



Requirements and design of powertrains for eVTOLs

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Abstract The potential future of personal transportation and taxi services may be in some sectors beneficially amended with electric vertical take-off and landing (eVTOL) aircraft. Currently, dozens of companies are actively engaged in the development of eVTOLs, with the imminent commercialization of several vehicles. This article delves into the requirements, the present trends and powertrain technologies surrounding VTOL flight mechanisms. The main challenge for eVTOLs is that the propulsion system becomes part of the primary flight control system and therefore is critical for controlling the vehicle. This puts much higher demands on availability and safety of the powertrains than in conventional aircraft. Furthermore, as mainly propellers and fans are used for control that feature a constant or only slowly varying pitch angle, the thrust has to be dynamically changed using motor speed changes resulting in demands on motor acceleration and deceleration which are far beyond those of other transportation applications. Finally, if lift-to-cruise eVTOLs are considered, conflicting requirements are put on the powertrain, where high power is required for rather short times during take-off and landing whereas a rather low continuous power at high powertrain efficiency is needed during the prolonged wing-borne operation phase. This article provides an overview of regulatory and flight physics for eVTOLs. Thus, requirements for the electrical powertrain are deployed with focus on battery, electric motor, thermal management and HV circuit. As in the

case of ground-based vehicles, all these parts must be carefully selected, designed and co-optimized i. a. with focus on weight, energy or safety, but on trend with much more challenging aviation standards to be met.

Keywords Electric Vertical Take-Off and Landing (eVTOL) aircraft · Electrical powertrain · Electric airborne propulsion · eVTOL powertrain design · Urban Air Mobility (UAM) · Advanced Air Mobility (AAM) · Special Conditions for Small-Category VTOL Aircraft (SC-VTOL)

Anforderungen und Design von Antriebssträngen in eVTOLs

Zusammenfassung Die potenzielle Zukunft des Personenverkehrs könnte in einigen Sektoren durch elektrische Vertical Take-Off and Landing (eVTOL)-Flugzeuge vorteilhaft verändert werden. Derzeit arbeiten Dutzende von Unternehmen aktiv an der Entwicklung von eVTOLs, wobei die Kommerzialisierung mehrerer Flugzeuge unmittelbar bevorsteht. Dieser Artikel befasst sich mit den Anforderungen, den aktuellen Trends und den Antriebstechnologien für VTOL-Flugmechanismen. Die größte Herausforderung bei eVTOLs besteht darin, dass das Antriebssystem Teil des primären Flugsteuerungssystems wird und somit entscheidend für dessen Regelung ist. Damit ergeben sich wesentlich höhere Anforderungen an die Verfügbarkeit und Sicherheit des Antriebsstrangs als bei konventionellen Flugzeugen. Da zur Regelung hauptsächlich Propeller mit konstantem oder nur langsam veränderlichem Steigungswinkel verwendet werden, muss der Schub dynamisch über Motordrehzahländerungen geregelt werden, was zu Anforderungen an die Motorbeschleunigung und -verzögerung führt, die weit über derer anderer Transportanwendungen

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hinausgehen. Schließlich werden bei eVTOLs widersprüchliche Anforderungen an den Antriebsstrang gestellt, da während des Starts und der Landung für kurze Zeit eine hohe Leistung erforderlich ist, während bei den längeren Cruise-Betriebsphasen eine eher geringe Dauerleistung bei hohem Wirkungsgrad des Antriebsstrangs benötigt wird. Dieser Artikel gibt einen Überblick über die Regelungstechnik und Flugphysik von eVTOLs. So werden die Anforderungen an den elektrischen Antriebsstrang mit Schwerpunkt auf Batterie, Elektromotor, Thermalmanagement und HV-Kreislauf dargestellt. Wie bei bodengebundenen Fahrzeugen müssen all diese Komponenten sorgfältig ausgewählt, konstruiert und gemeinsam optimiert werden; u. a. mit Fokus auf Gewicht, Energie oder Sicherheit, dies aber tendenziell mit den viel anspruchsvolleren Luftfahrtstandards, die erfüllt werden müssen.

Schlüsselwörter Electric Vertical Take-Off and Landing (eVTOL) aircraft · Elektrischer Antriebsstrang · Elektrischer Antrieb in der Luftfahrt · eVTOL Antriebsstrang-Design · Urban Air Mobility (UAM) · Advanced Air Mobility (AAM) · Special Conditions for Small-Category VTOL Aircraft (SC-VTOL)

1 Introduction

1.1 Aviation history

For the first century of aviation, aircraft basically all looked alike—A fuselage for carrying payload, wings to generate lift and an empennage at the tail to provide stability and control. This type of aviation—kicked off by the first powered flight of the Wright Brothers in December 1903 (which to be precise had the empennage in the front) still dominates classical fixed-wing aircraft today—thus the successful flight of Wilbur and Orville Wright in the dunes of Kitty Hawk is considered as the first revolution of aviation. It was driven by pioneers, often organized in small and medium enterprises.

Canard configurations with the empennage in the front and flying-wing designs without dedicated empennage did never make it to significant production numbers while still representing a rather minor variation of the basic type of aircraft as introduced above.

In contrast to that, the second revolution of aerospace after the second world war where the introduction of the jet engine made the world smaller and larger aircraft opened the perspective to travel to other continents for large parts of society was powered by large corporations and billions of taxpayers' money.

In parallel, the advent of the helicopter provided independence from airport infrastructure, however at the expense of highly complex articulated rotors requiring a swashplate to implement cyclic and collective blade control at high bandwidth. Together with

the main rotor gear and the consequential need for a sophisticated lubrication system, helicopters feature many complex moving parts resulting in high maintenance effort and lower safety and availability than conventional fixed wing aircraft.

Thanks to the rapid progress in many non-aerospace domains, suddenly radically new and disruptive flying systems become feasible. Enabling technologies are electric powertrains (comprising batteries, battery and power management, energy distribution, electronic speed controllers and motors all featuring high efficiency, energy and power density), high-performance inexpensive and miniaturized inertial sensors with decreasing drift, high accuracy satellite navigation, inexpensive rugged embedded computational power but also carbon material based lightweight construction. This is further supported by new manufacturing methods like 3D printing, the power of computational development methods like simulation, model-based design, automatic code generation or model-based safety analysis. All of those ensure a much higher maturity and quality of a future product even before the first physical part needs to be built and thus reduces amount of and time for costly iterations involving the actual vehicle hardware.

This new type of aviation characterized by electrification and automation is often referred to as the third revolution of aviation. EVTOL vehicles often addressed as “flying taxis” might be the most visible representatives of these new groups of aerial vehicles.

Despite the bloomy promises of some players in the field, the new vehicles will never make it a serious contributor to mass transportation. Yet there is a multitude of serious applications like serving remote island or mountainous regions or providing medical response services (see Fig. 1) or critical small latency deliveries that justify the development of such types of vehicles.

1.2 Regulatory framework

Regulators in all relevant certification domains including the FAA (Federal Aviation Administration) and EASA (European Aviation Safety Agency) have realized that due to the large variation between the different approaches to such new vehicles, it is no longer possible to have dedicated design guidelines for its components. Therefore, a shift in paradigm was introduced from design-based certification to performance-based certification where instead of requiring compliance with restrictive design requirements, general performance and safety characteristics were defined where aircraft manufacturers now need to show compliance. In Europe this paradigm shift happened in 2017 with the introduction of Amendment 5 of the Certification Specification CS-23 for small airplanes. How compliance with the required characteristics is demonstrated is up to the company applying for certification, however, so-called Acceptable Means of

Fig. 1 eVTOL test flight (medical response service eVTOL)



Compliance (AMC) published by the regulator provide guidance. Nowadays, these AMCs are not just written by the regulator—rather they comprise industry consensus standards of peer groups in institutions like ASTM, EUROCAE, SAE or RTCA which are then endorsed by the regulator.

Currently EASA provided a special condition (SC) for the certification of small-category VTOL aircraft with a take-off mass of up to 3175 kg (7000 lbs.) where the endorsed AMCs are permanently extended and revised based on the actual learning curve. The related peer group in Europe suggesting AMCs is EUROCAE Working Group WG-112.

SC-VTOL differentiates between two types of vehicles, introducing the category basic which only requires the capability for safe controlled emergency landing after failures while the category enhanced (pursued by most current developers), which is mandatory for commercial passenger transport and operation in congested areas with high population density requires safe continued flight and landing even after failures. It raises the safety bar to a very high level, specifying quantitative targets for the accepted probabilities of catastrophic, hazardous, major and minor events on the same level as for large commercial airplanes like an Airbus A380.

Acceptable means of compliance for system development processes are given in the SAE ARP4754B, for safety analysis in the SAE ARP4761A, for software development in the RTCA DO-178C, for airborne electronic hardware in the RTCA-DO254 and for environmental qualification in the RTCA DO-160G.

As basis for certification of electric and hybrid propulsion systems, EASA published the special condition SC E-19.

The purpose of this rather lengthy introduction was to explain (1) the novel certification mindset introduced for new vehicles like VTOLs focused of safety and performance assurance to be able to serve the vast multitude of vehicle types and to (2) introduce

at least the top level of the applicable standards and documents.

In the following chapters, this, together with a consideration of the specific dynamic characteristics of eVTOL airplanes, allows the deduction of requirements to the electric powertrain and its contributing components.

2 Flight physics aspects relevant for the electric powertrain

This section addresses the dedicated dynamic characteristics of eVTOL vehicles that result in requirements on the electric powertrain, which are different from those in regular electric planes or many other modes of transportation. Focus is put on so-called lift-to-cruise vehicles, which during cruise use conventional wings to produce lift for compensating gravity, but also multicopters are considered, which continuously require propulsive power to counter gravity.

One of the big arguments favoring eVTOL vehicles is arguably their simplicity. Rigid fixed-pitch propellers are directly mounted to the output shafts of electric motors, forming a so-called lift-thrust-unit (LTU). This results in a cost-effective, low-complexity setup with a minimum number of rotating parts, no complex gears, no swashplate like in a helicopter, no need for a lubrication system with all its contributing components, no complex combustion engine with all the associated subsystems and accessories like fuel tanks, pumps, feeders, venting systems, etc. Also, no hydraulic actuation systems are required, again resulting in the necessity for many secondary installations. All those elements just mentioned for conventional VTOL planes like helicopters cause high manufacturing costs and maintenance efforts, reducing availability and boosting operational costs.

However, as the rotors are not articulated, thrust changes are produced by rapid changes in the shaft rotational speed, and thrust differences between distributed LTUs produce moments. This—in con-

trast to helicopters and conventional fixed-wing aircraft—means, that at least during powered-lift-borne flight phases, the LTUs become part of the primary flight control system. This has two implications—a dynamic one requiring much faster rates of change in thrust in- and decrease than for conventional propulsion systems (including ground-based transportation) and a safety/systems aspect, as loss of control has a much higher criticality than just loss of propulsion. On the other side, the efficiency of thrust generation (power required per Newton of thrust) is also an essential aspect as especially the still limited energy density of batteries poses a drastic constraint on range and endurance of battery electric flying vehicles.

2.1 Power consumption for thrust

The first consideration is the power required for hovering during powered lift flight phases. For the ideal power consumption per thrust, momentum theory, which considers momentum, energy, and continuity along a one-dimensional flow can be used. A straightforward derivation can be found in [1].

The power P [W] required per thrust T [N] is dependent on the density of the fluid ρ [kg/m^3] and the so-called disk loading T/A which is the thrust T in [N] generated per area A in [m^2].

$$\frac{P}{T} = \sqrt{\frac{1}{2\rho} \cdot \frac{T}{A}}$$

This equation shows that from a hover efficiency point of view, it is beneficial to have disk loading that is as small as possible by maximizing the area over which the thrust is generated. Using a conventional helicopter (with the complexity of a swashplate) rotating at constant speed is the ideal solution here, with the main limitation being the blade tip speed. As we will see below, large propellers also feature a large mo-

ment of inertia and therefore cannot be quickly accelerated and decelerated for quick changes in thrust and moments respectively (As a side note, if the propeller were in an infinite duct, the power required per thrust would be reduced by 1/2, however, people claiming this effect on their side may have a slightly euphemistic interpretation of infinity.)

Therefore, a reduction in disk loading can be achieved by increasing the number of LTUs rather than by an increase in propeller/rotor diameter. Given that in systems with unarticulated rotors, we need to generate moments by differential thrust using the lever arms between the center of gravity of the vehicle and the LTUs and the load torque around the motor axis, at least four propellers are required anyway. The required balance between stability, safety, controllability and performance can be met by providing at least four propellers, each with its own speed-control for fast and precise response. This leads to the classical quadrotor layout, which is controlled by changing the size and direction of a dominant force (the sum of the four individual propeller forces). Direction changes are performed by changing the attitude of the system to be discussed in detail later.

Increasing the number of propellers, however, causes the area demand to grow much faster than the actual effective thrust area. Furthermore, interaction effects between the flow of different propellers must be considered. Placing propellers in sequence in flow direction (coaxial propellers) does not constitute a full equivalent increase in area, as the flow exiting the first propeller disk is already accelerated and, therefore, leads to a higher induced angle of attack at the second disk, reducing its efficiency.

2.2 Controllability and maneuverability

Next, we consider controllability and maneuverability. As already mentioned above, the fundamental dynamic concept of flying vehicles, whether it is conven-

Fig. 2 Powered lift aircraft angles

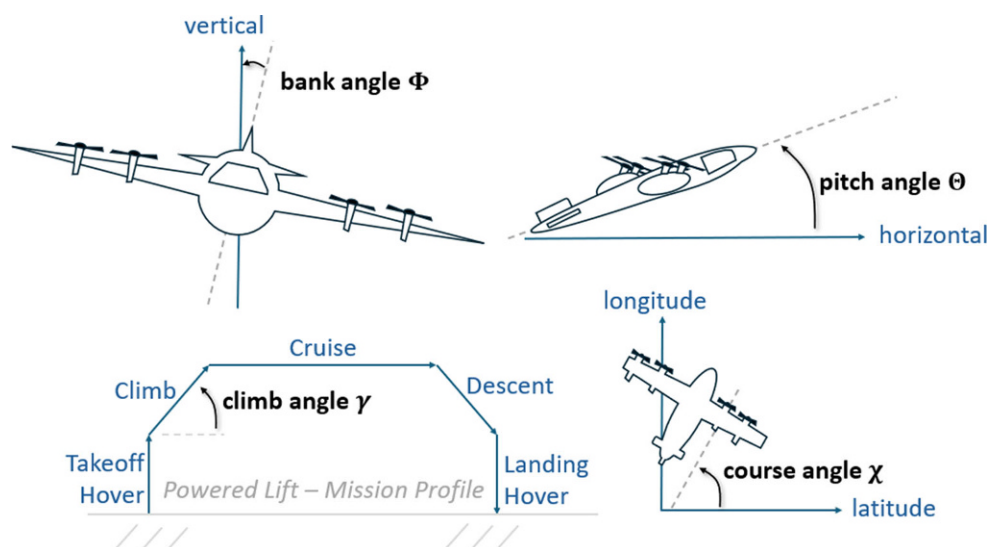
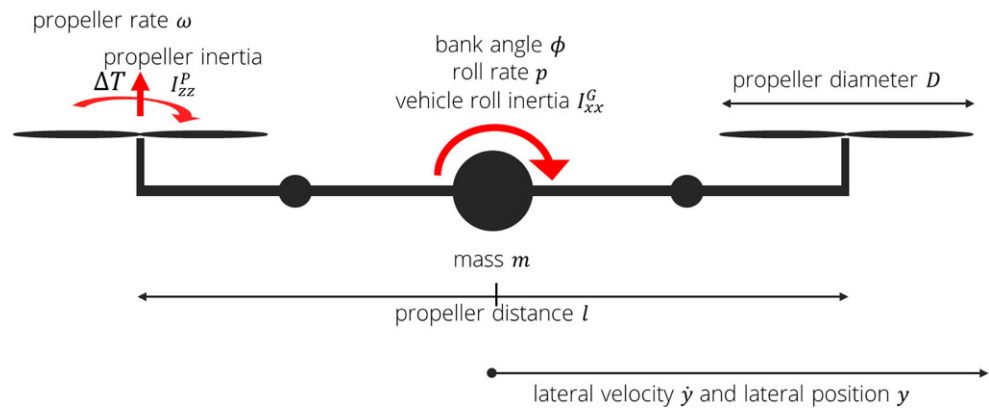


Fig. 3 Causal chain for a maneuver in the lateral direction



tional fixed-wing planes, classical helicopters, multicopter, or lift-to-cruise type eVTOLs is to have a dominant force to counteract gravity that can be quickly changed in magnitude. Changes in its direction are performed by changing the attitude of the whole vehicle. As this force typically is perpendicular to the direction of flight, it means that the difference between this force and the component of gravity being perpendicular to the actual direction of flight leads to a curvature of the trajectory leading to a change in the direction of flight (causing either a change in the climb angle γ , causing a $\dot{\gamma}$ or a change in the course angle χ constituting a turn rate $\dot{\chi}$), see Fig. 2. Around the hover condition at zero or low kinematic velocity, the tilted main force would either cause a lateral acceleration if the vehicle is banking (aircraft tilt during turns for steering, bank angle Φ) or a longitudinal acceleration if the pitch angle Θ is changed.

For a conventional aeroplane, the dominant force would be the lift, where the magnitude can be modulated by changing the angle of attack α , the angle between the incoming airflow and the body-fixed-longitudinal axis of the airplane in its symmetry plane. For a helicopter, it would be the main rotor force, which at constant rotor speed is changed by simultaneously changing the pitch angle of all rotor blades (“collective bled control”). For a multicopter, it would be the sum of all the propeller forces used to compensate gravity. Individual propeller forces are changed by changing motor speed as the propellers cannot (quickly) change their blade pitch angles.

The attitude of the vehicle is changed via its moment dynamics—for a classical fixed-wing aircraft, the primary control surfaces aileron, elevator, and rudder due to their location far away from the vehicle’s center of gravity, and the resulting big lever arms create moments around the roll (x), pitch (y) and yaw (z) axes respectively. For a classical helicopter, roll and pitch moments are generated using the cyclic blade control, which oscillates the pitch of the individual rotor blades once over a revolution, so the resulting thrust vector is slightly tilted, no longer acting through the center of gravity (CG), causing a moment due to the lever arm between the new (slightly rotated) line of

action of the rotor force and the CG. The yawing moment is generated by changing the collective blade pitch of the tail rotor or fenestron. For a multicopter, moments are generated by thrust differences between individual propellers controlled by different speed and the lever arms of the lines of action of those thrust forces to the CG. For yawing moments, the difference in torque of propellers producing different thrust is used (it is important to mention that in all professional larger multicopters, the axes of the propellers are not parallel to each other) and deliberate installation inclinations are used to augment the generation of yawing moments.

Four controls are needed to implement this classical control paradigm (change force magnitude and direction). This leads to a sequential setup of moment and force dynamics. The resulting causal chain is illustrated for a so-called side-step maneuver for a movement in the lateral, i.e. y position (see Fig. 3).

By changing the electric current ΔI for two opposing propellers, the torques around the propeller shafts for those two propellers are changing, which, considering Newton’s Second Law for angular momentum leads to an angular acceleration $\dot{\omega}$ of the affected propellers, inversely proportional to the propeller moment of inertia I_{zz}^p around its rotation axis which after one integration leads to a difference in of the two propellers considered. This asymmetric change in speed results in a difference in thrust ΔT , which, via the distance of the propellers from the center of gravity generates a vehicle level rolling moment. Using Newton’s second law for the angular momentum again, now considering the vehicle moment of inertia around its roll axis in the CG, I_{xx}^G , we get an angular acceleration \dot{p} around the roll axis which after a second integration becomes a roll rate p which constitutes a rate of change $\dot{\phi}$ in the bank angle causing the vehicle to bank after the third integration. This now in turn tilts the resulting force vector (sum of all propeller forces) to feature a component parallel to the earth surface $F_y = T \cdot \sin \Phi$. Using this time Newton’s second law for the linear momentum, this time considering the mass m of the vehicle, we get a lateral acceleration, which, after the fourth integration results in a lateral velocity

\dot{y} which only after five integrations leads to an actual change in the lateral position y . This physical cause-consequence chain is recapitulated here:

$$\Delta I \rightarrow \dot{\omega} \xrightarrow{\int} \omega \rightarrow \frac{\Delta T \cdot l}{I_{xx}^G} \rightarrow \dot{p} \xrightarrow{\int} p \rightarrow \dot{\Phi} \xrightarrow{\int} \Phi \rightarrow \frac{T \cdot \sin \Phi}{m} \\ \rightarrow \ddot{y} \xrightarrow{\int} \dot{y} \xrightarrow{\int} y$$

Another issue is that disturbances like lateral gusts directly cause an aerodynamic force on the body of the vehicle and thus directly cause a lateral acceleration and then after only two integrations a lateral displacement whereas we can only counter after five integrations with our controller. The minimum derivative order of the variable to be controlled which we can algebraically influence with our input is called the relative degree of the output. Here, we suffer from the fact that the relative degree of the lateral position with respect to a disturbance is only two, while the relative degree with respect to our control input is five.

The unit of the moment of inertia is $[kg \cdot m^2]$ this would suggest a proportionality to the square of the diameter/radius. However, this is wrong as the additional mass $dm = \rho(r) \cdot A(r) \cdot dr$ also needs to be considered, leading to a more than cubic relationship between propeller diameter and its moment of inertia (of course reducing solidity and other tricks may reduce the inertia a bit—but also the generated thrust).

As for the given example, the variables of interest to be controlled are lateral velocity and ultimately lateral position, it means that there are four or five integrations between the available control input (the motor current) and the response variables to be controlled. To be successful in control, we need to step backward from the desired output variable to our physical input, ensuring that the dynamics of the next inner variable is always at least a factor of two to three faster than the actual variable. This does not only hold for the bandwidth of small perturbations around steady state operating points but especially also for saturation effects (absolute value and rate saturations) for larger inputs.

For larger scale eVTOLs this means that

1. There is a limit to the diameter of the propellers to be used as the physical cause-consequence chain introduced above leads to increasingly adverse ratios of peak current to steady-state current during maneuvering if the propeller diameter is increased to achieve given maneuverability targets.
2. The passive deceleration of a propeller shaft by the load torque of the propeller may be too small, requiring active deceleration. This may sound trivial in the beginning—however burning the recuperated energy with a shunt resistor may cause heat problems and given the high number of control cycles when flying in disturbed air may also constitute a waste of energy. The obvious solution of feeding back the recuperated energy to the system also

bears challenges related to fault propagation and segregation.

3. Over dimensioning the propulsion system may lead to an unbearable weight penalty.

Thus, here we already see a conflict between the two objectives thrust efficiency (calling for large rotor diameters) and controllability/maneuverability (rather demanding small diameters).

Of course, it would be beneficial, if instead of changing the attitude of the whole vehicle, direct forces could immediately be generated in the direction of interest (“direct force control”). If direct control of every dimension is to be assumed, we need at least six independent control variables (in case of a multicopter six LTUs), spanning the whole six-dimensional moment and force space. The maneuverability of the vehicle is often depicted as a six-dimensional volume displaying linear and angular accelerations that can be generated directly by means of the available control effectors (LTUs for a multicopter).

While such “fully actuated” vehicles do exist for small drones, they would turn out to be quite inefficient for larger vehicles as large forces would have to be kept available in directions orthogonal to gravity which would only be used for maneuvering but not be able to contribute to compensating gravity. Therefore, the most frequent solution is to tilt the axes of the LTUs with respect to the vertical by small angles below 15° making use of the fact that the sine of small angles quickly changes its value whereas the cosine stays close to one for quite some angle range as can easily be seen from the first two terms of the Taylor series which for the sine is $\sin x = x - (1/6) \cdot x^3$ while for the cosine we have $\cos x = 1 - (1/2) \cdot x^2$, approximating $180/\pi$ by 60. This means that at 15° more than a quarter of the force of an LTU already acts in the horizontal plane whereas less than 3.5% are lost in the vertical direction.

This approach now allows to generate direct forces—however it requires at least six LTUs and the authority, i.e. amplitude of the direct lift generation in the horizontal plane remains limited. At least, if optimized cleverly, it can generate some lead and therefore quicken the responsiveness to commands.

Especially when human pilots command high level variables which are many integrations away from the physical control effectors like translational velocities (translational rate command) directly in a closed-loop manner, low bandwidth and especially saturations quickly lead to so called pilot induced oscillation—a state where the coupled pilot vehicle systems become unstable although the airplane itself would still exhibit a stable behavior. Here, the lag of the aircraft response related to the pilot input is the relevant aspect—if the phase lag between command and response becomes 180° , the coupled system becomes unstable (this description is for the sake of compactness slightly simplified).

The next aspect are failures—following SC-VTOL, no single failure condition may lead to a loss of the vehicle, meaning that if a LTU or a battery fails, the aircraft for SC-VTOL category basic needs to ensure a controlled emergency landing, whereas in category enhanced even needs to be capable of safe continued flight and landing.

This immediately means that as the failure of an LTU or battery (amongst many others) need to be explicitly considered, the aerial vehicle needs a significantly higher number of LTUs and batteries than required for nominal flight. Furthermore, it needs to be considered that being now a vital part of the primary flight control system, the available control power does not only have to be sufficient for just flying (which in technical terms is trimming the vehicle) but also for stabilization (in many domains, the inherent dynamics in hover is unstable—not only the LTU forces but also the pace of their build-up and decay must be sufficient for stabilization), disturbance rejection for all disturbances to be expected and maneuvering (meaning to provide sufficient handling quality characteristics to a human pilot).

These characteristics—trim, stabilization, disturbance rejection and maneuvering must not only be ensured in the nominal case, but also in the presence of the above-mentioned failures (of course with an allowed degradation in handling qualities and a reduced flight envelope). One consequence is that when the functionality must be provided by remaining elements in case of a failure, some of the remaining components (batteries and LTUs) might be operated at significantly increased load levels for an extended period of time.

For lift-to-cruise vehicles, which are utilizing wings for cruise flight, powered lift is only required during vertical take-off and landing, and the transition from hover to wing borne flight and back. Including all foreseeable contingencies, no more than five minutes of powered-lift flight at one time need to be considered.

Currently, two major solutions can be found for the powered lift system—either dedicated LTUs are used, which are deactivated in wing-borne lift flight phases (e.g. Autoflight Prosperity or eMagicAircraft eMagicOne) or so-called vectored thrust is used where either the propeller or the whole LTU (Joby S8) or even the whole wing including LTUs (Dufour Aerospace) are tilted and used for both domains of flight. There can also be combinations of both, where some LTUs are used in both modes whereas others are exclusively used in hover (Vertical Aerospace or Archer may serve as examples). In case of tilting LTUs, often variable pitch propellers are used—however not in the sense of fast collective blade pitch control for dynamic maneuvering but rather slow adjustment like in a constant speed propeller to have optimized blade pitch for the different domains of flight.

To find related requirements SC-VTOL Subpart B (Flight) specifies both—performance requirements

(particularly for climb, take-off and landing—MOC-2 SC-VTOL Issue 3) and the process to assess minimum acceptable handling qualities (MOC SC-VTOL Issue 2).

2.3 Summary on requirements for powertrain

Now how do all the items listed above get together? A list of conclusions can be drawn on the requirements to the propulsion systems of eVTOLs:

- The formal EASA rules applicable are SC-VTOL [2] and SC-E19 [3] including the latest issues of the different Means of Compliance (MOC) documents—which in turn reference third party industry consensus standards, e.g. by ASTM, RTCA or SAE
- In general, SAE ARP4754B (System Development) [4], SAE ARP4761A (Safety Assessment), RTCA DO-178C (plus supplements—Airborne Software), RTCA DO-254 (Airborne Electronic Hardware) and RTCA DO-160G (Environmental Qualification) may serve as basis for development efforts
- LTUs are part of primary flight control and thus are essential for controllability or safe continued flight and landing. Therefore:
 - A sufficient level of redundancy must be established to be able to compensate the failure of a LTU, a battery or a battery management system—the power system must not contain any single point of failure which can lead to a catastrophic event.
 - MOV 4 VTOL.2300 specifically addresses common mode failures, where all components of the same type are assumed to fail simultaneously, e.g. due to false requirements or a design error.
 - Fault isolation and segregation are important aspects—a failure in one component must not compromise the correct functioning of other components, especially not of the ones which are considered a redundancy for the failed component
 - To avoid total loss of thrust/power on single LTUs multi pole motors with multiple independent motor controllers and possibly independent power sources might be a solution
 - Coaxial arrangements might not be considered a sufficient redundancy, especially if the propellers are ducted
- The dynamics of the LTUs—at least during powered lift flight phases—constitutes the “actuation dynamics” for flight control—therefore they need to satisfy high demands with respect to the involved dynamics.
 - The acceleration time constants assuming a first order response behavior of the motors need to be very small to provide sufficient dynamics around the roll axis on the aircraft level
 - A sufficient ratio of peak torque to continuous torque (i.e. peak current to continuous current) must be available for the LTUs to ensure that even

for larger input amplitudes no rate saturation effects occur which would lead to a loss in phase reserves and jeopardize closed-loop stability

- To avoid couplings between attitude changes and thrust axis, it is important that thrust increase and decrease can happen at the same rate. Therefore, it is important that active braking is used to slow down the motors rather than relying on the load torque alone
- The available torque must be dimensioned for failure cases where due to a failed LTU or battery, the remaining motors have to take over. It is not sufficient, if the vehicle is just trimmed—there must be sufficient margins in thrust amplitude in rate to ensure stabilization, disturbance rejection and maneuvering. Handling qualities and performance may be degraded in case of failures occurring at defined low probabilities, however, sufficient capabilities for either a controllable emergency landing (SC-VTOL category basic) or safe continued flight and landing (SC-VTOL category enhanced) must remain.
- When operating after degradation or failure, the remaining LTUs and batteries might operate at elevated performance levels for extended periods of time, leading to high thermal loads in the system.
- If the same LTUs are used for both—powered lift flight phases and providing traction during wing borne flight, the load conditions are very different as during hover and (re-)transition, power demand is high whereas during wing-borne flight, the continuous power demand and also the required bandwidth for dynamic power changes is low. In case of a dedicated system for powered lift, there will be rather short phases with high power demands whereas during wing borne flight the system is to be deactivated. In total for the continuous operation of the powered lift system, no more than five minutes at one time need to be considered. It is assumed that in nominal operation, powered lift ops for take-off and transition or re-transition and landing are less than two minutes each. It needs to be ensured that even in case of foreseeable failures, the maneuvers foreseen in SC-VTOL for the take-off and landing procedures can still be safely executed for category enhanced without violating the published spatial volume boundaries.

- General requirements to the (electric) power and propulsion system of eVTOLs beyond the maneuvering and performance requirements addressed above can be found in Subpart E of SC-VTOL.

3 Requirements and design criteria on the powertrain

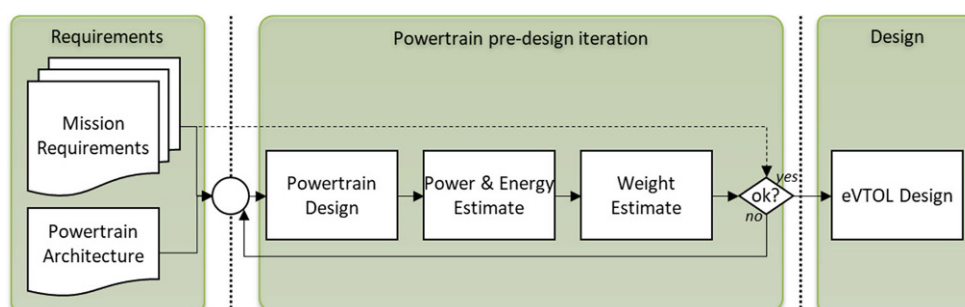
The powertrain of an eVTOL aircraft is a complex system that includes both electrical and mechanical components. The electrical sub-system consists usually of several parallel batteries, inverters, and electrical motors, while the mechanical sub-system includes transmissions, differentials, rotors and thermal system. The powertrains are designed for maximum energy efficiency and driving stability, with components such as brushless DC motors, automatic or manual transmission, and lithium-ion battery packs. The powertrain architectures underscore the essential role of power electronic converters, including AC–DC and DC–DC converters. Wide bandgap (WBG) devices, exemplified by silicon carbide (SiC) and gallium nitride (GaN), stand out for their capability to withstand higher operating voltages and temperatures. Moreover, SiC and GaN devices are more compact and lighter, and can be utilized at higher switching frequencies. Further, thermal management is an essential part to maintain operation temperatures of battery, power electronics and motors within specified windows. Beside liquid cooling, also air cooling may be considered to reduce weight and complexity. The electric propulsion architectures are designed for a given eVTOL range, aircraft type, payload and flight profile. Figure 4 depicts the design methodology of the powertrain from drafting requirements to full eVTOL design. Due to the high impact of the powertrain on the full vehicle behavior, this step plays an important role and careful consideration must be taken when composing its.

The following sub-chapters highlight the main components for the powertrain.

3.1 Battery

The requirements for airborne propulsion batteries involve several key metrics, including energy and power density, cost, life and safety, see Fig. 5. These

Fig. 4 Outline of the iterative powertrain design methodology in eVTOL aircraft



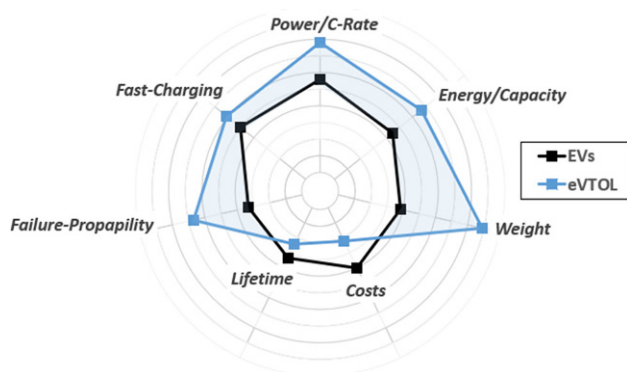


Fig. 5 Battery requirements in eVTOL powertrain phase

metrics influence the design of battery cells, their packaging, and control systems. In comparison to ground transportation and portable electronics, aviation necessitates a focus on extra high energy density usable for flight including reserves for landing, as well as increased requirements on packaging (e.g. integration into wings), life, and safety. Safety is especially for eVTOLs very crucial to address wing-less emergency landing, so batteries must be carefully designed to work safely in different harsh conditions, including high temperatures and fast charging. The powertrain should be constituted of several independent batterie (and motor) systems in parallel, also with variation of battery types in case of technical issues with one specific battery type. Further, reliable batteries are essential for uninterrupted power to critical systems like avionics and controls. Further, the batteries are essential part of aviation safety regulations, especially those set by the FAA and EASA, which are, i.a. responsible for approval and certification of eVTOLs.

The batteries must work well in various temperatures to ensure reliable operation (airborne conditions are harsher than land-based ones). Battery preconditioning may be considered to heat the batteries prior to take-off which requires efficient full load operation. The number of times a battery can be charged and discharged is important for its lifespan, hence the costs. E.g., 2000 cycles of fast-charging and discharging can be assumed as appropriate [5, 6]. Similar like in automotive regulations—which are currently in discussion—a minimum end-SOC should not be under-shooten. A minimum end-SOC of 72–80% is currently in discussion for EVs [7], this should be seen also as a minimum requirement for eVTOLs, when passing the mentioned 2000 cycles.

Given the critical importance of weight in the design of eVTOLs, the use of high-specific-energy batteries becomes paramount. The Li-ion battery emerges as a top choice, thanks to its attributes such as high cell-specific energy (150–300 Wh/kg), substantial voltage capacity, lower self-discharge rate, scaling effects and absence of a memory effect. Beyond high specific energy, these batteries must be engineered to meet the demanding peak power requirements, especially for

high disk-loading like during hovering. According to [8], even a minimum of 400 Wh/kg energy density on pack level are required for urban air mobility vehicles which is currently not met yet. For commuter aircraft, this increases even much higher to 1200–2000 Wh/kg, which could be—also in the near future—only addressed with additional energy sources like fuel cells. The cell-specific energy density is normally approximately 1/3 higher than the pack-specific energy density. This results in the requirement of batteries with ~530 Wh/kg on cell-level. Despite notable advancements in battery technology, the maximum specific energy achieved is approximately 300/350 Wh/kg on cell-level, which is according to [8] still below target. This conflict can be relaxed, when e.g. more efficient eVTOLs are developed, shorter mileages (<50 km) are accepted or battery performances are increased, see next chapter with innovations.

Usually, the batteries are seldom discharged to low levels due to the substantial flight energy reserves required. C-rate, representing a battery's power capability in relation to capacity, varies across aviation applications, with urban air mobility systems having particularly high C-rate requirements. In comparison, electric vehicles today usually operate at peak C-rates up to 2.5 C [9], which means that with a 100 kWh battery, a maximum power of 250 kW is available for short-term accelerations. eVTOLs require similar C-rates during cruising (e.g. 0.75–1.5 C) but have a much higher power requirement during hovering making up to 2.5–6 C [5, 10]. Assuming a typical energy density of 200 Wh/kg for a battery, this results in a power demand of up to 1000 W/kg for takeoff and landing hovers which have the highest power demand and hence determine the battery's peak C-rates. Further, this makes up to 300 W/kg during cruise mode which defines the battery's continuous C-rates.

Quick charging is helpful to decrease the time between flights. Power and capacity of battery must be considered therefor. In [10], 11 different fully electric eVTOL applications are listed with a power level of 70–1216 kW and a mileage of 10–266 km. A representative calculation is then made in [10] for a 205 km 4-person eVTOL flight utilizing a 77 kWh battery, requiring 450 kW power (5.8 C) for hovering and 147 kW power (1.9 C) for cruising. To charge the battery fast for availability for next mission, 70% (144 km or 54 kWh) should be charged within max. 10 min. This ends up in 324 kW, respectively 4.2 C.

3.2 Battery innovations

Recently, several innovations in battery development are hitting the market. Some of them, like LFP-Li-Ion or Na-Ion batteries are promising to find its way in ground-based applications, but due to lower energy densities compared to best-in-class NMC Li-Ion batteries, these types are rather not promising for aircrafts. Especially with focus on aviation, by trend,

significantly higher energy densities are expected e.g. with Lithium-Sulfur Batteries (550 Wh/kg) [7], Solid State Batteries (500 Wh/kg) [9], and Highly Advanced Li-Ion Batterie concepts (500–700 Wh/kg [10, 11]). In common, these approaches and technologies are up to now demonstrated on a rather small scale, being still in research and development at a TRL of 4–7 (Technology Readiness Level) with commercialization expected in 5–10 years according to pertinent battery road maps [11, 12]. Three relevant and largely credible future battery concepts for aviation are presented in the following.

3.2.1 Solid state batteries

The currently in aviation intended NMC Li-Ion batteries may lack the safety standards required for aviation due to flammability concerns. With solid-state batteries, liquid electrolyte chemicals can be eliminated and relaxing the associated safety risks. These batteries are likely to boast double the energy density of today's NMC Li-Ion batteries. While solid-state batteries are still undergoing testing and remain costly to produce [12], e.g. NASA's advancements in C-rate improvement bring battery-powered planes closer to reality, albeit with extensive testing needed before commercial use becomes feasible. The solid-state batteries have according to [13] a capacity of 500 Wh/kg, which could significantly increase efficiency and mileage.

3.2.2 Advanced NMC li-ion condensed battery

In 2023, CATL made a significant announcement about their collaboration on a civilian electric passenger aircraft project. The company is diligently incorporating aviation-grade standards and rigorous testing to ensure compliance with aviation-level safety and quality requirements. The Condensed Battery with a so-called ultra-high energy cathode and NMC chemistry boasts at an energy density of up to 500 Wh/kg. It integrates high specific energy positive electrodes, new negative electrodes, novel separator membranes, and other innovative material systems for a comprehensive and advanced battery system [14].

3.2.3 Advanced li-ion pouch lithium battery

Latest research results from renowned researchers in China are causing a stir as they herald a significant increase in energy density. Impressive figures of 711 Wh/kg gravimetric energy density and even 1653 Wh/L volumetric energy density take center stage [15]. This is accomplished by combining all possible efforts like employing a high-capacity lithium-rich manganese-based cathode and a thin lithium metal anode. This is complemented by high-loading electrodes and the precise injection of a lean electrolyte. Further, the structural stability of the cathode material across an expanded charge/discharge voltage range is optimized, as well as the deposition/dissolution behavior of the interfacial modified thin lithium elec-

trode. Such a significant increase in energy density could mean a breakthrough for battery-powered aircraft. Even though, these are first positive test results, further (long-term) tests will be needed to investigate if also other factors like stability and cost targets can be met.

3.3 Electric motors

Beside the battery, electric motors are the other enabler of the implementation of eVTOLs. Electrified powertrains consist of lesser number of components than gas turbines or other mechanical drive trains and have therefore lower maintenance and operational costs, thus a reduction of the overall costs. Each eVTOL is equipped with multiple motors that are required for different tasks, such as cruise flight, take off, hover or landing. Depending on the configuration, the motor can be used either for all tasks or multiple motors are used for each task independently. In addition, electric motors are emission-free and have lower noise emission. However, during the design phase of such an electric propulsion system and the choice of the fitting electric motor, different mission-focused and safety/reliability-focused requirements must be considered [16].

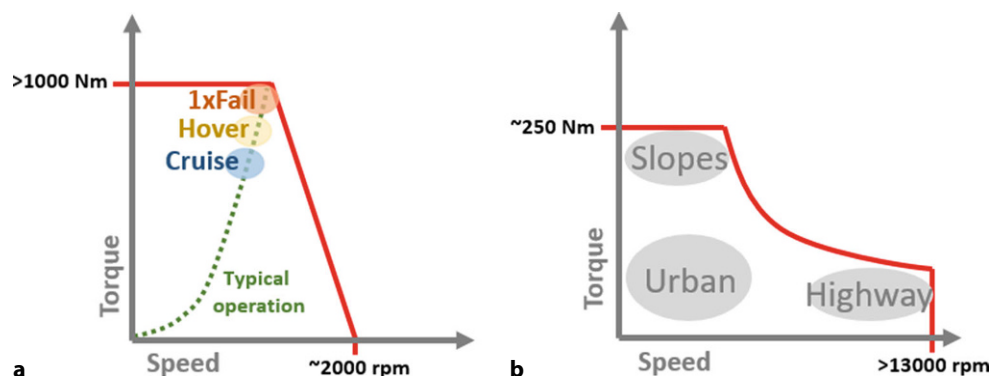
3.3.1 Motor requirements

eVTOLs motor requirements are unlike other EV applications, such as automotive vehicles. Rather than operating at high speed, the motors used in aviation applications require high torque and high power to rotate a large rotor and low speed to reduce noise emission during operation [10]. One example for such application is the CityAirbus prototype by Airbus, operating at around 950 rpm [17]. This prototype uses an electric propulsion unit from Rolls Royce delivering a constant torque of 1300 Nm at a mass of 50 kg, resulting in a power-to-weight ratio of around 3 kW/kg and a torque-to-weight ratio of around 30 Nm/kg [18], compared to an automotive motor, such as the Bosch SMG180 with 2.5 kW/kg and 6.25 Nm/kg [19], especially the difference in torque-ratio is significantly higher.

This different requirement becomes also clear when looking at the motor characteristics of both applications, shown in the following Fig. 6, where automotive motors show a more variable speed-torque-characteristic depending on the usage, such as highway drive or urban drive, while aviation motors operate mostly in the high torque region. While automotive motors can be operated up to very high speeds like seen in a typical motor map limited by back-EMF, an aviation motor operates in much lower speed regions on only 1 typical operation line, limited by the early peaking of torque.

Beside the mission focused requirements another key requirement that influences the design of the motor is the weight of the aircraft, also maximum takeoff

Fig. 6 EM characteristics eVTOL vs. Automotive



weight (MTOW). It defines the power demand of the eVTOL that the propulsion system needs to provide to lift and operate. To reduce the overall weight, it is crucial to have a motor with a high power- and torque density, so that a lightweight motor provides sufficient power. Since the increase in range always relates to the increase of weight as well, it is important to maximize the utilization of the electric motors. The weight also influences the choice of materials, extending from typical aluminum and steel structure to a lighter solution such as titanium or metal matrix composites, however tradeoffs between costs and efficiency must be done [20].

Due to reliability and safety aspects, generally distributed systems with a certain level of redundancy are used. This is simply implemented by distributing the motors to multiple batteries and navigation sensors, which allows the still operable motors in case of engine or batteries failure to cover the demanded load [21].

Therefore, the following technical key requirements for the design of electric motors used in aviation, particularly in electric aircraft and electric vertical take-off and landing (eVTOL) applications, can be summarized as:

1. *High Power- and Torque Density:* Electric motors for aviation need to provide high power and torque density to ensure efficient propulsion while keeping the weight of the motor and associated components low.
2. *Weight:* Weight is a critical factor in aviation. Electric motors must be designed to be lightweight without compromising on their power output. Reduced weight contributes to overall aircraft efficiency and performance, which increases the possible flight distance.
3. *Reliability:* Aviation demands high levels of reliability. Electric motors must operate consistently and reliably under various conditions, including different altitudes, temperatures, and flight phases. Reliability is crucial for ensuring the safety of the aircraft and its passengers.
4. *Redundancy:* To enhance safety, electric aircraft often incorporate redundant systems, and electric

motors are no exception. Redundancy ensures that if one motor fails, the aircraft can still maintain control and operate safely.

5. *Environmental Considerations:* Electric aircraft are often promoted as a more environmentally friendly option. As such, electric motors should be designed to produce minimal noise and, most importantly, zero emissions during operation.
6. *Regulatory Compliance:* Electric motors must adhere to aviation safety regulations and standards set by aviation authorities. Compliance with these regulations ensures that the electric motors meet the necessary safety and performance requirements.
7. *Maintenance and Serviceability:* Electric motors should be designed for ease of maintenance and serviceability. Quick and efficient maintenance is essential to minimize downtime and ensure the continuous airworthiness of the aircraft.

3.3.2 Motor variants and details

Meeting the previously mentioned requirements is essential for the successful integration of electric motors into aviation applications, supporting the development of electric aircraft with enhanced performance, safety, and environmental sustainability. Electric motors used in aviation, especially in the context of electric aircraft and electric vertical take-off and landing (eVTOL) vehicles, are designed to meet these requirements related to power, weight, efficiency, and reliability. Mainly brushless DC and permanent magnet motors are used, but also induction motors or switched reluctance motors find use in such applications. BLDC motors are particularly prominent in aviation due their high efficiency, reliability, and high power-to-weight ratio. Currently compact solutions are available that can be used when lightweight, high torque and efficiency is required. Also, BLDCs have reduced maintenance costs due to their simple structure. The second prominent solution is the PMSM, it offers similar benefits as the BLDC.

BLDC motors are also differentiated between in-runner and out-runner motors. As the name suggests, in the outrunner setup the propeller is attached to the rotating case of the motor, while for in-runner motors the propeller is attached to the output shaft. Both

configurations find their applications, but the latter is usually used, because of its compactness and the torque density can simply be increased by increasing the number of poles [22].

These motors are often used in a direct drive configuration, on one hand it reduces the complexity of the system and increases efficiency and reduces weight of the propulsion system by removing components such as the gearbox, but on the other hand, it increases the torque demand of the rotor since there is no translation between propeller and motor. The connection between the electric motor and the propeller in an eVTOL aircraft involves a system of mechanical components that transmit power from the motor to drive the propeller. The specifics of this connection can vary depending on the eVTOL design.

The propeller hub, to which the propeller blades are connected, is attached to the output shaft of the rotor in a direct drive configuration, in some cases a reduction gearbox is applicable to modify speed and torque of the motor output. This is required if the motor operates at high speed >10,000 rpm and the speed needs to be reduced to operational speed of a drone ~2000 rpm. The propeller blades are aerodynamically designed to generate the required thrust to lift the vehicle. The connection between the motor and the propeller is crucial for the overall performance and efficiency of the eVTOL. Furthermore, the transmission system contains bearings and couplings that ensure smooth transfer of power from motor to propeller. A control system, often integrated with the aircraft's avionics and flight control systems, manages the speed and pitch of the propeller. This control system ensures that the propeller operates at optimal conditions for take-off, cruise, and landing.

3.3.3 Electric aircraft motor benefits

The shift towards electric motors in aircraft comes with numerous advantages:

1. **Flexibility:** The use of electric motors provides flexibility in control and allows for precise adjustments in thrust, contributing to the agility and versatility of eVTOL aircraft during vertical take-off, transition to horizontal flight, and landing.
2. **Quiet Operation:** Electric aircraft are quieter than those with traditional jet or combustion engines, contributing to reduced noise pollution. Distribution propulsion using multiple small electric motors further enhances quietness compared to single, larger combustion systems.
3. **Environmentally Friendly:** Electric aircraft, whether airplanes or eVTOLs, produce no greenhouse gas emissions during operation. This aligns with environmental concerns, as air travel currently contributes to approximately 2.5% of total greenhouse gas emissions.
4. **Safety:** eVTOL manufacturers anticipate enhanced safety compared to traditional aircraft, with multi-

ple propellers and systems designed to redistribute power in case of motor failure.

5. **Lower Maintenance Costs:** Electric motors have fewer parts compared to gas turbine and combustion engines, leading to lower maintenance costs. The reliability of electric motors, proven in various applications such as vehicles, contributes to cost-effectiveness.

3.4 Thermal management

eVTOLs require for a robust thermal management system. The success of such a system lies in its capacity to accumulate heat at a specific location and then transfer it to a designated area for safe dissipation. The core components of these systems encompass the key elements:

- Heat Collection Components (e.g., cold plates or liquid-cooled enclosures)
- Transport Components (e.g., fans, pipes, hoses, connectors, and pumps)
- Heat Rejection/Dissipation Equipment (e.g., heat exchangers, fins)

Cooling of electric motors, batteries and power electronics in aviation is crucial to maintain optimal performance, prevent overheating, and ensure the safety and reliability of the aircraft. Several cooling methods are employed to manage the heat generated during the operation of powertrain in aviation:

1. **Air Cooling:**
 - *Direct Air Cooling:* Components may be designed with fins or other structures to facilitate the direct flow of air over their surface. This natural convection helps dissipate heat into the surrounding air.
 - *Forced Air Cooling:* Fans or blowers can be integrated into the design to actively force air over the motor or battery. This method enhances cooling efficiency, especially during periods of high-power demand, high ambient temperature or when the aircraft is on the ground.
2. **Liquid Cooling:**
 - *Direct Liquid Cooling:* In this method, a liquid coolant (usually water or a specialized coolant) circulates directly through channels in the battery or jackets within the motor. The liquid absorbs heat which is and is then circulated to a heat exchanger where the heat is dissipated into the air or another cooling loop.
 - *Indirect Liquid Cooling:* The liquid coolant flows through a separate cooling loop, and a heat exchanger transfers heat from e.g. the motor to the coolant. This method allows for greater control over the temperature of the motor.
3. **Oil Cooling:**
 - Some electric motors, particularly those used in aircraft propulsion, are designed to be oil-cooled. The oil circulates through the motor, absorbing

heat, and is then directed to an external heat exchanger for cooling.

4. Advanced Thermal Management Systems:
 - Advanced thermal management systems may include a combination of cooling methods, such as a combination of air and liquid cooling. These systems often use sensors and control algorithms to optimize cooling based on real-time operating conditions. Some systems incorporate active control systems that adjust the cooling mechanisms based on real-time temperature data. This can optimize cooling efficiency and prevent overheating.
5. Composite Materials:
 - Materials with high thermal conductivity, such as certain composites, can be used in the construction of motor components to enhance heat dissipation.

The choice of cooling method depends on specific component design, power requirements, and operational conditions of the aircraft. These factors need to be carefully considered to ensure that the components operate within their temperature limits, contributing to the overall safety and efficiency of electric aviation systems.

In general, an air-cooled system should be preferred due to less weight and less components which could failure. To ensure even high heat dissipation at high-load points, a carefully and very efficient air cooling with high turbulent airflow must be strived for.

Beside cooling, also the heating of battery and cabin is relevant, which can be facilitated with electric heaters in a liquid cooling system. Pre-conditioning of the battery before take-off must be considered. If no liquid cooling is available, e.g. a self-heating strategy of the battery can be pursued. Such a pulse-discharge heating method converts a small portion of electricity (e.g. 5%) by changing internal structure via switching processes into heat to increase the battery temperature [23]. Heating may also be required prior to fast-charging as Li-Ion batteries should not be operated below 20°C. The need for heating strongly depends on the use cases and mission profiles which must be clearly defined prior to deployment.

3.5 HV circuit

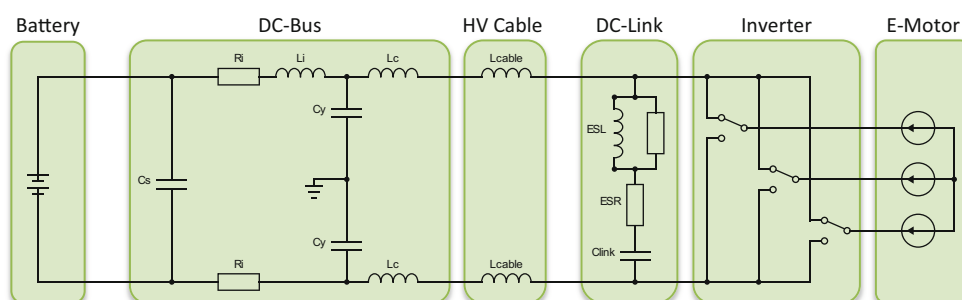
The powertrain, consisting of the battery, inverter, and electric motor, plays a crucial role in the success of electrified aircraft. In this section, we explore the intricacies of powertrain design, and the challenges engineers face in developing a robust and efficient system.

Figure 7 shows the fundamental components of the powertrain. At the heart of every electric powertrain is its battery system. The battery system feeds power into the DC-bus, which is a power distribution system shared by the high-power components. High voltage cables transmit the power towards the inverter. The inverter is responsible for converting the direct current (DC) from the battery into alternating current (AC) to power the electric motor. There, the DC-link capacitor helps prevent the transients on the load side from going back to the distributor side. It also serves to smoothen the pulses on the AC side.

A challenge in the interaction between battery, inverter and electric motor are high peak values and steep edges in the switching currents, which lead to high fluctuations in the voltages, which in turn have a negative impact on the service life of the components in the power train: due to the rapid switching within the inverter, not only does the direct current change due to the changing operating points, but it also incurs a superposition of alternating currents. The ripple is caused by the semiconductor circuit when converting the battery's direct voltage into alternating voltage with variable frequency and amplitude for the engines or into direct current with a different voltage level, e.g., for the low-voltage vehicle electrical system. Although each of these power circuits has a DC capacitor and additional filters to reduce noise during switching, this current and voltage ripple should not be underestimated. Depending on the size of the DC capacitor, the ripple can be more or less pronounced, accordingly reducing lifespan of the battery. The service life can decrease significantly compared to pure DC stress, even dropping to around half of lifetime, see [24].

One way to reduce ripple is to build the inverter circuits with modern wide band gap (WBG) switches, e.g., based on silicon carbide (SiC), instead of the previous silicon IGBTs. This means that much higher

Fig. 7 Schematic representation of an electric powertrain including the essential components



switching frequencies—around 10–40 kHz instead of < 10 kHz—are achieved, which in turn enables a more precise simulation of the required voltage and current curves, so that the resulting ripple is reduced. This advantage results in either a reduced size of the DC-Link capacitor or an increased service life of the battery [25]. showed an example of how doubling the switching frequencies and reducing the DC link capacitor resulted in a lower current ripple level, as well as reduced cost, volume and weight of the DC link.

Unfortunately, there is also a drawback in choosing SiC over silicon IGBTs: Silicon Carbide power devices emit a wider spectrum of electromagnetic waves which pose a fundamental danger of jamming radio and inducing unwanted behavior in electronic systems nearby [26, 27]. While the latter showed, that the minimum losses of two comparable units of the two technologies may drop by more than 80% at 30 kHz, only SiC could effectively implement a 60 kHz operation frequency, as the switching speeds in terms of rise and fall times are three times higher in the case of silicon IGBTs, thus rendering it incapable of switching at higher speeds. Switching at higher speeds in power electronics can generate electromagnetic noise, interfering with sensitive avionic components such as navigation systems, communication equipment, and flight control systems. Cable length exacerbates this issue by acting as an antenna, amplifying the propagation of electromagnetic noise throughout the aircraft. Additionally, parasitic elements in the system further contribute to the noise, complicating the mitigation process. Implementing robust shielding techniques and EMI filters can attenuate electromagnetic interference, preventing it from reaching sensitive avionic components. Since EMI filters are implemented using passive elements, their size and weight decreases with higher switching frequencies, thus making SiC with its higher switching-speeds more favorable. Nevertheless, the filters' contribution to the overall converter weight, size and efficiency still has a significant impact. Further improvements could be made by splitting the EMI filter into a hybrid active-passive system of filters. While the active part may affect the lower frequency region, the passive part can be designed for higher-frequency band attenuation with smaller and more light-weight components [28].

While most high-power applications using SiC technology are to be found in the automotive area, direct transferring that knowledge is limited due to some variations in the powertrain—in eVTOLs mainly BLDC motors are chosen for propulsion, whereas the automotive industry has focused strongly on multi-phase synchronous machines [29]. demonstrate, that also for DC power controls, SiC may pose a valid improvement over silicon, as they present an efficiency of 99.52% at 500 kW operation, resulting in a specific power of 112 kW/kg. Again, steep voltage transients (dv/dt) and currents (necessary to increase the switching frequency) may pose problems on the

entire circuit, e.g., short-circuit protection. While silicon devices may outlast more than 10 μ s of short circuit, SiC devices reduce this time to only a few microseconds [30]. Thus, SiC-based devices require much faster protection circuits, while maintaining their immunity to noise. The high dv/dt and high switching frequencies also result in unwanted interactions between converters and the load, as well as the source. Due to the transmission line effect, the steep pulses may lead to the well-known voltage doubling effect. While the critical cable length for voltage doubling used to be tens of meters for silicon devices, fast SiC devices reduce this number to only a few meters. Especially in aircrafts, matching the cable inductances is an issue, when batteries, inverters and motors are separated farther, and supporting capacitors cannot be placed freely due to structural restrictions. Therefore, special measures can be taken, such as intelligent gate control using soft switching by switching on/off additional gate resistors or implementing several voltage sources for the gate driver circuitry. At the other end of the power device, it is also possible to add voltage filters to limit the dv/dt the load experiences [31].

While SiC is becoming more state-of-the-art in vehicles, gallium nitride (GaN) appears to be a possible, inexpensive alternative for use in vehicles. GaN is already widely used in DC-DC converters, but its feasibility for high-performance aviation applications has not yet been proven. However, the required high performance of such applications cannot be provided by a single element, i.e., several switches would have to be parallelized. This process requires precise planning and an optimized design of the system in the design phase, where the structurally induced spread of parasitics between individual switching elements should be considered; at least to the extent that the cooling system can ensure thermal compensation. Furthermore, even faster switching processes than with SiC devices pose even stronger requirements for short-circuit protection in the range of a few hundred nanoseconds rather than microseconds [32]. In general, all restrictive properties of SiC hold true for GaN in an even more restrictive manner, due to the more extreme switching capabilities of GaN HEMTs (High-Electron-Mobility Transistor).

4 Conclusion

It was presented that the battery is most likely the key component for the commercial breakthrough of eVTOLs. Only the continuous further development of battery technologies will enable a significant increase in energy density (kWh/kg) and thus corresponding ranges and flight times. This should or must also be accompanied by further improvements in safety, lifetime, and fast charging capability. As remarkable aspect, it must be taken into account that battery developments enter the aviation market generally 2–3 years

later due to certification processes, this fact further tightens the relevance of battery deployment.

Designing the powertrain of an eVTOL, several technical and environmental aspects must be considered. When it comes to the choice of motor, different requirements must be fulfilled, that relate to providing sufficient power and torque as well as fulfill safety and reliability aspects. Driving range is still limited in eVTOLs since increased range goes hand in hand with increased weight, therefore, optimizing the utilization of electric motors and increasing the efficiency is crucial. Nevertheless, the electrification results in numerous advantages, especially reduced environmental impact, flexibility and reduced maintenance costs can be pointed out. Currently virtually no of-the-shelf controllers are available for EMs fulfilling airborne software and hardware standards (e.g. addressing Common-Mode Failures).

Due to the advantages at both, device and system level, SiC- and GaN-based power electronics will dominate electrification in aviation. While SiC and GaN devices are evolving rapidly, devices with acceptable voltage limits—2000 V for SiC and 650 V for GaN—are already quite mature in terms of performance, cost and reliability. These commercially available devices are also already being used successfully in many applications, including relatively high-power applications such as electric vehicles.

Due to the high dynamics made possible by the fast-switching transients and high switching frequencies, there is no question that SiC- and possibly GaN-based power electronics will also be developed and used for functions in eVTOL applications. Above all, this results in a smaller space requirement and a significantly lower system weight.

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