was announced in April 2021. Pipistrel aims for a market introduction in 2028 to 2030 [39].

The company HES Energy Systems, originally from Singapore, works together with Aerospace Valley in Toulouse. In 2018, the aircraft Element One was announced, which is designed to fly four passengers for 500 to 5000 km, depending on whether the hydrogen is stored in gaseous or liquid form. There is no more recent news on the development status of the aircraft [40].

APUS is a German company working with two programmes: the APUS i-5 flying testbed arena for hybrid electric aircraft together with Rolls-Royce and development of the hydrogen powered APUS i-2 aircraft. The APUS i-2 is a four-seat aircraft with a range of 800 km that utilises the APUS TubeStruct technology, which permits up to 25% higher specific energy density compared with standard hydrogen fuel tanks [41]. According to the report by the consultant company Roland Berger, the project was announced in 2019 [42]. There is no more recent information on the status of the project.

The American based Universal Hydrogen is working together with MagniX to retrofit a De Havilland Canada DCH-8 Q300. This is a 56-seat commonly used type of aircraft that will be powered by a fully electric fuel cell powertrain. Due to the large hydrogen modules, the aircraft will have a reduced capacity of 40 seats. The aircraft will be powered by a pair of two-megawatt Magnix electric motors. The hydrogen will act as a battery, producing electricity as it runs through the fuel cells. The range will be 740 km and the plane will be ready for market in 2024 [43].

In addition to fuel cells, hydrogen can be directly utilized in engines through combustion. Airbus hopes to develop a zero-emission aircraft by 2035 based on a hybrid-hydrogen powertrain. Modified gas turbine engines are powered through hydrogen combustion. They work based on three concepts: turbofan, turboprop and blended-wing body. The turbofan concept uses two hybrid-hydrogen turbofan engines to power the plane. The turboprop concept is powered by two hybrid-hydrogen turboprop engines. In both cases, a liquid hydrogen storage and distribution system is used. The third concept, the blended-wing body, looks different from a traditional aircraft. The aircraft is powered by two hybrid-hydrogen turbofan engines and the liquid hydrogen storage is underneath the wings [44]. No additional technical information about the different aircraft has been found.

2.3 Hybrid electric aircraft

There are two types of hybrid electric aircraft: parallel hybrid and serial hybrid. A parallel hybrid is a plane with both an electrical engine and an internal combustion engine, which work in parallel to provide thrust for the aircraft. In a serial hybrid, the propellers are powered by one or several electrical motors and the electricity comes from batteries or fuel cells and from a generator powered by a turbine engine.

Ampaire is an American company developing a hybrid electric aircraft called the Electric EEL. The aircraft is a converted conventional three-seat Cessna 337 (Skymaster). One of the two motors are powered by a pack of batteries. It has a range of 640 km. The first test flight in 2019 used both the conventional and the electric powertrains. Ampaire is working with Mokulele Airlines in Hawaii to demonstrate the benefits of electrical flying [45]. In November 2020, the Electric EEL aircraft had a 20-minute flight from Maui’s Kahului Airport across the island to Hana and back on a single charge. It was the world’s first demonstration flight along an actual airline route [46]. Ampaire is also working on future projects, including rebuilding of a 19-seat DHC6 (Twin Otter) turboprop aircraft into the Eco Otter SX. The range of this hybrid electric plane will be 320+ km using a 1 MW power source. This project is in cooperation with National Aeronautics and Space Administration (NASA) [47]. The company aims to receive FAA certification in 2023, with passenger service commencing in 2024 [48].

American Zunum Aero is developing a hybrid electric aircraft intended for market introduction in 2023. This 12 seater will have a range of 1100 km and an engine that powers the electrical generator for the aircraft. This generator will supplement stored energy in the plane's batteries with a peak power of 500 kW during key stages of flight and over long ranges. The aircraft will be able to cruise and land on turbo-generator power alone, offering full redundancy [49].

UK-based start-up Faradair is developing the 18-seat propeller-driven triplane BEHA M1H. The aim is to be ready for market in 2026 and to produce 300 planes by 2030 [50]. At the end of 2020, the company announced a cooperation with MagniX for providing electrical motors for the aircraft. The aircraft is being built as a hybrid electric, with a biofuel-powered generator providing electricity to a pair of 750 horsepower MagniX motors [30].

Boeing and NASA are collaborating on Subsonic Ultra Green Aircraft Research (SUGAR) to develop a hybrid electric aircraft (Boeing Sugar VOLT hybrid) [51]. Not much information is available from after 2017, other than it will have 135 seats and be ready for the market in 2030–2050 [52].

The British Electric Aviation Group (EAG) has designed a 70+ seat Hybrid Electric Regional Aircraft (HERA), which will be ready for market in 2028. It will have a range of 1480 km, and the hybrid electric powertrain is designed to be able to switch to fully electric without requiring any mechanical retrofitting [53].

2.4 Electric vertical take-off and landing

Electrical aviation is an exciting and innovative field, and the electrical vertical take-off and landing aircraft (eVTOL) are perhaps the most ground-breaking approach. The concept of eVTOLs is basically a merger between a helicopter/drone and an aircraft. eVTOLs can do vertical take-offs and landings, during transit are able to utilize the aerodynamic benefits of having wings in forward movement.

As far as infrastructure goes, this gives the eVTOL a major advantage as it only requires a flat surface to land and take off from. As interesting as eVTOLs are, they are a different type of electrical aircraft. Their estimated range are mostly around 30–35 km and usually designed to be able to carry two passengers together with luggage [54]. This makes them not an alternative for commercial flights but rather a new type of taxi transportation, independent of conventional roads. At this point in time, eVTOLs are primarily a future competitor to taxicabs. However, as development progresses, it seems like an eVTOL is closer to market introduction at this time than an electric aircraft for passenger transport.

3. Charging infrastructure of electric aircraft

Charging infrastructure for electric aircraft needs to provide a plug that can be connected to the aircraft with a certain effect. In this early stage of electric aviation development and implementation, charging stations will probably be mobile and provided by the aircraft company.

Electrical demand depends on how the aircraft is operated. For a quick stop at an airport, fast charging is required, and for longer times on the ground, slow charging requiring a lower capacity is needed. Battery backups is another option for using slow charging systems for fast charging of an aircraft.

The time required for charging depends on battery capacity, state of charge and time available to charge. If the aircraft is capable of a battery swap, the depleted batteries could be charged at a slower rate [55].

In May 2020, the first charging station in Sweden was inaugurated at Dala Airport AB in Borlänge. Dala Airport AB, AB Dalaflyg and Fyrstads Flygplats AB (Trollhättan-Vänersborg) had received financial support from Klimatklivet, which is a subvention from the Swedish Environmental Protection Agency for measures contributing to reduction of carbon emissions [56]. The charging stations are of the same type as fast chargers for electric cars and were installed by Hybrida in cooperation with the battery charging company CTEK [57]. Skellefteå Airport provides a power supply of 1 MW at airside. This will allow electric aircraft with their own charger to connect and charge. By providing a connection point, electric aircraft can use the airport even though there are no charging standard in place yet.

Pipistrel has their own charging infrastructure that can be connected to the grid through a mobile charging station or through an installed fast charger able to charge two or four airplanes simultaneously. The charging station for two aircraft has a power of 2 x 20 kW. The time to fully charge a Pipistrel Alpha Electro (60 kW power) is one hour [58]. ByeAerospace aircraft eFlyer2 and 4 uses the same standard as fast chargers for electric cars [59].

The Australian company Electro.Aero presented their mobile DC charger with a power of 30 kW in 2019. It is able to handle 300 to 1000 V depending on the infrastructure at the airport. The charger is constructed to connect to 3-phase 50 A and fit under the wings of most aircraft [60].

In Hawaii, the company Ampaire has started a one-month demonstration programme along a commercial air route. For the flight trials, the only change to ground equipment was the requirement to wire a Mokulele hangar with a 3-phase outlet. Ampaire has been working with the Hawaii Department of Transportation and the Hawaiian Electric Company to explore longer-term infrastructure solutions to support a fleet of hybrid or fully electric aircraft [61].

4. EMC standards of charging infrastructure

4.1 Current status

There is currently no global standard for charging aircraft at airports. In fact, there are no global standards at all when it comes to heavy duty vehicles or aircraft. But there are organizations working towards establishing a global standard, the biggest of whom seems to be CharIn [62]. They started working on developing a standard under the name High Power Charging for Commercial Vehicles (HPCCV). This standard, according to CharIn, would handle up to more than 2 MW and be used for charging in the range of 200–1500 V and 0–3000 A. That should be enough to meet the needs of heavy-duty electric vehicles with battery pack as large as around 1 MWh [63]. In the autumn of 2020, the first prototypes were shown when the National Renewable Energy Laboratory (NREL), in partnership with CharIn hosted an event for testing and evaluating high-power EV charging connectors currently under development by the industry. This is part of development by vehicle and equipment manufactures on HPCCV, which has been renamed Megawatt Charging System (MCS) and is based on the Combined Charging System (CCS) standard. MCS are for outputs beyond 1 MW [64].

Parallel to the work by CharIn, the standardization organization Society of Automotive Engineers (SAE) is also working on high-power charging. There are, however, no concrete specifications related to electric aircraft [65]. So standardization is still very much a work in progress. As a consequence, today's solutions for electric aircraft in operations are to bring their own charger or use the same standard as for cars. In the next section, the EMC standard for electric vehicle charging stations will be introduced.

4.2 Introduction to IEC 61851-21-2: 2018

The IEC 61851-21-2 defines the EMC requirements for any off-board components or equipment of such systems used to supply or charge electric vehicles with electric power by conductive power transfer (CPT), with a rated input voltage, according to IEC 60038: 2009, up to 1 000 V AC or 1 500 V DC and an output voltage up to 1 000 V AC or 1 500 V DC [66]. The latest version is 1.0, which was published in 2018.

The standard defines two test environments: class A for non-residential environment and class B for residential environment. All the tests are performed based on the methods in the IEC 61000 series.

For immunity, tests shall be performed in the following two operating modes: 1. Waiting mode-to simulate when the EUT is fully powered up and connected to a vehicle but not charging (for example, when the batteries are fully charged or if waiting for the power grid to decide when to charge); 2. Charge mode- during testing, the EUT shall be operated at 20 % of the maximum rated power ±10 %. If this is not possible according to IEC 61851-1 : 2017, the percentage may be raised.

A functional description and a definition of performance criteria during, or as a consequence of, the EMC testing shall be provided by the EUT manufacturer and noted in the test report

Table 1. Immunity tests defined in IEC 61851-21-2: 2018.

Phenomenon	Basic standard	Performance criteria
Electrostatic discharge (ESD)	IEC 61000-4-2:2008	B
Radiated RF fields	IEC 61000-4-3:2006/AMD2:2010	A
Electrical fast transients/bursts	IEC 61000-4-4:2012	B
Voltage surges	IEC 61000-4-5:2014	B
Conducted RF fields	IEC 61000-4-6:2013	A
Voltage dips and interruptions	IEC 61000-4-11:2004 (≤ 16 A) IEC 61000-4-34:2005/AMD1:2009 (> 16 A)	B

Table 2. References for evaluation of low frequency (LF) phenomena in IEC 61851-21-2: 2018.

Phenomenon	Basic standard
Harmonic currents	IEC 61000-3-2:2014 (≤ 16 A/phase) IEC 61000-3-12:2011 (> 16 A, ≤ 75 A/phase)
Voltage fluctuations and flicker	IEC 61000-3-3:2013 (≤ 16 A/phase) IEC 61000-3-11:2017 (> 16 A, ≤ 75 A/phase)

based on the following criteria: 1. Criteria A-The EUT shall continue to operate as intended within the tolerances defined by the EUT manufacturer during and after the application of the appropriate tests. It shall not change the state in which it is operating; 2. Criteria B-The EUT shall continue to operate as intended within the tolerances defined by the EUT manufacturer at the completion of the applicable tests. Additionally, during the application of the appropriate tests the primary functions of the charger shall be maintained. Secondary functions may degrade in performance during the test but shall resume to the original condition subsequent to testing; 3. Criteria C-During and after completion of the appropriate tests, the EUT can change to a failsafe condition. This state requires user intervention to restart the charge cycle or the automatic resumption of charging if the safety conditions have been fulfilled as defined in IEC 61851-1:2017.

The immunity requirements are specified in Table 1 according to the type of power input (AC or DC) and environmental classification (residential or non-residential) of the EUT to be tested.

For emission, tests shall be performed in the following operating modes: 1. 20 % of maximum rated power ±10 % (if this is not possible according to IEC 61851-1:2017 the percentage may be raised); 2. 80 % of maximum rated power ±10 %; 3. with any load allowing the operation of the electrical vehicle supply equipment (EVSE), if the power input and output are directly connected in charge mode. In this special case, testing with 20 % and 80 % is not necessary. The operating mode for testing shall be one complete charge cycle with all outlets.

An overview showing the references for evaluation of disturbance phenomena in the low frequency (LF) range is given in table 2.

Table 3. Disturbance voltage limits for class A equipment for AC power input port.

Frequency range (MHz)	**Rated power of ≤ 20 kVA**		**Rated power of > 20 kVA**		**High power electronic systems and equipment, rated power of > 75 kVA**	
	Quasi-peak dB(μV)	**Average** dB(μV)	**Quasi-peak** dB(μV)	**Average** dB(μV)	**Quasi-peak** dB(μV)	**Average** dB(μV)
0.15-0.5	79	66	100	90	130	120
0.5-5	73	60	86	76	125	115
			90	80		
5-30	73	60	decreasing linearly with logarithm of frequency to		115	105
			73	60		

Table 4. Disturbance voltage limits for class B equipment for AC power input port.

Frequency range (MHz)	**Quasi-peak** dB(μV)	**Average** dB(μV)
0.15-0.5	66 decreasing linearly with logarithm of frequency to 56	56 decreasing linearly with logarithm of frequency to 46
0.5-5	56	46
5-30	60	50

Table 5. Disturbance voltage limits for DC power input port.

Frequency range (MHz)	**Rated power of ≤ 75 kVA**		**Rated power of > 75 kVA**	
	Quasi-peak dB(μV)	**Average** dB(μV)	**Quasi-peak** dB(μV)	**Average** dB(μV)
0.15-0.5	79	66	100	90
0.5-5	73	60	86	76
			90	80
5-30	73	60	decreasing linearly with logarithm of frequency to	
			73	60

The disturbance voltage limits of table 3, table 4 or table 5 apply for the power input port, respectively to the type of power input (AC or DC) and environmental classification (class A or class B) of the EUT to be tested.

The electromagnetic disturbances above 30 MHz caused by the EUT shall not exceed the limits specified in table 7 to table 10 for class A and class B respectively. The highest frequency up to which radiated emission measurements shall be performed is defined in table 6.

Table 6. Required highest frequency for radiated measurement.

Highest internal frequency (f_x)	**Highest measured frequency**
$f_x \leq 108$ MHz	1GHz
108 MHz $< f_x \leq$ 500 MHz	2GHz
500 MHz $< f_x \leq$ 1 GHz	5GHz
$f_x >$ 1 GHz	5×f_x up to a maximum of 6 GHz

Table 7. Requirements for radiated emissions at frequencies up to 1 GHz for Class A equipment.

Frequency range (MHz)	**Measurement**		**Class A limits** dB(μV/m)
	Distance (m)	**Detector/bandwidth**	**Test site: OATS or SAC acc. to CISPR 16-1-4:2010 and CISPR 16-1-4:2010/AMD1:2012**
30-230	10	quasi peak/120 kHz	40
230-1000			47
30-230	3		50
230-1000			57

Table 8. Requirements for radiated emissions at frequencies above 1 GHz for Class A equipment.

Frequency range (GHz)	**Measurement**		**Class A limits** dB(μV/m)
	Distance (m)	**Detector/bandwidth**	**Test site: FSOATS acc. to CISPR 16-1-4:2010 and CISPR 16-1-4:2010/AMD1:2012**
1-3	3	Average/1 MHz	56
3-6			60
1-3		Peak/1 MHz	76
3-6			80
1-3	10	Average/1 MHz	46
3-6			50
1-3		Peak/1 MHz	66
3-6			70

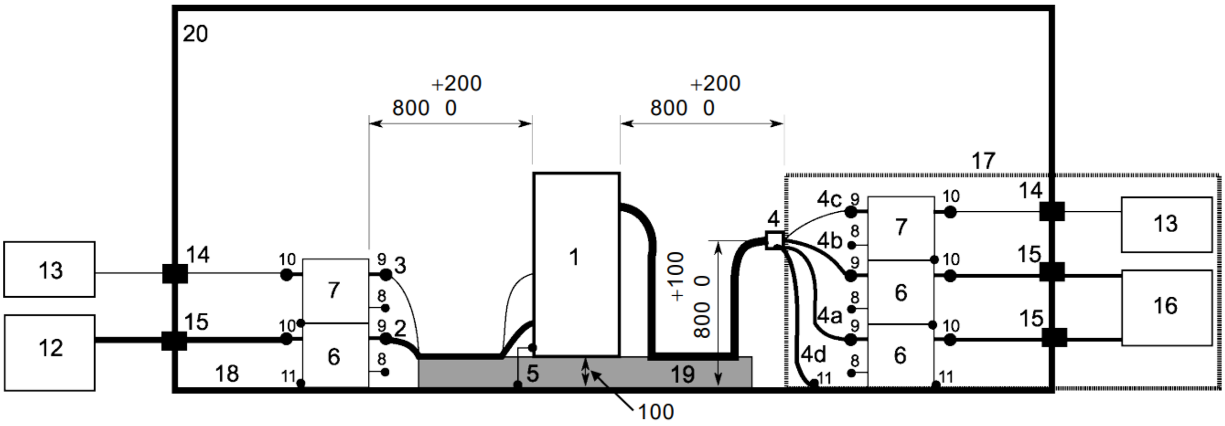
Table 9. Requirements for radiated emissions at frequencies up to 1 GHz for Class B equipment.

Frequency range (MHz)	**Measurement**		**Class B limits** dB(μV/m)
	Distance (m)	**Detector/bandwidth**	**Test site: OATS or SAC acc. to CISPR 16-1-4:2010 and CISPR 16-1-4:2010/AMD1:2012**
30-230	10	quasi peak/120 kHz	30
230-1000			37
30-230	3		40
230-1000			47

Table 10. Requirements for radiated emissions at frequencies above 1 GHz for Class B equipment.

Frequency range (GHz)	**Measurement**		**Class B limits** dB(µV/m)
	Distance (m)	**Detector/bandwidth**	**Test site: FSOATS acc. to CISPR 16-1-4:2010 and CISPR 16-1-4:2010/AMD1:2012**
1-3	3	Average/1 MHz	50
3-6			54
1-3		Peak/1 MHz	70
3-6			74
1-3	10	Average/1 MHz	40
3-6			44
1-3		Peak/1 MHz	60
3-6			64

Dimensions in millimetres



IEC

Key

1 EUT (floor standing)

2 power input port

3 signal/control port or wired network port

4 CPT port (end of charging cable/vehicle inlet)

- 4a CPT port – power line 1
- 4b CPT port – power line 2
- 4c CPT port – other than power lines
- 4d PE-ground connection

5 ground strap of EUT chassis (only if this is required in the EUT manual)

6 termination of power lines (AMN (for AC) or AN (for DC) acc. to Annex C)

7 termination for signal/control port or wired network port (ISN acc. to Annex C)

8 measuring port terminated with 50 Ω

9 EUT port of termination

10 supply/load port of termination

11 low impedance ground connection of termination chassis

12 AC mains or DC power supply (placed outside of test site or inside if non disturbing)

13 communication simulator/ stimulating and monitoring system (placed outside of test site or inside if non disturbing)

14 feed through filter

15 AC/DC power feed through filter

16 power load (placed outside of test site or inside if non disturbing)

17 AE/vehicle simulator (shielding might be necessary)

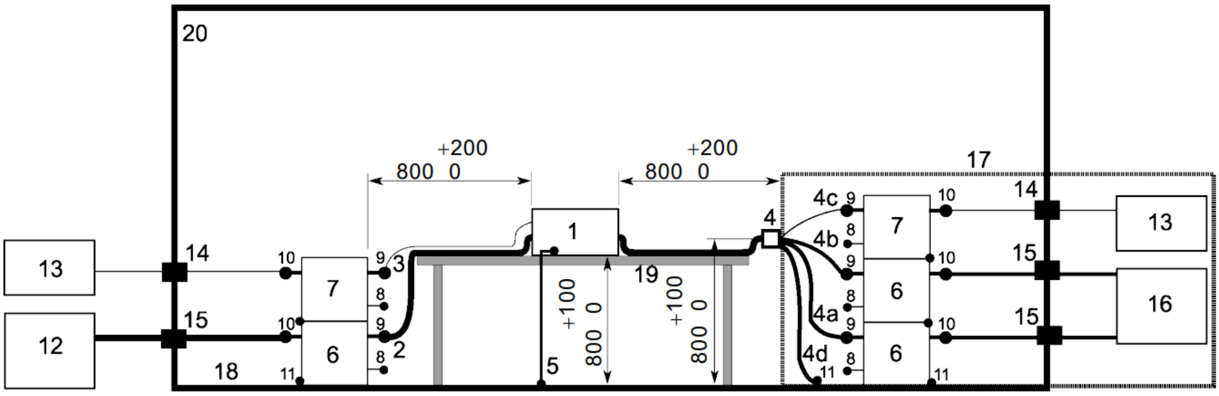
18 ground plane

19 insulation support with low permittivity

20 shielded enclosure or ALSE or test site

Figure 1. Example test setup for floor standing equipment for radiated and conducted emission and immunity. Taken from IEC 81851-21-2: 2018.

Dimensions in millimetres



IEC

Key

1) EUT (table top and wall mounted)

2) power input port

3) signal/control port or wired network port

4) CPT port (end of charging cable/vehicle inlet)
    - 4a CPT port power line 1
    - 4b CPT port power line 2
    - 4c CPT port other than power lines
    - 4d PE-ground connection

5) ground strap of EUT chassis (only if this is required in the EUT manual)

6) termination of power lines (AMN (for AC) or AN (for DC) acc. to Annex C)

7) termination for signal/control port or wired network port (ISN acc. to Annex C)

8) measuring port terminated with 50 Ω

9) EUT port of termination

10) supply/load port of termination

11) Low impedance ground connection of termination chassis

12) AC mains or DC power supply (placed outside of test site or inside if non disturbing)

13) communication simulator/ stimulating and monitoring system (placed outside of test site or inside if non disturbing)

14) feed through filter

15) AC/DC power feed through filter

16) power load (placed outside of test site or inside if non disturbing)

17) AE/vehicle simulator (shielding might be necessary)

18) ground plane

19) non-conductive table

20) shielded enclosure or ALSE or test site

Attention is drawn to the user of such test setups in regard of hazardous voltages due to high earth leakage currents. Advice should be sought from duly qualified personnel before switching on the laboratory's system power sources to ensure that injury or damage is not caused to test personnel or equipment.

Figure 2. Example test setup for table top and wall mounted equipment for emission and immunity. Taken from IEC 81851-21-2: 2018.

The test setups in Figure 1 and figure 2 are suitable for emission and immunity tests as appropriate. Further advice is found in the appropriate basic standards (for example the use of assigned coupling/decoupling networks).

The cables of the EUT shall: 1. hang vertically at the side of the EUT to the insulation support ($\varepsilon_r \leq 1{,}4$), at (100 ± 25) mm above the ground plane; 2. be such that any extraneous length thereof shall be placed on the insulation support (z-folded, if necessary).

5. Conclusion

Electric aircraft are gaining popularity due to their environmentally friendly nature. Compared with electric vehicles, the development of electric aircraft is still at an early stage. Most available electric aircraft nowadays are two-seaters which are able to fly only short distances. Ongoing research centers on safety, load-carrying capacity and battery durability. It is certain that at a later stage, EMC will become an important issue of research because an electric aircraft, along with its charging station, can both be victims of EMI or sources of EMI.

There are no global standards in terms of EMC requirements of electric aircraft and its charging infrastructure. Some standardization in underway and is expected to be published in the coming years. Since charging stations for electric vehicles and airplanes are basically the same, one feasible solution is to treat electric airplanes as electric vehicles and apply EMC standards such as IEC 61851 series and IEC 61000-6 series.

The next step in the ongoing project is to perform radiated (and possibly conducted) emission measurements on electric airplanes and charging stations at an airport environment to see if the emissions exceed the limits in CISPR32/EN 55032. One important issue would be if emissions disturb communication systems of the airport. It should be noted that there is no clear global classification of an airport environment (whether it should commercial & light-industrial or industrial environment). In this case, even if the emissions exceed the limits in CISPR32/EN 55032, they might still not affect communication systems. Therefore, another question worth considering is that if it is necessary to establish a special category for airport environment.

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