BSc Thesis

eVTOL Design Propulsion System

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by

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Abstract

In this thesis, a closer look will be taken into the design of a propulsion system of an eVTOL (electric Vertical Take-off and Landing aircraft). The primary goal of the eVTOL is to maximize the payload for a given maximum take-off weight and the eVTOL has to go into service in 2030. To make an as light weight as possible propulsion system, an investigation will be done for the propeller length and the number of rotors, which is present on a given eVTOL design. In addition to this, different drive choices will be discussed and an optimal drive choice will be made. For this drive, a closer look will be taken in efficiency optimisation. From these parameters a design example will be given using the current state-of-the-art drive technology. In addition to this possible future drive, developments will be taken into account.

Preface

The basis for the research originates from our passion for Electric vehicle's and to a lesser extend aerodynamics. As electronic vehicles get more affordable, combustion vehicles are being phased out of modern culture. This is already visible in the automotive industry, but soon even airplanes and helicopters will suffer the same transition. It is of great importance that when the time is there we'll be ready and have a solid concept to start producing these electronic aircraft.

In writing this thesis we were lucky to have the guidance of Gautham Ram Chandra Mouli, who introduced us to the subject and who guided us through the project. We would like to express our enormous thanks to Jianning Dong who helped steer us in the right direction when we got turned around and answered all our question regarding the subject. Furthermore we would like to thank Daniele Ragni and Tomas Singe, who helped us with the aerodynamic knowledge necessary for this project. Last but not least we want to thank Wiljan Vermeer for his support.

Contents

List of Units and Abbreviations

Units

A	Current line density $[A/m^2]$
B	Magnetic flux density $[Wb/m^2]$ or $[T]$
D	Diameter of the propeller $[m]$
E	Energy $[J]$
f_{sw}	Switching frequency $[Hz]$
n	Angular velocity $[rev/s]$
n_{prop}	Number of propellers
m_{drive}	Mass of the electrical motor $[kg]$
I_s	Stator phase current
J	Advance ratio $[-]$
k_{ed}	Eddy current loss constant $[-]$
k_h	Hysterisis loss constant $[-]$
k_t	Thrust coefficient $[-]$
k_q	Torque coefficient $[-]$
P	Power $[W]$
$P_{conduction}$	Conduction loss $[W]$
P_{copper}	Copper loss $[W]$
P_{eddy}	Eddy current losses $[W]$
$P_{Hysteresis}$	Hysteresis losses $[W]$
$P_{switching}$	Switching losses $[W]$
Q	Torque $[Nm]$
R_s	Phase resistance $[\Omega]$
R_{DSon}	On-state resistance $[\Omega]$
S	Area of the acutator disk $[m^2]$
S_q	Specific torque $[Nm/kg]$
T	Thrust $[N]$
t	Time $[s]$
v	Velocity of the eVTOL in a medium (air) $[m/s]$
V_{rotor}	Rotor volume $[M^3]$
ρ	Density of air $[kg/m^3]$
ω	Angular speed $[rad/s]$

Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
BLDC	Brushless DC
EIS	Entry Into Service
EATS	Electric Aircraft Technologies Symposium
EV	Electric Vehicle
eVTOL	electrical Vertical Take-Off & Landing
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IM	Induction Machine
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MTOW	Maximum Take-Off Weight
NASA	National Aeronautics and Space Administration
PMSM	Permanent Magnet Synchronous Machine
RPM	Revolutions Per Minute
SiC	Silicon Carbide
SRM	Switched Reluctance Motor
UAM	Urban Air Mobility

1 Introduction

This bachelor thesis started with the AIAA/IEEE EATS eVTOL design competition [1]. This is a design competition in which a team of students is required to design an eVTOL (electric Vertical Take-Off and Landing aircraft). The most important design goal for the eVTOL is that the payload is as large as possible for the given maximum take-off weight of 2.5 metric tons. In addition to this, there may be no emission of CO_2 at the vehicle level. Furthermore, the eVTOL design originates from an increasing academic interest in Urban Air Mobility or UAM in short. This is because with the coming technology it becomes feasible to make an all-electric widely available zero-emission UAM.

1.1. Programme of requirements

The main design information that had to be provided are Aircraft design, Electrical design, and a concept of operation, which suits the aerodynamic and the electrical design. For the aerodynamic and electrical design, some requirements were set. These are:

- Range: 100km plus an additional 25km of backup
- Cruise speed of 135kts, which is approximately 250 km/h or 70 m/s
- Operating altitude relative to the ground: 150m (500 ft), and maximum altitude above sea level: 1,070m (3,500 ft)
- Maximum take-off weight (MTOW): 2.5 metric tons
- Anticipated entry of service in 2030
- A fully electric or hybrid of electric and combustion, which produces zero CO_2 at vehicle level

To realize a well-rounded and integrated concept together with the Energy storage subgroup and the Control subgroup and attempt an extra set of requirements were setups. These requirements originate from the points where the designs interface with one another. These additional requirements are given in Section 1.5.

From this point, an aircraft design has been made with all subgroup together as that was deemed as the hardest part to meet the requirements of the challenge. Since the team constisted of electrical engineers only a lot of background research needed to be done to find a solution. This made aircraft design quite difficult and it is certain that the aerodynamic design of the eVTOL is not optimal and thus requires futher research.

1.2. General eVTOL design

The general concept of the eVTOL design has been covered in the energy storage subgroup report, but as some design constraints are the result of the choices made in the general aerodynamic design some considerations are still covered here.

Firstly, a literature study was done on existing eVTOL concepts and aerodynamic effects as this were out of the field of electrical engineering and thus fairly new to us. After this literature study was done, a basic concept was made. There would be a fuselage with two sets of wings attached to it as this would give the most optimal solution for flying 100km with the additional 25km backup.

On each wing, propellers will be put for the propulsion of the aircraft. For the size and number of propellers, an analysis will be made. In any case, the propellers would be made at such an angle that they do not overlap but still be as perpendicular as possible to the wing. As can be seen in Figure 1.1

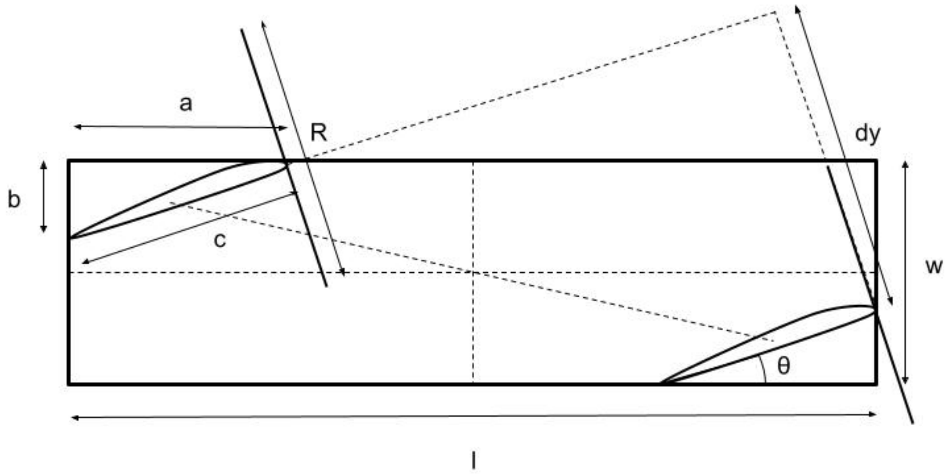


Figure 1.1: A simplified image of the wing and propeller placement

and on the front page of the thesis.
Finally, a model was created to calculate the drag this model would have for each flight phase (take-off. cruise and landing). This gives a minimal model to design the electrical part of the eVTOL, which is the main goal for the bachelor thesis.

1.3. Subgroups

After the general design was made, the group was split into different subgroups to design more in-depth parts of the eVTOL. A subdivision is also required by the bachelor project. The main goals of these subgroups are:

1. The Energy Storage subgroup - the energy storage subgroup is responsible for finding a storage solution for the eVTOL and is responsible for finalizing the aerodynamic design of the eVTOL
2. The propulsion subgroup - The propulsion subgroup is responsible for the choice of the inverter, motor and propeller design of the eVTOL
3. The Control subgroup - The control subgroup is responsible for the control design of the aircraft. In addition to this, they are also responsible for the communication options of the eVTOL.

1.4. Propulsion

For the propulsion subgroup, the main goal is to design a lightweight propulsion solution. To do so, first, a broad view of the available drive and inverter options are reviewed to identify possible solutions and investigate the current state-of-the-art technology to create a baseline. After the most promising technologies are identified, these technologies will be taken a closer look at to get more familiar with the constraints of these devices to be able to give a realistic design on a current propulsion system. Furthermore, since the eVTOL only has to be able to enter service in 2030 an analysis is made for near-future optimizations that could be expected for the current technology. After all, these are taken into consideration, an analysis will be done to give realistic figures on the weight of a potential eVTOL propulsion system. As stated in the subgroup division, the design for a storage solution is not included in the part of the design. However, it is noted that some propulsion considerations may influence the energy storage design and weight and vice-versa. These will also be taken into account for this design.

1.5. Propulsion subgroup Program of requirements

To choose the system some boundary conditions need to be set. There are two types of requirements. This first type of requirements is the requirements that directly follow from the AIAA/IEEE challenge [1] and general aircraft design. The second type of requirements are requirements, which originate from the design of other subgroups of this other bachelor end project.

The first requirements followed from the challenge and the eVTOL concept chosen.

- The propeller diameter must fit on two sets of wings which both have a span of 12 meters
- The motor much not be of such size that it blocks the airflow from the propeller.
- The propulsion system must be powerful enough in all flight cases

The following requirements followed from the design of other subgroups:

- Voltage: 800V. This is to minimise current flow and thus minimise the weight of the cables.
- Peak power: 700 - 800 kW. The peak power the battery can deliver during takeoff.
- Thrust during take-off: 34kN. The amount of thrust generated during take-off at a vertical acceleration of $3ms^{-2}$.
- Thrust during cruise: 2.1kN. The amount of thrust generated to remain at cruise velocity.
- Redundancy: Be able to safely land when one rotor fails.

2 Background

2.1. Possible Drive Types

There are a lot of architectures of possible electrical drive, but as can be seen in electrical cars only some are useful for this kind of applications. The main options are Permanent Magnet Synchronous Machine (PMSM), Induction Motor (IM) and Switched Reluctance Motor (SRM) [2] [3]. These options will be explored and evaluated to find the best drive for the project.

2.1.1. Switched Reluctance Motor

This drive type has not been used a lot yet in electrical cars or eVTOL designs. This is mainly because SRM experiences a lot of torque ripple [2], which can give vibrations while flying. The effects are managed reduced by using power electronics to minimise these negative effects.
A benefit of the SRM is that they are quite reliable and fault-tolerant. Finally, they are relatively cheap as they do not require rare resources which could also give a cost advantage. SRMs provide a power density of approximately 2 to 4.5 kW/L [2], which is not the highest volumetric performance of the drives, but it is certainly workable. The specific power density can be found to be 9 kW/kg for a 25000 RPM drive [4]. To compare this to other drives. This figure is normalized to 1.8 kW/kg at 5000RPM One disadvantage of this, is that these drives have a very high rotational speed, which makes them hard to use in a direct drive system. Using a gearbox is possible but reduces the reliability of the system. Aside of that, gearboxes also give an efficiency reduction and extra weight ([5] proposes a planetary gearbox design with a 97% efficiency and a weight of 3 kg for their target high motor). This makes it hard to work with an SRM for full-electric aerospace applications as the main propeller drive. Additionally, the achievable efficiency of an SRM is approximately 85%-90%, which is acceptable, but higher efficiencies are can be achieved by other motor options. [2].

2.1.2. Induction Machine

The induction machine has windings on its stator and a squirrel cage rotor. To produce torque, a three-phase power on the stator is required. A benefit of the induction machine is that they are quite easy and cheap to make, which could be a big advantage from a business perspective. Additionally, they also offer low torque ripple and thus a very smooth operation. The IM is very robust and provides high reliability due to its simple design. The only flaw in this reliability is that the induction machine is not fault tolerant, which means that if a fault were to happen it is really hard to recover from it, which for aero applications is quite a disadvantage.
The induction machine offers quite a low specific power of around 2.4 kW/kg for a 12,000 RPM drive [4], which normalized to 5000RPM is 1 kW/kg. Additionally, the efficiency of the Induction Machine is also lower with efficiencies from 80% to 86% [2].
Conclusively, the induction machines do have something to offer as it is less expensive and very robust, but due to the lack in performance, it is not suited for aircraft drive applications.

2.1.3. Permanent Magnet Synchronous Motor

The final and last option considered for electrical aircraft applications is the Permanent Magnet Synchronous Machine. This is a brushless design. Theoretically, such drive can be fed with sinusoidal waves or square waves. If such drive is fed with a square wave it is often referred to it as a brushless

DC drive (BLDC), feeding it with a square wave offer much lower torque performance and adds torque ripple to the output. Therefore feeding it with a sine wave is preferred. Then it is called a Permanent Magnet Synchronous Machine (or PMSM), because of the benefits. The PMSM is the only considered option of the two for the final design.
PMSM drives offer good controllability and can be made fault-tolerant with a proper PMSM and inverter design. A drive is fault-tolerant when it's relatively easy to recover from situations that happen out of control. For instance, a bird flies into the propeller and this generates a sudden torque spike. Aside from this they also offer low torque ripple. The only main disadvantage is that PMSM drives require quite some rare earth magnets, which makes them expensive to make and only so many are made. There are proposals for PMSM, which do not used the rarest materials, but they are still not at the same performance level [6].
However, because of these rare earth magnets a high efficiency can be realised which ranges from 90% to 96% in peak performance [2][3]. Thereby they also offer the highest specific power at low speeds, which is about 13.2 kW/kg at 11,500 RPM [7, Fig. 3]. If this is normalized to 5000RPM this would give a specific power of 5.75 kW/kg. Given this, the PMSM is a good option for aircraft powertrain solutions and thus the preferred option. Also, another difference compared to IM and SRM is that the high-efficiency range is more concentrated for RPM but wider for torque [2, Fig. 4]. This can also be an advantage because in aircraft engineering the aircraft is made to fly at a specific cruise speed, which generates quite a small range in rotational speed.

2.1.4. Conclusion

Table 2.1: Comparison of electrical drive types [2] [3]

Motor Type	Power density [kW/L]	Specific Power [kW/kg] [1]	Motor Efficiency [%]	Costs	Redundancy
SRM	2 - 4.5	1.8	85 - 90	Low	High
IM	2 - 3	1	80 -86	Medium	Medium
PMSM	3 - 10	5.75	90 - 96	Very High	Medium

1) Normalized at 5000RPM

Given drives from Table 2.1 the PMSM seems to be the best solution despite its big disadvantage in costs. It offers the best specific power density which makes it the best solution to reduce payload. Additionally, its efficiency is the highest which could also reduce the required battery capacity, which saves weight. So, a PMSM drive will be chosen for the power train.

2.2. Inverter

After the motor type is chosen, a closer look at the inverter will be taken. The inverter is the bridge between the batteries, the control system and the drive. Since a PMSM drive requires three phases sine wave to operate, a three-phase inverter needs to be made of the voltage source inverter type (VSI). The VSI type is a type of converter with six switches (2 for each phase). One of these two switches is turned on and the other is turned off. In that way, the phase is either connected to ground or the DC-supply voltage. In that way, an AC sine wave is created using PWM signals. An example of this topology can be seen in Figure 2.1

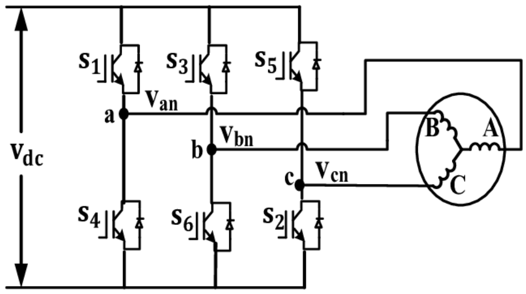


Figure 2.1: An overview of a Voltage Source Inverter (VSI) inverter topology with IGBT switches [8]

Do note that if an SRM is chosen for each phase a H-bridge configuration is required instead of a VSI system, which is another disadvantage of SRM as it requires more costs since more transistors are required.
In order to make an inverter, a transistor type has to be chosen. The main goal of the inverter is to convert the energy as efficiently as possible. This saves weight because it will reduce the required battery and cooling capacity. Additionally, a high switching frequency is required ($f_C > 10kHz$), because a sine wave is needed to drive the PMSM drive. A higher switching frequency will result in a smoother output of the drive and it will increase the efficiency of the drive as the magnetic field will be more like the ideal situation.

2.2.1. Transistor Types

The Insulated Gate Bipolar Transistor (IGBT) is a mature technology. It is a combination between the MOSFET and the Bipolar transistor and was for quite a while the most efficient transistor to switch high voltages and currents since MOSFET based devices would break down under the higher voltages.
The Silicion-Carbide MOSFET (SiC) is a newer type of transistor, which proves to be very efficient. It has much lower switching losses than IGBT because the switching delay is much lower. This also makes that SiC's can operate at a higher switching frequency. The downside of using SiC is a slightly higher conduction resistance compared to IGBT. [9] and they tend to have more voltage overshoot and parasitic capacitance's due to the higher switching speed. [10]. However, compared to IGBT they can reach higher inverter efficiencies and inverters based on SiC can have 25% to 50% lower switching losses. [11]. Therefore SiC MOSFET is preferred as lower switching losses gives a lower requirement on the battery and cooling capacity. The differences can also be seen in Table 2.2.

Table 2.2: Comparison of SiC MOSFET and IGBT parameters [9][10]

	Threshold voltage [V]	Power-on loss [mJ]	Power-off loss [mJ]	Inverter efficiency [%]	Rise / Fall dV/dt [$kV/\mu s$]
SiC Mosfet	0	1.1	0.6	98.8	9 / 10.2
IGBT	0.7	2.05	2.1	97.8	5 / 5

2.2.2. Speed control

For a PMSM and IM motor, there are two possible types of speed control the first is Field Oriented Control (FOC) and the other Direct Torque Control (DTC). The benefit of DTC is that is faster in increasing the torque delivery. Thereby it offers quite easy control of the system. The benefit of Field Oriented Control on the other hand is that it generates much less harmonic distortion (THD) in the output current signals, which allows for quite some less torque ripple at the output of the drive. Because torque ripple is highly undesired, FOC is preferred over DTC despite the extra cost of sensors and the complexity of the technique.[12]

2.2.3. Inverter design

Since SiC MOSFET proves to be the more efficient technology due to its higher efficiency and lower cooling requirements, SiC-based switches will be chosen. In the power, range that's probably required for the eVTOL a choice can be made between a discrete package and a module. The module offers a more complete solution with the cooling included in the packaging. However, this reduces the flexibility in the creation of an optimal cooling solution and thus a discrete package seems to be a better option. This is because the placement of the wing will most certainly allow for a lot of cooling options as the cooling can be provided by the airspeed of the vehicle.

To make a final choice between SiC and IGBT also two modules are compared, which is shown in Table 2.3.

Table 2.3: Comparison of losses between a SiC based module and IGBT based module at I = 400A and T=25°C

	Wolfspeed SiC-based module	Infineon IGBT-based module
Type	Wolfspeed CAB400M12SM3 [13]	Infineon FF400R12KT3_E [14]
DC bus Voltage	800 V	1200 V
Continous current	400A	400A
Turn on energy loss per pulse	4.1 mJ	18 mJ
Turn off energyloss per pulse	3.9 mJ	30 mJ
Drain to source on resistance	4 mΩ	4.8 mΩ [1]
Recovery energy	0.3 mJ	20 mJ
Total conductive loss I =400 A, T = 25°C	640 W	792 W
Total switching loss I = 400A, T = 25°C	332 W @f_{sw} = 40kHz	544 W @f_{sw} = 8kHz

1) This is deduced from the forward voltage at 400A and the resistance towards the pins

From this table, it can be observed that for similar operating conditions the SiC module will create 350 W less heat than the IGBT version. Do not that the SiC is switching at a much higher frequency in this case. For inverters, a higher switching frequency usually means a better sine wave approximation, which usually translates to better motor performance. Added to that is that a higher switching frequency allows for smaller passive filters (smaller inductors and capacitors) which can contribute significantly to these designs. In short the SiC's ability to have lower switching losses at a much higher switching frequency should allow for a smaller, lighter and more efficient design than the IGBT would be able to provide.

According to [15], specific power densities of up to 23.2 kg/kW are already used in current SiC MOSFET inverter technology. According to [16], 50 kW/kg is within reach for 2025. This is backed by a recent release by Wolfspeed [17], which have made a module, that can reach 50 kW/kg. Therefore it is considered that for the eVTOL 50 kW/kg regarding the power electronics is within reach if cooling can be increased without compromising weight. This figure could even be higher. However, there is no indication that the cooling can be increased significantly from this. Efficiencies are considered within the range of 97% - 99% for SiC technology [9] [18]. These figures are for a single module.

If modules are combined in parallel heat can be spread and on-state resistance can be reduced. A trade-off that needs to be made between these benefits and the switching losses. As the device is more easily cooled due to the spread of heat. The temperature will typically be lower in the device itself, which also reduce the switching losses. Therefore a lower load on the SiC does not always give an increase in efficiency [19]. Despite this, a benefit of inverters in parallel could be that this adds reliability to the system. For this reason, adding more inverter modules can still be considered even though it may give a slightly lower efficiency or a slightly higher weight.

3
Physical background

To make a lightweight power system. It is good to understand, which concepts are on that basis of the design. First of all, a Permanent Magnet Synchronous Machine is chosen based on chapter 2. It is assumed that the design cannot get a lot more efficient. With 92% - 96% efficiency in the main operating region, it is unlikely that a lot of ground can be made there. The main goal is to design an as lightweight as possible eVTOL and a lot of development can still be seen in the power-weight-ratio of these drives. In the last few years the a specific power increase of over 20% for electric motors as well as an increase of over 40% in power electronic specific weight [2] can be seen. Furthermore, the influence of propeller design parameters on the efficiency and weight will be explained.

3.1. Motor

To reduce the weight of the propulsion system, first, some basic principles of electrical drives must be understood. The power can be determined based on two metrics, rotational speed (ω [rad/s]) and torque (Q [Nm]). These are combined in Equation 3.1.

$$P = Q \cdot \omega \tag{3.1}$$

So, to achieve high power for our system a high torque, a high rotational speed or both are required. For a higher rotational speed, this doesn't come with an increase in mass. However, this cannot be said for torque. The total torque from the system can be calculated using Equation 3.2 [3].

$$Q = V_{rotor} \cdot 2 \cdot A \cdot B \tag{3.2}$$

In equation 3.2, it can be seen that for a certain drive the torque can only be increased by an increase in volume (V_{rotor}), the current line density (A) or the magnetic flux density (B). The current line density and magnetic flux density can only be increased by decreasing the locally generated heat, which can only be resolved by optimizing the cooling of the device internally.

Do note that this also explains why the PMSM delivers the highest torque density. Since cooling is the main limiting factor, A and B can be higher for a PMSM, because the magnetization can be done without the use of any current due to the permanent magnets. This cannot be said for IM and SRM, which have a metal rotor with induced magnetic flux. Therefore SRM and IM require more current and thus generate more heat for the same output power.

Therefore it can be said that for a certain technological baseline only the volume of the rotor can be adapted to change the amount of torque a drive can deliver. Thus for a certain technology Equation 3.3, the relationship between torque and volume will hold.

$$Q \propto V_{rotor} \tag{3.3}$$

For a simple approximation it could also be said that the V_{rotor} is proportional to the weight of the machine. Dot note that this is not always truly the case as for some drive types, the relative size of to stator compared to the rotor changes for instance. So it could be said that there is a relation to the size of the rotor and the weight of the drive, but it is not linear.

$$Q \propto m_{drive} \tag{3.4}$$

Conclusively it can be said that the weight of the electrical drive system is mostly determined by the torque that is required during flight and the rotational speed the drive has to deliver has a minor influence on the weight.

3.2. Propeller

The design of the propeller can pose a great influence on the ratio between the required speed and the required torque by the electrical drive and thus on the design. To find the thrust (T $[N]$) generated by a given propeller Equation 3.5 can be used.

$$T = k_t(J) \cdot \rho \cdot n^2 \cdot D^4 \tag{3.5}$$

In which k_t is the thrust coefficient, which is characteristic for each propeller shape. The k_t value also depends on the advance ratio, which can be calculated using Equation 3.6.

$$J = \frac{v}{n \cdot D} \tag{3.6}$$

From Equation 3.5, it can be seen that the relation between the rotational speed and the diameter partially depends on the variable k_t. However, since the order of the diameter is to the power four compared to the first power of k_t, it is concluded, that $n \propto 1/D$ for a given thrust. A direct relation cannot be given, because the change in k_t depends on the exact shape of the propeller.

The torque required because of the thrust is given by Equation 3.7. Also for Equation 3.7, there is a constant, in this case, k_q, which is given by the shape of the propeller. This one also depends on the advance ratio.

$$Q = k_q(J) \cdot \rho \cdot n^2 \cdot D^5 \tag{3.7}$$

To find out what the effect on the torque (Q $[Nm]$) is relative to the size of the propeller. Because the change in k_q is not known and does depend on the exact shape of the propeller, a direct relation between Q and D cannot be given. However, due to the order of k_q and D. It can be said that $Q \propto D$ for a given thrust.

Finally, for a static case, which is assumed to be during vertical take-off when flight speed is low. The power required for flying in an optimal case can be given by momentum theory. Of which the formula is shown by Equation 3.8.

$$P = \sqrt{\frac{T^3}{2 \cdot \rho \cdot A}} \tag{3.8}$$

Equation 3.8 can be rewritten to:

$$T = \sqrt[3]{P^2 \cdot \rho \cdot \frac{1}{2} \cdot D^2 \cdot \pi} \tag{3.9}$$

This means that to generate the same thrust with a smaller blade of the same shape, there exists a relation $P \propto 1/D$ in the take-off and landing case. Therefore, if a smaller blade during take-off is used, an increase in power can be experienced.
This is also true for the dynamic scenario as propellers do get more efficient if the diameter increases. Increasing the diameter also increases the torque requirement for a propeller [20], which as discussed later may give some disadvantages for the electrical drive. Beneficially to electrical drives on the other hand, as the diameter is decreased also the RPM goes up. However, increasing the RPM can only be done to some extend. This is due to the loss in propeller efficiency if the tip speed reaches subsonic speeds. In addition to this, if subsonic speeds are reached by the tip of the propeller also the noise emissions go up considerably, which is undesirable for the eVTOL in urban environments.

3.3. Conclusion

From section 3.2 it can be seen that the ratio between torque and rotational can be adjusted by the diameter of the propeller. A smaller diameter will require less torque and higher rotational speed. However, both of them do not scale equally and thus higher powers are required for lower diameters However from section 3.1, it can be seen that a lower torque scales with a lower system weight which is the primary goal in this thesis. In addition to this for most applications, the high-efficiency range of the motor can be set on the required point. Therefore in the next chapter, it will be investigated whether a low system weight can be achieved by sizing the propellers. Additionally, the number of propellers will also be adapted, since the peak powers of the vertical flight cases exceed the power that is expected to be delivered by the energy storage system.

4 Methodology

To find the most optimal, weight-efficient solution for the eVTOL. A method is created to determine the best solution for the power train. Since there is a lot of development in the market, there will probably not be a set answer for now. Hence, a good optimization will be based on two power density scenarios. In the first scenario, it is assumed that at the moment the eVTOL comes to market the specific power (kW/kg) will remain the same as the current state-of-the-art technology. Aside from this base scenario, there will be a scenario with some growth. In the growth scenario, the specific power will approximately be doubled, which is in line with the expectations from [15].

4.1. Design cycle

To optimise the weight in these two scenarios a design cycle is created. For this, the first step is making an aerodynamic concept. This is done with the other subgroups at the start of the project and gives a rough estimation of how the aircraft will look and perform. From this concept come certain requirements for the powertrain. These are mainly based on the power requirements To keep flying.
For this thesis, it meant that the type and number of propellers needed to be determined. This will be further explained in chapter 5. After a propeller design, the drive and inverter choice needed to be taken, which will also be further explained in chapter 5. The motor and inverter design could then give the requirements on the electrical energy storage, who will deliver the power to the electrical system. Additionally, the control subgroup will give the input for the motors in the total system. After the motor and inverter design is done this design cycle could be repeated. An overview of this can be seen in Figure 4.1.

4.2. Propeller

To see the effect of the length of the propeller, a calculator [21] will be used to generate propeller data for a set of propellers. From these propellers, a profile will be made for the dynamic and the static part of the flight. The dynamic part is the part for which the vehicle speed also has to be taken into account. This is the cases when in cruise flight. The static case applies to the case where the aircraft moves slowly. This is during the take-off phase and the landing phase. For these three cases, the required torque and RPM will be set. This will be done for propellers with a diameter ranging from 1.5 metres to 3 metres. The upper boundary is set because for even larger propellers the torque would go too high

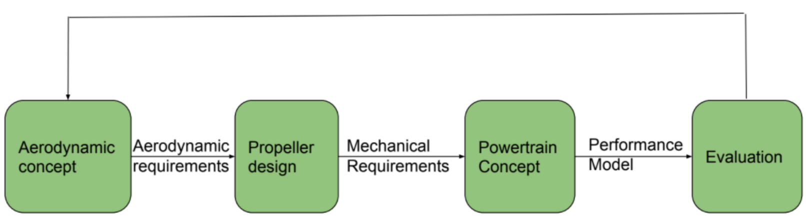


Figure 4.1: Design cycle of the propulsion group

for the electrical motors. On the other hand, if the propellers go smaller than 1.5 meters, a high too high rotational speed is required to generate enough thrust.

Aside from different lengths, also different numbers of propellers will be considered. This influences the amount of thrust required per propeller. This will also be done for a range from 4 to 20 propellers with increments of four. The increment of four is taken because the eVTOL design is set to two wings. The body of the eVTOL doesn't allow for a propeller based in the middle. Therefore increments of four have been taken. The maximum size of 20 is set because given the design limits, only the smallest propellers would fit.

4.3. Motor

After the propeller requirements are made, different drive types are chosen to take into account the change of specific torque over the continuous torque. A particular current state-of-the-art drive series is taken and the torque and motor current are interpolated to give a realistic view of possible options. For the advance in technology, it is assumed that $A \cdot B$ increase linearly. From this data also a weight estimation will be made, which will give an estimation for the weight of the propulsion system when the eVTOL enters service in 2030

4.4. Evaluation

After the propeller data and motor data are combined, estimation on the weight of the drive will be given on each scenario. Thereby also the peak powers will be taken a look at because a battery can only deliver a limited amount of power for its capacity. This is often quantified by the C-rate. It is good to take this into account for the final design since this could also require additional weight for the energy storage system.

5
Final design

This chapter will discuss the final design. This design resulted from the method discussed in chapter 4 and the considerations from chapter 3.

5.1. Considerations

As discussed in chapter 3, the biggest design constraint for our propulsion system is the peak power the can be delivered by the battery. This is because smaller rotors allow for lower torque motors which are in turn lighter than equal power high torque motors. The problem is that disk actuator theory suggests that the power used for hover or low-speed manoeuvring is closely related to the propeller area. A compromise can be found by increasing the number of rotors to decrease the peak power used during take-off.

5.1.1. Propeller Diameter

Another limitation is a combination of the competition and the selected aircraft design. The rules state that the maximum take-off area is a 15-meter diameter circle. The selected aircraft design is a fuselage with 2 sets of wings, on the front and the back. This brings the wingspan to about 12 meters. Knowing these limits one can predict that the rotor diameter is going to fall somewhere between 1.5 and 3 meters, as much larger than 3-meters would not fit for multiple motors per wing, and rotors larger than 3 meter diameter would require so much torque that the motors would always be way too heavy. The rotor is also not going to be smaller than 1.5 meters, as these motors will require a peak power in the range of 1 to 2 Megawatts. This means that the small rotors are unlikely to result in a lighter design as the battery will have to be too big, even with some kind of hybrid solution. In the end rotor diameters from 1.5 to 3 meters are considered with 0.1-meter interval and for every diameter solutions of 4, 8, 12, 16 and 20 are considered. This is because these are the only numbers that can be nicely divided over every wing.

Firstly the solutions that will not fit on the wing are filtered, the results are seen in Table 5.1;

In this table, anything marked green is geometrically possible to fit on our plane. Yellow would be exactly on the limit and red would be impossible. Yellow options will be considered.

5.1.2. Mass

Now for all green and yellow options, a total mass will be constructed. This is done by first finding the required torque and then by using a specific torque estimation. The required torque can be found by using momentum theory, however, the authors found that this was not the best way. Instead, it was chosen to use a calculator provided by an actual propeller manufacturer[21]. The results were similar to what was found to be slightly worse than using momentum theory because it was including several propeller imperfections. Using the calculator Figure 5.1 is created.

	Total Diameter [m]	Number of rotors 4	8	12	16	20
Propeller Diameter [m]	1.5	3	6	9	12	15
	1.6	3.2	6.4	9.6	12.8	16
	1.7	3.4	6.8	10.2	13.6	17
	1.8	3.6	7.2	10.8	14.4	18
	1.9	3.8	7.6	11.4	15.2	19
	2	4	8	12	16	20
	2.1	4.2	8.4	12.6	16.8	21
	2.2	4.4	8.8	13.2	17.6	22
	2.3	4.6	9.2	13.8	18.4	23
	2.4	4.8	9.6	14.4	19.2	24
	2.5	5	10	15	20	25
	2.6	5.2	10.4	15.6	20.8	26
	2.7	5.4	10.8	16.2	21.6	27
	2.8	5.6	11.2	16.8	22.4	28
	2.9	5.8	11.6	17.4	23.2	29
	3	6	12	18	24	30

Table 5.1: Total Diameter for different propeller numbers and diameters

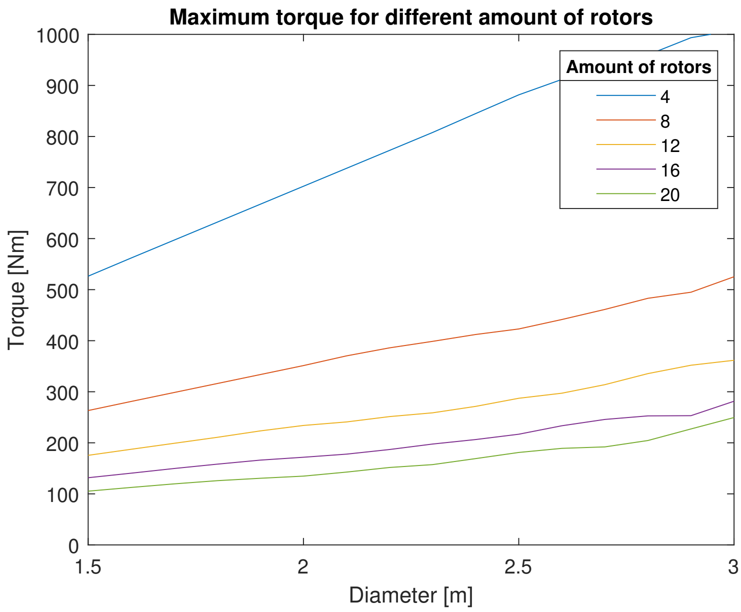


Figure 5.1: Maximum propeller torque for different numbers and diameters of propellers

Next up is the specific torque. As the eVTOL only needs to be in service in 2030 it is not limited by the motors that are on the market right now. In theory, it is possible to develop a motor to specification. To construct a reasonable estimation for this motor the EMRAX motors [22] are used as an example because they have a wide range of motors that are close to this use case. Using the datasheets a relationship between continuous torque and mass is estimated. The resulting estimation can be found in Figure 5.2.

It is worth mentioning that the take-off phase lasts about 30 seconds and is followed by a long horizontal acceleration stage. What this means is that the motor cannot be selected on its peak torque but must be selected on its maximum continuous torque, a torque it can handle indefinitely. Therefore the torques in Figure 5.2 is the continuous torque mentioned in the datasheet of the motors and not the peak torque. Here it is mentioned as being the continuous torque for liquid-cooled motors. In this design, liquid cooling is not intended. However, the authors argue that these motors still qualify, as they only have to provide this torque for about a minute and the air temperature at 1000m is at average only 8.5°C. The motors also have plenty of time to cool down during cruise before having to apply themselves again during landing.

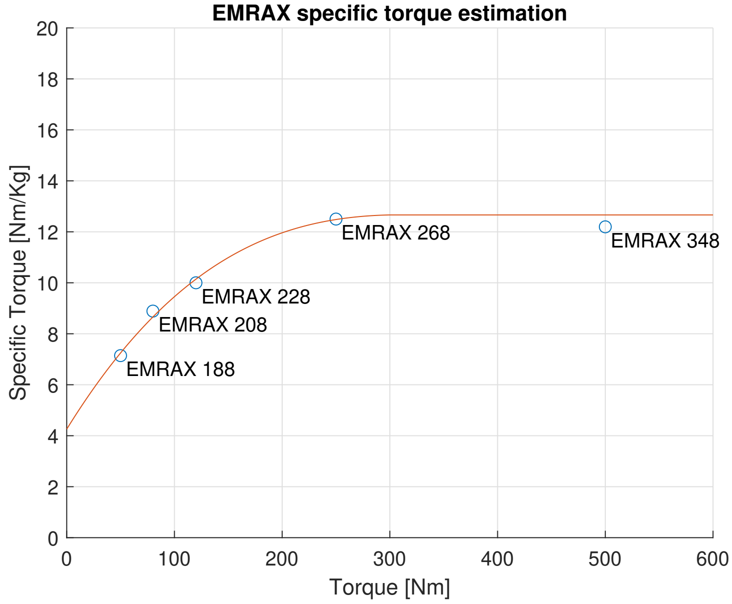


Figure 5.2: The specific torque of various EMRAX motors and interpolation.

From this relationship, it is easy enough to find the mass per motor, and from that the total motor mass. In short, the equation used is this.

$$m = n_{propeller} \cdot \frac{Q}{S_q} \tag{5.1}$$

- n_{prop} The number of propellers, and thus the number of motors.
- S_q Specific Torque [Nm/kg].
- Q Torque [Nm]

And thus now the total mass for all different diameters and propeller numbers is:

From Figure 5.3 it is easy to spot that an eVTOL with 8 propellers and a propeller diameter of 1.5 meters is the lightest solution for 167.7 kg. However, this solution actually will not be possible due to peak power limitations from the energy storage. This will be further examined in the next subsection.

5.1.3. Power

The power during take-off can also be found using Equation 3.8. However, just as with the torque it was chosen to go with a manufacturers calculator instead. The results were again close to the momentum theory result with imperfections taken into account. The peak power for every concept can be seen in Figure 5.4

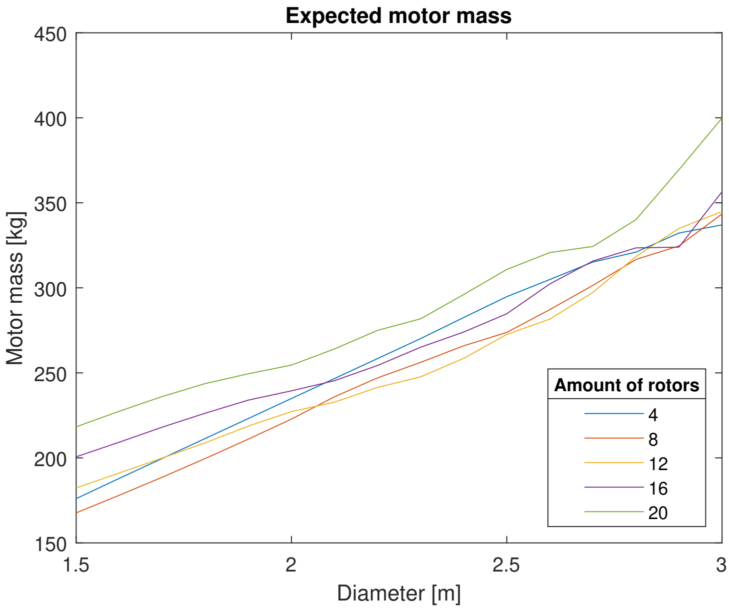


Figure 5.3: The expected motor mass for different propeller numbers and diameters

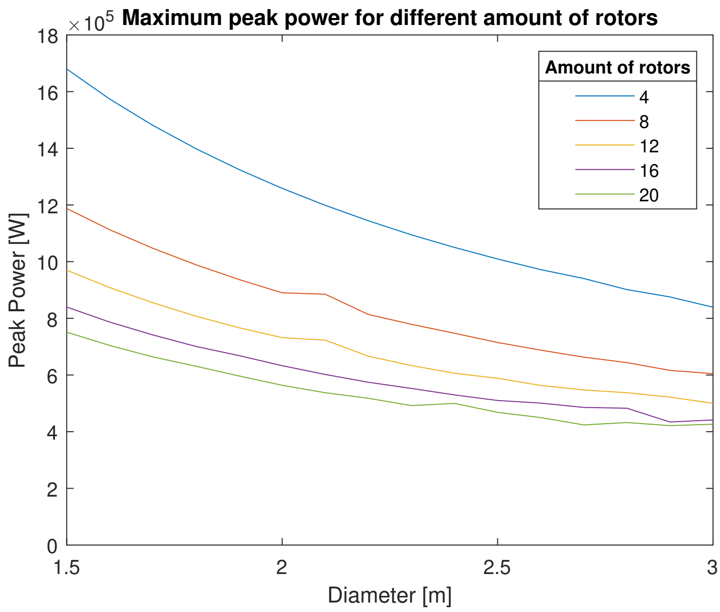


Figure 5.4: Peak power for different propeller numbers and diameters

5.1.4. Result

From Figure 5.4, Table 5.1 and Figure 5.3 it is possible to find the optimal setup for a given possible peak power. From the energy storage subgroup, it is known that the maximum possible peak power for take-of lies somewhere in between 700-800 kW. From this, the best possible solution is a 12 rotor version with 2-meter diameter propellers.

	Torque	Peak power	mass	Torque density
1 Motor	234 Nm	61 kW	18.9 kg	12.4 Nm/kg
12 Motors	234 Nm	731 kW	227.2 kg	12.4 Nm/kg

Table 5.2: Preferred Motor characteristics

5.2. Realisation

5.2.1. Current

In this section, parts will be presented that would fit this design if they were picked in today's market. As the EMRAX motors have been looked at so closely it is not a surprise that there is one that fits decently. The EMRAX 268 motor fits well within the torque specifications and is only about 1 kg heavier. This would bring the motor total to 240 kilograms. The propeller calculator mentioned before also provides a rotational speed, which is around 2800 rpm for take-off and 2000 rpm for cruise. The EMRAX 268 datasheet states that for this rpm range it boasts a 96% efficiency. With this, an inverter that can deliver about 200 kilowatts will suit this motor fine, as that is its maximum power. Smaller sized inverters are possible but will not be able to power the EMRAX to its full power, which may be necessary during turbulence or when a motor fails. The CRD200DA12E-XM3 from Wolfspeed [23] is chosen as a preferred design. It is a reference design of their newest generation SiC technology and is rated for the selected bus voltage and power that is chosen for this project. It also supports encoder feedback, making the control system more robust.

EMRAX 268 AC HV	
Rated Voltage	800 V
Rated Current	125 A
Rated Power	70 kW
Max Power	160 kW
Max Speed	3600 rpm
Weight	20 kg
Cooling	Air

Table 5.3: Details of the EMRAX 268 motor [22]

5.2.2. Future

Even though the EMRAX motors are not that old, innovation is happening all the time. Therefore a small look into the future capabilities of PMSM drives will be taken. In 2025 it is expected that PMSMs can have a torque density of approximately 20 Nm/kg [15]. There are still many opportunities to improve current high-quality PMSM motors. As discussed before in Chapter 2 and 3, the main limitation for the current PMSM drive is the temperature in the PMSM motor. One way that is still being researched are different structural design for motors which allow for more efficient cooling, but this is not the only option. Also, new materials are being investigated as these would allow for a lower resistance or higher temperatures. [6].

If the specific torque target of 20 Nm/kg can be met, an 8 Nm/kg improvement would be made. In this situation scenario a 12 propeller, 2-meter design would still give the best performance a motor weight of 143.8 kg.

6
Energy

Having found the total mass of the motors in chapter 5. The next step is finding out what the total power used during the mission will be. This is necessary for proper battery sizing. To do this properly a load profile of the mission will be made, in combination with efficiency profiles of both the inverter and the motor. Combining both of these profiles one can find a total energy consumption for the entire mission.

6.1. Workflow

To determine the effect the motor choice has on total system weight. Only determining the size of the propeller will not suffice. Not only because the total energy required depends on the size of the propellers, but also because the efficiency of the motor and the inverter depend on torque and rotational speed delivered. However, for the latter, as can be seen in Section 6.3 this can be tweaked to fit the demand.

To create an energy demand for every case, first, a mission profile will be made. This is a profile in which for every flight case the rotational speed en torque is present. The creation of torque and rotational speed value for every moment will be discussed in Section 6.2. From that point, the power for every moment of the flight will be calculated using $P = Q \cdot \omega$. Secondly, the motor and inverter efficiency will be calculated using the method provided in 6.3. These efficiencies will then be used to calculate the power that is required by the battery. This will be done by combining the efficiency with power that has been calculated before. The last step in determining the power is using $E = P \cdot t$ to find the energy for each increment. When all these incremental energies are combined, the total required energy can be calculated.

Together with the energy densities from the battery system estimation and weight estimation of the motor and the inverter. The total effect on system weight from the propulsion system can be given and optimised.

6.2. Mission profile

The creation of the mission profile is separated into two cases. The first part consists of the creation of mission profiles for static cases. These are the cases where the flight speed of the eVTOL are really low and are thus valid for vertical take-off and vertical landing because in those phases of the flight the flight speed is quite low (the average is 5m/s). The second case is the dynamic case. In the dynamic flight case, it is assumed that the eVTOL has a vehicle speed. This is valid for the cruising part of the flight since in that part it can be said that the vehicle speed does have an effect on performance (vehicle speed during cruise is 70 m/s)

6.2.1. Static case

For the static case no airspeed is considered. Therefore, momentum theory does apply, which is given by Equation 6.1.

$$P = \sqrt{\frac{T^3}{2 \cdot \rho \cdot A}} \tag{6.1}$$

A downside of momentum theory is that it does not offer a relation between the rotational speed and the torque. To make a good mission profile for the torque in the static case, momentum theory thus does not provide enough information. Therefore for the static case, a propeller calculator is used [21] in that way a distinction is made between torque and RPM. As can be in Chapter 5 and Section 6.3, this distinction can have quite some effect on the design of the propulsion system.

6.2.2. Dynamic case

For the dynamic case, the formulae, which were also given in Chapter 3 do apply. These are $T = k_t(J) \cdot \rho \cdot n^2 \cdot D^4$ (Equation 3.5) and $Q = k_q(J) \cdot \rho \cdot n^2 \cdot D^5$ (Equation 3.7). From these equations, the required rotational speed and torque can be calculated using the thrust [N] given by the Energy Storage subgroup.
However, as was already mentioned in Chapter 3, the k_t and k_q parameters are determined by the shape of the propeller. To get a good reference for the requirements on the eVTOL. The propeller calculator from [21] is used to obtain a good estimation on k_t and k_q.

6.2.3. Conclusively

By using the two flight cases in each phase of the flight a mission profile can be set up for the rotational speed and torque separately. From that point on the required power can be estimated for an ideal case. If this data is also combined with the efficiency maps, which will be presented in the next section. A good estimation can be made for the peak power and the total energy which has to be provided by the energy system.

6.3. Efficiency profile

A motor and inverter often come with an existing efficiency profile right in their datasheet, as is the case with the EMRAX motors [22]. This enough for a few operating points, but for this project, a solution was desired where one could fill in any mission profile and the total energy could be calculated. This led to a solution where a model of the motor and inverter would be useful.

6.3.1. Motor Loss

The losses experienced inside of a motor can be categorized into a total of 3 different types of losses. These are copper losses, iron losses and friction losses.

Copper losses
The copper losses in a motor drive describe the losses in the phase windings. These losses arise due to the electrical resistance of the copper itself.

$$P_{copper} = 3 \cdot I_s^2 \cdot R_s \tag{6.2}$$

Where I_s is the phase current in RMS, R_s is the phase resistance and as there are 3 phases it is the total times 3. However as one ideally would like to map these losses to torque and rotational velocity, this equation is not entirely sufficient. To relate this loss to torque one can use the torque constant, which for the EMRAX 268 is $k_T = 1.9$[22]. Note that torque is noted with Q rather than T to avoid confusion with thrust.

$$k_T = \frac{\sqrt{2}}{3} \cdot \frac{Q}{I_s}, I_s = \frac{\sqrt{2}}{3} \cdot \frac{Q}{k_T} \tag{6.3}$$

Combining Equation 6.2 and Equation 6.3 it is possible to find an equation for the copper loss that is dependent on torque.

$$P_{copper} = \frac{2}{3 \cdot k_T^2} \cdot Q^2 \cdot R_s \tag{6.4}$$

This loss holds up to the rated rotational velocity, as above that the torque is not just dependent on current but also on voltage. For this area Equation 6.2 will be used.

Iron loss
Just like copper loss describes the loss generated in the copper windings, iron loss describes the loss generated in the iron core. One form of iron losses is hysteresis losses. Hysteresis losses exist because of the magnetisation and demagnetization in the core, constantly aligning and realigning the magnetic dipoles with the changing magnetic field [24]. Another form of loss in the core comes from eddy currents, where the changing magnetic field induces small current loops inside of the iron. This is mitigated by making the core of thin laminations[25].

Both of these losses are dependent on rotational speed and behave as a second-order system.

$$P_{eddy} = k_{ed} \cdot \omega^2 \tag{6.5}$$

$$P_{Hysteresis} = k_h \cdot \omega \tag{6.6}$$

Where k_{ed} and k_h are approximated to be constants. Their exact value is not able to be derived from a motors datasheet but can be estimated through a linear regression algorithm that will attempt to fit the motors efficiency graph to the loss model.

Other losses
It is worth mentioning that some other losses will be omitted. These are losses due to friction and wind resistance. They will not be further explored because friction takes the form of a first-order system, just like eddy current loss and for wind resistance losses the propellers wind resistance is assumed to be much higher than that of the rotor.

All motors also experience a small constant loss, even when stationary and under no torque. This is due to the complex harmonics and standing waves from the fast switching inverters. For a better possible fit, these will be taken into account.

6.3.2. Inverter

The next component in the flow of energy is the inverter module. Here an efficiency module will be built as a function of torque and rotational velocity of the motor. In this case, a constant temperature of 25°C is assumed. This is mainly because it mainly influences the switching losses which are constant over all velocities, and thus will not influence the optimal operating region. What also is not taken into account are other losses due to harmonics and passive components. This is because that is not a degree of insight that is being looked for at this point in development. Were this inverter developed this should not be omitted.

Conduction Losses
Conduction losses are comparable to the copper losses of the motor, as they are the result of current running through a resistive medium. The equation is then also similar to Equation 6.2. The only part of this equation that instead of the phase resistance the on-state resistance of the transistor is used.

$$P_{conduction} = 3 \cdot I_S^2 \cdot R_{DSon} \tag{6.7}$$

For the CAB400M12XM3 [13] the drain-source resistance during its on-state (R_{DSon}) is around 4mΩ. Now, this is dependent on current but one would rather that this is dependent on torque. For this one can use the torque constant in Equation 6.3 to write the following relation.

$$P_{conduction} = \frac{2}{3 \cdot k_T^2} \cdot Q^2 \cdot R_{DSon} \tag{6.8}$$

Switching Losses
Switching losses for Sic MOSFET inverters can be modelled when one knows the average energy lost during switching. This information is often found ready in the datasheet for a set operation window. The CRD200DA12E-XM3 [23] that was chosen in chapter 5 uses the CAB400M12XM3 [13] module. The datasheet of this module includes a plot for a drain-source voltage of 800 volts, which suits the voltage chosen for this project.

Table 6.1: Relation between Drain-source current and Switchingloss

Drain-source current (A)	100	200	300	400	500	600	700	800
Energy lost (mJ)	3	6	9	13.5	16	18	23	27

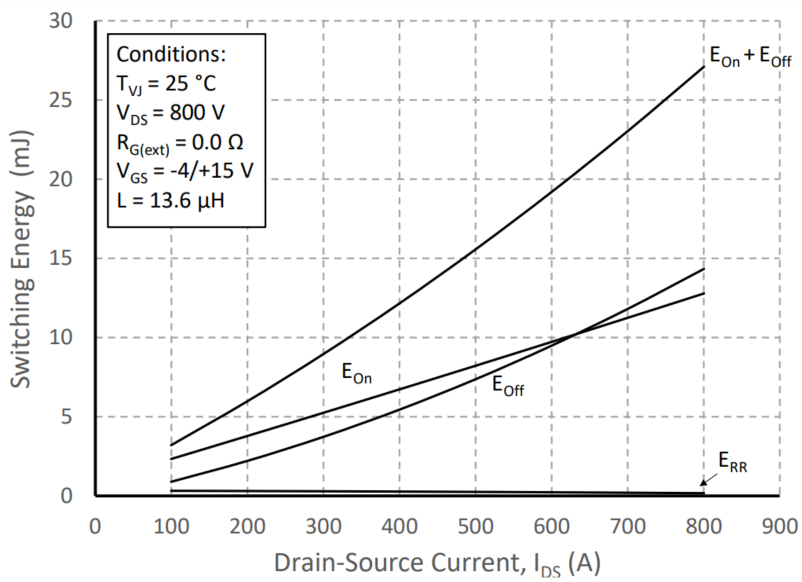


Figure 6.1: Switching Energy of the CAB400M12XM3 [13]

From this graph, one can construct a table for the total energy loss for a given current.

As this is the total amount of energy lost during one single switch, all one needs to do to find the total switching losses is multiply this amount of energy with the switching frequency and the number of transistors.

$$P_{switching} = 6 \cdot Energylost * f_{sw} \tag{6.9}$$

Result

Now when the conduction losses and switching losses are calculated one can plot the inverters efficiency graph. For the CRD200DA12E-XM3 the efficiency can be seen in Figure 6.2.

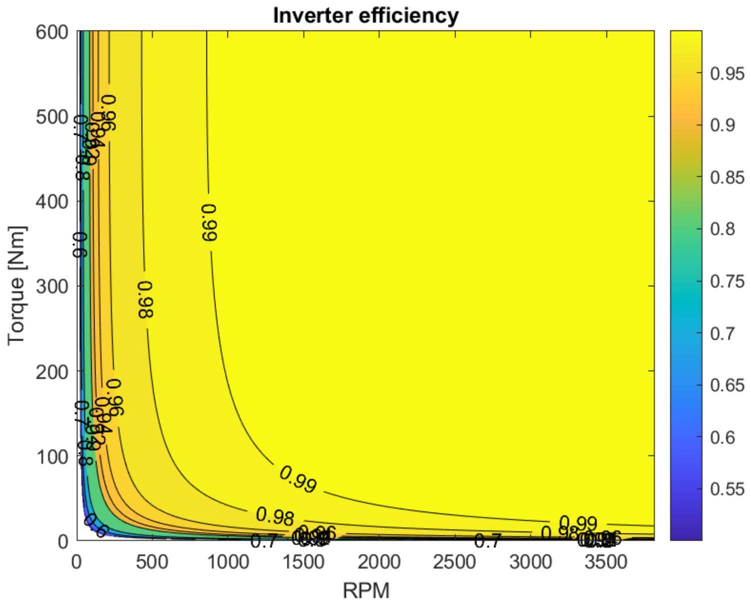


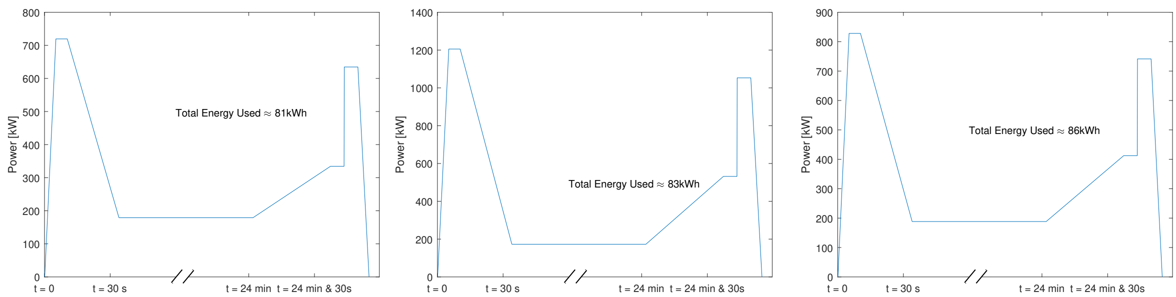
Figure 6.2: Efficiency of the CAB400M12XM3

The operating region of the motor is somewhere between 2000 and 2800 RPM as found in subsection 5.2.1. This means that the entire range of rotational velocity lies in the high-efficiency region of this inverter, above 98%. This will help in cooling the inverter and keeping the cooling system weight down.

As stated at the beginning of this section the reader should keep in mind that the actual efficiency could be lower due to harmonics and passive components and will also decrease for higher temperatures.

6.4. Total Energy

The total energy required by the battery of the system will be calculated by combining the mission profile and the total energy profile it can be seen that approximately the same amount of energy is used for bigger and smaller propeller variants. However, the variant with the smaller props does have a much higher peak power requirement. These results can be seen in Figure 6.3.



(a) 3 diameter radius of 8 propellers using the EMRAX 268 drives

(b) 1.5 diameter radius of 12 propellers using the EMRAX 268 drives

(c) 2 diameter radius of 12 propellers using the EMRAX 268 drives

Figure 6.3: A comparison of the total required energy of three different setups

7
Conclusion

The question that we set out to research was the question: ”What is the max payload (in kg) that can be achieved for an eVTOL aircraft”. In this thesis, the propulsion part of this aircraft is researched. The goal ultimately is to get the propulsion system to be as light as possible, as the total maximum weight is predetermined and set at 2500kg. As this aircraft had to fly over 100km at high speeds it was determined that the best way to minimise powertrain weight is to make sure that the cruise stage requires as little power and energy as possible. From this, the decision was made to go for a lift and cruise type aircraft. These types of air crafts come in different concepts, depending on what changes the vector of thrust. A few examples are tilt-rotor aircraft, tilt-wing aircraft and independent thrust aircraft. The aircraft discussed here changes its entire orientation. This way it does not require heavy and complex mechanisms to rotate wings or motors and thus it increases its reliability and weight.

From this point, the wing area and configuration was to be determined and ultimately decided to be 2 sets of wings. The challenge dictated that the aircraft must be able to take off within a 15-meter diameter circle and so the wingspan of each wing set was set to be at 12 to fit inside this circle. After this, the rotor count and size needed to be determined. The goal was to find a solution where the sum of all motors would be as small as possible. In the end, it was found that for current technology the lightest configuration was 12 rotors of 2m diameter. Lighter options were geometrically possible but would require enormous amounts of peak power during take-off. From this configuration, a set of motor requirements was constructed that allowed for a preliminary motor and inverter selection. These were then modelled to finally find a total energy consumption for an entire flight.

7.1. Solution

This section contains details of all the components that were chosen for the final powertrain, as well as a summation of the final weight of the system.

Table 7.1: Details of the EMRAX 268 motor [22]

EMRAX 268 AC HV	
Rated Voltage	800 V
Rated Current	125 A
Rated Power	70 kW
Max Power	160 kW
Max Speed	3600 rpm
Weight	20 kg
Cooling	Air

Figure 7.1: EMRAX 268

Figure 7.2: Wolfspeed CRD200DA12E-XM3 inverter

Wolfspeed CRD200DA12E-XM3	
Rated voltage	800 V
Rated Current	240 A
Max switching frequency	80 kHz
SiC Module	CAB400M12XM3
Weight	6.2 kg

Table 7.2: Details of the Wolfspeed CRD200DA12E-XM3 inverter [23]

Wolfspeed CAB400M12XM3	
Rated voltage	1200 V
Rated Current	400 A
On state resistance	4.0 mΩ
Switching Energy 800V, 400A	12 mJ

Table 7.3: Details for the Wolfspeed CAB400M12XM3 SiC Half-Bridge Module [13]

Total Weight	Quantity	Per unit weight	Total Weight
EMRAX 268 AC HV	12	20.0 kg	240.0 kg
Wolfspeed CRD200DA12E-XM3	12	6.2 kg	74.4 kg
Total			314 kg

Table 7.4: Total weight for the system

7.2. Recommendations

This aerodynamic vehicle discussed in this thesis has been entirely conjured up by a group of 6 electrical engineering students in a period of 1 quarter year. It is safe to say that for this aircraft to flex its wings there are a lot of stones still left unturned. In this section, a few major ones will be briefly introduced and discussed, so that it may provide a starting point for future engineers to take up this challenge.

- **Propeller design** This is the biggest one. Entirely lacking the knowledge to design and simulate a propeller from the ground up the authors had to rely on a calculator from a propeller manufacturer that did not provide insight into what exactly was happening. This calculator was also limited to purely unducted rotors with 2 blades and was likely intended for propellers of a much smaller diameter, as the largest one that the manufacturer sells is a 37-inch propeller, slightly less than a meter.
- **Aircraft design** Just like the propeller design the authors think that there is room for improvement in the rest of the aircraft, from wing shape to the core concept. There are a lot of design consideration and processes that were not explored to their fullest so the authors recommended starting from the bottom with this one.
- **Drag sensitivity** One thing that the authors failed to accomplish was a way to evaluate the effect the rotor diameter has on drag. The fuselage lies at an angle to prevent propeller overlap. The angle used here was for the case of 8 rotors of 3 meter diameter. If the rotor diameter were to shrink the fuselage could be flatter during cruise, decreasing its frontal surface and thus decreasing its drag. However the drag coefficient would also be affected and to model this was out of the

scope of this project.

- **Boost pack** As found in chapter 5 the peak power required for taking off becomes very high to the point that the design is constrained by the power the energy storage can deliver. A way to remedy this might be by applying a sort of ”boost pack”, likely taking the shape of lithium capacitors designed to deliver a higher peak power during take-off so that a smaller rotor diameter and motor size may be chosen.
- **Extended inverter modelling** In this thesis the inverter performance is modelled at a quite basic level. It does not include harmonics, the influence of passive components and the temperature-dependent nature of the system. These are all things that in this model will cause a lower total efficiency. They become rather more important when this system is realised as the harmonics will cause dangerous voltage spikes at the motors power terminals, and higher temperatures make the system less efficient, thus also increasing temperature once again.

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