

CRANFIELD UNIVERSITY

M. BICZYSKI

SWITCHED RELUCTANCE MOTOR ACTUATING
SYSTEMS FOR MULTIROTOR AIR VEHICLES

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING
Aerospace

PhD
Academic Year: 2021–2022

Supervisors: Dr J. F. Whidborne, Dr R. Sehab, Prof. P. C. K.
Luk, Dr G. Krebs
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Abstract

Among the race to net zero emissions, new vehicle concepts are thriving. Multirotor air vehicles are popular for consumer-grade applications like sport or photography, but they are also considered to solve the challenges of Urban Air Mobility. By analysing the multirotor vehicles and their typical faults, the highest severity of faults is attributed to the actuating system, of which the central component is the electric motor. Comparing available technologies, switched reluctance (SR) motors are deemed a promising solution due to their high degree of fault-tolerance, ruggedness, sustainability and the lack of permanent magnets. Therefore, this study presents a process of designing an SR motor actuating system for use in multirotor vehicle applications. The efforts are focused on achieving desired functionality and documenting technical challenges, rather than achieving an optimal design.

A pre-study on multirotor vehicle sizing methodology based on databases of off-the-shelf components is presented. This is then expanded to cover systems with electric motors in general. Based on sizing specifications, a set of SR motors is optimised for a range of vehicle weights. One design (corresponding to 8 kg quadrotor vehicle) is chosen for further analysis and manufacture. A PI controller-based control solution is developed and implemented, along the model of the whole actuating system in a simulator. Simulated performance is compared with that of a reference BLDC motor actuating system. In addition, system behaviour is analysed in the presence of uncertainties and injected faults. Results are expressed in terms of Loss of Effectiveness (LOE) metric used for the development of fault-tolerant control. The SR motor actuating system is then verified to be of adequate performance and good fault-tolerance, especially against open circuit faults in

one or two phases. However, the system was found to be susceptible to position sensing system failure. In a preliminary comparison with BLDC motor actuating systems, the designed system is comparable in terms of performance, advantageous in terms of fault-tolerance and of considerably higher weight, which is attributed to immaturity of the technology. Sources of the SR motor system advantages are identified as reluctance torque and separation of phases, and recommended for further study.

Keywords

Multicopter; UAV; Actuating system; Switched reluctance; Electric motor; Fault-tolerance; Reliability.

Thesis Summary

One of the main concerns of the current age is the ongoing global warming. Human activity already has caused the observed global mean surface temperature to reach about 1°C higher compared to the pre-industrial revolution level. There is a possibility to halt the warming by reducing the CO_2 emissions and non- CO_2 radiative forcing. Already regions, cities, companies and higher education institutions are pledging to reach their net-zero targets. The transport sector is a big contributor to green house gases (including CO_2), emissions. This has led to re-think the concept of air transportation in search of ways to reduce reliance on fossil fuels and greenhouse gases emissions. New paths pursued include completely novel vehicle designs, centred around the Urban Air Mobility (UAM) concept.

Multicopter air vehicles are one of such designs. At large sizes, these are thought to carry passengers over short distances in densely populated urban areas. But even at small and medium sizes, they have become immensely popular as unmanned air vehicles (UAV), with applications ranging from sport and recreation, through surveillance systems to package delivery. With the introduction of more and more of such vehicles into the public airspace, the question of safety becomes vitally important. Although small unmanned multicopters have relatively low kinetic energy, thus being unable to damage structures, they still pose a threat to humans on the ground or other vehicles in the air. This situation escalates when passenger-carrying vehicles are considered and the possible consequences of a failure worsen. Therefore, there is benefit in researching multicopter vehicle systems (specifically actuating systems) of enhanced robustness and improved resilience to ensure the ability of safely landing in case of a fault or failure.

Fault is a state of the system that might lead to failure or malfunction of the vehicle. Typically, in a multirotor faults can occur in sensors, actuating system (motors, converters and battery) or in vehicle's structure. The worst case scenarios are loss of efficiency of complete loss of an actuator, which can change dynamics of the vehicle leading to instability. Most faults leading to critical consequences happen in the actuating system and conventional preventive measures add excess weight leading to decrease in performance.

Actuating system architecture is mainly determined by the motor technology used. The two most popular motor technologies currently are the induction motor and brushed DC motor. The first one, although reliable is not powerful enough at sizes considered for multirotor propulsion. The second is used only in toys due to low reliability because of physical commutator. Most multirotors nowadays use brushless DC motors due to their high power density and reasonable reliability. However, reliance on rare earth magnets is not suitable for safety-critical applications such as UAM. They are prone to demagnetisation in high temperatures and the spinning rotor can still induce voltage, even if the motor is unpowered, for example during a fault. A solution might lie in reluctance machines. Out of two designs analysed - synchronous reluctance motor and switched reluctance motor - the latter is more promising.

Although SR motor electrodynamics and control may seem complicated, basic drive systems are actually easy to realise thanks to high-speed control units and smart sensors. However, it needs to be noted that this technology lacks universality, as controllers are tied to motors due to the need of accurate switching based on commutation angle data, which is unique to every motor design. In addition, modern control techniques require even more specific motor data to ensure high-efficiency and reliable operation.

As a pre-study, simple models and component databases are used to develop the actuating system sizing methodology. In addition, expected flight time for the sized system is obtained. The approach has simple inputs (MTOW) and outputs (flight time), as well as reduced number of iterative loops, therefore can be computed quickly to obtain preliminary actuating system design or as a part of another routine. The results were valid-

ated with a number of examples using data from commercial small- and medium-sized vehicles. Because of its dependence on databases, the methodology is of limited usability in designing SR-based actuating systems. The motor database included only BLDC motor data. However, the approach can still be used to size propellers and obtain speed and torque data.

To this end, this approach - based primarily on understanding the actuating system as a dynamical system - is extended to cover a wider set of motor technologies used. Requirements and assumptions are put forth to create a versatile tool. The approach is used total of three times throughout the study, with models of increasing complexity, to design and simulate the SR motor actuating system.

A ready-made SR motor actuating system is not available, specifically one tailored to the needs of multirotor applications. Another issue is the need for the motor controller to be designed specific for a given machine to maximise the speed and torque capabilities. Therefore, for this study, a novel SR motor was designed with load specification (propeller) in mind and with a focus on minimising assembly weight. As the power density in the chosen topology is much lower than in comparable permanent magnet motors, it was decided to focus on the fault-tolerance aspect in the design process. That way, performance became a secondary concern and had only to be kept at the level ensuring the feasibility for the multirotor application. Therefore, the machine used in the study was a conventional 4-phase SR motor with 8 stator teeth and 6 rotor teeth.

Out of 39 specification sets analysed, 12 had converged within constraints. During the optimisation process 6946 unique configurations were tested. This creates a suitable dataset for both qualitative and quantitative analysis. The resultant designs cover the range of lifting ratios from 1 to 2.2 kg/rotor . Assuming quadrotor configuration, these would suit 4 to 8.8 kg vehicles. The achieved efficiency range of 55-73% for the motors themselves, is satisfactory for prototyping purposes, especially considering challenging application and immaturity of the technology.

During the motor manufacturing process, the effects of end windings and flux leakage

in 3rd dimension were estimated. These predicted a decrease in the energy stored in the magnetic field, resulting in significantly lower torque. With the small machine size in this case, the end winding length is close to the active winding length. The 2D FEM models used for motor optimisation ignored these effects to increase computation speed.

To resolve the resulting decrease in performance, a number of methods were investigated. Two general approaches of flux curve-shaping and voltage-based, with two methods each, were applied, with varying results. Manual modification of motor geometry was selected as the solution because of a better performance at similar price point to battery exchange method. The resulting, and manufactured, design is referred to as 71x15-30 (71 mm outer diameter, 15 mm stack length, 30 winding turns).

The SR motor actuating system simulator was developed using Simcenter Amesim 17. The simulator was built based on the structure discussed and adopted in the pre-study. Therefore, it follows a modular structure with each module corresponding to a specific component of the vehicle. Cascade PI control was chosen due to its robustness and suitability for systems with unknown dynamics. However, other control solutions were also investigated. Particularly, traditional voltage-PWM and current-hysteresis were found to be underperforming at high speeds. However, techniques that use inductance data are not well suited to be used for this application. For given output power, current demand computed from the inverse of inductance is very high, often exceeding component ratings and possible battery output. Coupled with relatively low voltage and limited current capacity, this makes the control solution unachievable, resulting in sub-par performance.

In a multirotor actuating system, during operation, there is only one desired output variable - thrust. The propeller links thrust to speed to torque with a set of simple characteristics. In this context, the analysis of performance can be simplified to how well the actuating system tracks the input thrust demand. The simulation results of SR motor actuating system are directly compared to BLDC motor measured data. Both systems follow the input signal reasonably well, with slightly higher accuracy of SR motor system. However, at a very high output level, SR motor actuator gets saturated because of the limited

range of the speed-thrust characteristic used in the controller.

The model developed was also used as a simulator to assess the motor performance and investigate the effects of faults and uncertainties. The uncertainty analysis has shown high resilience of the system against error in calibration or noise. However, the position sensing system is a vital element, but its additive and multiplicative types of uncertainties can significantly degrade effectiveness of the whole actuating system. Through fault simulation, SR drivers are found to be perfectly capable of continuing operation in case losing one or more phases, although with decreased performance. They are quick to recover and the main symptom is maximum thrust limitation and a slight decrease in dynamical properties. Combined with previously mentioned properties, this makes it a technology inherently suited for fault-tolerant, safety critical actuating systems.

All of the analysed uncertainties have behaved predictably, following simple curves or even straight lines. Except in the case of delays, increasing the error value gradually decreases effectiveness of the system. Therefore, in case of time-varying uncertainties it allows the control system enough time to react. In addition, SR motor actuating systems have been proven to be generally tolerant towards signal noise, which is one of the more common external disturbances.

It would be safe to estimate that the vehicles would be operated for only a few years before they are exchanged for a newer model. This would also be in line with the expected 5-year lifespan of electric machines in transport applications. Therefore, it makes sense to favour fault-tolerance over reliability, as ultra-long fault-free operation periods are simply not needed.

The two principles used in the SR motor actuating systems - reluctance torque and independent phases have the potential to transform electric machines of the future. Reluctance torque offers potentially lower losses (no copper in the rotor), but not all field energy is converted into work, which results in lower power factor and larger power stage. Separate phases at the motor, converter and control level offer fault-tolerance, but require special (large) power stages. Therefore, for now, these benefits could be used only in niche

applications. However, modern IPMSMs already take advantage of reluctance torque by shaping their magnets, in addition to producing reaction torque, and combining these two types of torque may be a promising approach.

In summary, this work highlights the importance of fault-tolerance in safety critical applications. In addition, multirotor air vehicles are proven to be a very challenging application. However, the designed SR motor actuating system has both reached satisfactory performance and high degree of fault-tolerance. When combined with fault-tolerant control, it may result in a highly resilient and safe vehicle. Although the current level of SR technology cannot compete with BLDC or PMSM in this application, it is worth investigating the principles of reluctance torque and phase independence and their application to other electrical machines. However, SR actuating systems may be of interest for eVTOLs, as the weight constraints are somewhat more relaxed. The benefits of fault-tolerance and the gradual decrease of efficiency with increasing uncertainties is much more important, as there are passengers on board.

Résumé de la Thèse

L'une des principales préoccupations de l'époque actuelle est le réchauffement climatique en cours. L'activité humaine a déjà provoqué une augmentation de la température moyenne à la surface du globe d'environ 1°C par rapport au niveau de la révolution préindustrielle. Il est possible d'arrêter le réchauffement en réduisant les émissions de CO_2 et le forçage radiatif non CO_2 . Déjà, des régions, des villes, des entreprises et des établissements d'enseignement supérieur s'engagent à atteindre leurs objectifs de réduction nette zéro. Le secteur des transports est l'un des principaux responsables des émissions de gaz à effet de serre (dont le CO_2). Cette situation a conduit à repenser le concept du transport aérien afin de trouver des moyens de réduire la dépendance aux combustibles fossiles et les émissions de gaz à effet de serre. Les nouvelles voies suivies comprennent des conceptions de véhicules totalement nouvelles, centrées sur le concept de mobilité aérienne urbaine (UAM).

Les véhicules aériens multirotors sont l'un de ces modèles. De grande taille, ils sont conçus pour transporter des passagers sur de courtes distances dans des zones urbaines densément peuplées. Mais même à petite et moyenne échelle, ils sont devenus immensément populaires en tant que véhicules aériens sans pilote (UAV), avec des applications allant du sport et des loisirs à la livraison de colis, en passant par les systèmes de surveillance. Avec l'introduction d'un nombre croissant de ces véhicules dans l'espace aérien public, la question de la sécurité revêt une importance vitale. Bien que les petits multirotors sans pilote aient une énergie cinétique relativement faible et ne puissent donc pas endommager les structures, ils constituent toujours une menace pour les personnes au sol ou les autres véhicules en l'air. Cette situation s'aggrave lorsque l'on considère les véhicules

transportant des passagers et les conséquences possibles d'une défaillance s'aggravent. Par conséquent, il est avantageux de rechercher des systèmes de véhicules multirotors (en particulier des systèmes d'actionnement) d'une robustesse et d'une résilience accrues afin de garantir la capacité d'atterrir en toute sécurité en cas de défaillance ou de panne.

Un défaut est un état du système qui peut entraîner une panne ou un dysfonctionnement du véhicule. Typiquement, dans un multirotor, les défauts peuvent se produire dans les capteurs, le système d'actionnement (moteurs, convertisseurs et batterie) ou dans la structure du véhicule. Les pires scénarios sont la perte d'efficacité ou la perte totale d'un actionneur, ce qui peut modifier la dynamique du véhicule et entraîner son instabilité. La plupart des défaillances entraînant des conséquences critiques se produisent dans le système d'actionnement et les mesures préventives classiques ajoutent un poids excessif qui entraîne une diminution des performances.

L'architecture du système d'actionnement est principalement déterminée par la technologie du moteur utilisé. Les deux technologies de moteur les plus populaires actuellement sont le moteur à induction et le moteur à courant continu à balais. Le premier, bien que fiable, n'est pas assez puissant aux tailles considérées pour la propulsion des multirotors. Le second est utilisé uniquement dans les jouets en raison de sa faible fiabilité due au collecteur physique. La plupart des multirotors utilisent aujourd'hui des moteurs DC sans balais en raison de leur haute densité de puissance et de leur fiabilité raisonnable. Toutefois, la dépendance à l'égard des aimants en terre rare ne convient pas aux applications critiques en matière de sécurité telles que l'UAM. Ils sont susceptibles de se démagnétiser à des températures élevées et le rotor en rotation peut toujours induire une tension, même si le moteur n'est pas alimenté, par exemple en cas de panne. Une solution pourrait résider dans les machines à réluctance. Sur les deux conceptions analysées - moteur à réluctance synchrone et moteur à réluctance commuté - la dernière est plus prometteuse.

Bien que l'électrodynamique et la commande des moteurs SR puissent sembler compliquées, les systèmes d'entraînement de base sont en fait faciles à réaliser grâce à des unités de commande à grande vitesse et à des capteurs intelligents. Il convient toute-

fois de noter que cette technologie manque d'universalité, car les contrôleurs sont liés aux moteurs en raison de la nécessité d'une commutation précise basée sur les données de l'angle de commutation, qui est unique à chaque conception de moteur. En outre, les techniques de contrôle modernes exigent des données encore plus spécifiques sur le moteur pour garantir un fonctionnement fiable et à haut rendement.

En guise de pré-étude, des modèles simples et des bases de données de composants sont utilisés pour développer la méthodologie de dimensionnement du système d'actionnement. En outre, le temps de vol prévu pour le système dimensionné est obtenu. L'approche a des entrées (MTOW) et des sorties (temps de vol) simples, ainsi qu'un nombre réduit de boucles itératives, et peut donc être calculée rapidement pour obtenir une conception préliminaire du système d'actionnement ou dans le cadre d'une autre routine. Les résultats ont été validés par un certain nombre d'exemples utilisant des données provenant de véhicules commerciaux de petite et moyenne taille. En raison de sa dépendance vis-à-vis des bases de données, la méthodologie est d'une utilité limitée pour la conception de systèmes d'actionnement basés sur le SR. La base de données des moteurs ne comprenait que des données sur les moteurs BLDC. L'approche peut néanmoins être utilisée pour dimensionner des hélices et obtenir des données sur la vitesse et le couple.

À cette fin, cette approche - basée principalement sur la compréhension du système d'actionnement en tant que système dynamique - est étendue pour couvrir un ensemble plus large de technologies de moteurs utilisées. Les exigences et les hypothèses sont mises en avant pour créer un outil polyvalent. L'approche est utilisée trois fois au total tout au long de l'étude, avec des modèles de complexité croissante, pour concevoir et simuler le système d'actionnement du moteur SR.

Il n'existe pas de système d'actionnement de moteur SR prêt à l'emploi, en particulier un système adapté aux besoins des applications multiréacteur. Un autre problème est la nécessité de concevoir un contrôleur de moteur spécifique pour une machine donnée afin de maximiser les capacités de vitesse et de couple. Par conséquent, pour cette étude, un nouveau moteur SR a été conçu en tenant compte de la spécification de la charge (hélice)

et en se concentrant sur la réduction du poids de l'assemblage. Comme la densité de puissance de la topologie choisie est beaucoup plus faible que celle des moteurs à aimants permanents comparables, il a été décidé de se concentrer sur l'aspect de la tolérance aux pannes dans le processus de conception. De cette façon, la performance est devenue une préoccupation secondaire et devait être maintenue au niveau garantissant la faisabilité de l'application multirotor. Par conséquent, la machine utilisée dans l'étude était un moteur SR conventionnel à 4 phases avec 8 dents de stator et 6 dents de rotor.

Sur les 39 ensembles de spécifications analysés, 12 ont convergé dans le respect des contraintes. Au cours du processus d'optimisation, 6946 configurations uniques ont été testées. Cela crée un ensemble de données approprié pour une analyse qualitative et quantitative. Les conceptions résultantes couvrent la gamme des rapports de levage de 1 à 2,2 kg/rotor. En supposant une configuration en quadrirotor, ils conviendraient à des véhicules de 4 à 8,8 kg. L'efficacité atteinte de 55-73% pour les moteurs eux-mêmes, est satisfaisante pour le prototypage, surtout si l'on considère l'application difficile et l'immaturité de la technologie.

Au cours du processus de fabrication du moteur, les effets des enroulements terminaux et des fuites de flux en 3 dimensions ont été estimés. Ceux-ci prévoyaient une diminution de l'énergie stockée dans le champ magnétique, entraînant une baisse significative du couple. Compte tenu de la petite taille de la machine dans ce cas, la longueur des enroulements d'extrémité est proche de la longueur de l'enroulement actif. Les modèles FEM 2D utilisés pour l'optimisation du moteur ont ignoré ces effets pour augmenter la vitesse de calcul.

Pour résoudre la diminution des performances qui en résulte, un certain nombre de méthodes ont été étudiées. Deux approches générales, l'une basée sur la courbe de flux et l'autre sur la tension, avec deux méthodes chacune, ont été appliquées, avec des résultats variables. La modification manuelle de la géométrie du moteur a été choisie comme solution en raison d'une meilleure performance à un prix similaire à celui de la méthode d'échange de batterie. Le design résultant, et fabriqué, est appelé 71x15-30 (71 mm de

diamètre extérieur, 15 mm de longueur de pile, 30 tours de bobinage).

Le simulateur du système d'actionnement du moteur SR a été développé en utilisant Simcenter Amesim 17. Le simulateur a été construit sur la base de la structure discutée et adoptée dans la pré-étude. Par conséquent, il suit une structure modulaire, chaque module correspondant à un composant spécifique du véhicule. La commande PI en cascade a été choisie en raison de sa robustesse et de son adéquation aux systèmes dont la dynamique est inconnue. Cependant, d'autres solutions de contrôle ont également été étudiées. En particulier, les techniques traditionnelles de modulation par largeur d'onde en tension et d'hystérésis en courant se sont avérées peu performantes à grande vitesse. Cependant, les techniques qui utilisent les données d'inductance ne sont pas bien adaptées pour être utilisées dans cette application. Pour une puissance de sortie donnée, la demande de courant calculée à partir de l'inverse de l'inductance est très élevée, dépassant souvent les valeurs nominales des composants et la sortie possible de la batterie. Couplé à une tension relativement faible et à une capacité de courant limitée, cela rend la solution de contrôle irréalisable, ce qui entraîne des performances inférieures à la normale.

Dans un système d'actionnement multirotor, pendant le fonctionnement, il n'y a qu'une seule variable de sortie souhaitée - la poussée. L'hélice relie la poussée à la vitesse au couple avec un ensemble de caractéristiques simples. Dans ce contexte, l'analyse des performances peut être simplifiée pour déterminer dans quelle mesure le système d'actionnement suit la demande de poussée d'entrée. Les résultats de la simulation du système d'actionnement du moteur SR sont directement comparés aux données mesurées du moteur BLDC. Les deux systèmes suivent raisonnablement bien le signal d'entrée, avec une précision légèrement supérieure pour le système du moteur SR. Cependant, à un niveau de sortie très élevé, l'actionneur du moteur SR devient saturé en raison de la plage limitée de la caractéristique vitesse-poussée utilisée dans le contrôleur.

Le modèle développé a également été utilisé comme simulateur pour évaluer les performances du moteur et étudier les effets des défauts et des incertitudes. L'analyse des incertitudes a montré une grande résilience du système face aux erreurs de calibration ou au

bruit. Cependant, le système de détection de position est un élément vital, mais ses types d'incertitudes additives et multiplicatives peuvent dégrader considérablement l'efficacité de l'ensemble du système d'actionnement. Grâce à la simulation de pannes, les pilotes SR s'avèrent parfaitement capables de continuer à fonctionner en cas de perte d'une ou de plusieurs phases, bien qu'avec des performances réduites. Ils se rétablissent rapidement et le principal symptôme est la limitation de la poussée maximale et une légère diminution des propriétés dynamiques. Combiné aux propriétés mentionnées précédemment, cela en fait une technologie intrinsèquement adaptée aux systèmes d'actionnement à tolérance de panne et à sécurité critique.

Toutes les incertitudes analysées se sont comportées de manière prévisible, en suivant des courbes simples ou même des lignes droites. Sauf dans le cas des retards, l'augmentation de la valeur de l'erreur diminue progressivement l'efficacité du système. Par conséquent, dans le cas d'incertitudes variant dans le temps, le système de contrôle a suffisamment de temps pour réagir. En outre, il a été prouvé que les systèmes d'actionnement à moteur SR sont généralement tolérants au bruit du signal, qui est l'une des perturbations externes les plus courantes.

On peut estimer que les véhicules ne seront utilisés que pendant quelques années avant d'être remplacés par un modèle plus récent. Cela correspondrait également à la durée de vie prévue de 5 ans des machines électriques dans les applications de transport. Il est donc logique de privilégier la tolérance aux pannes par rapport à la fiabilité, car il n'est tout simplement pas nécessaire de prévoir des périodes de fonctionnement sans pannes très longues.

Les deux principes utilisés dans les systèmes d'actionnement des moteurs SR - couple de réluctance et phases indépendantes - ont le potentiel de transformer les machines électriques du futur. Le couple de réluctance offre des pertes potentiellement plus faibles (pas de cuivre dans le rotor), mais toute l'énergie du champ n'est pas convertie en travail, ce qui entraîne un facteur de puissance plus faible et un étage de puissance plus important. Les phases séparées au niveau du moteur, du convertisseur et de la commande offrent

une tolérance aux pannes, mais nécessitent des étages de puissance spéciaux (de grande taille). Par conséquent, pour l'instant, ces avantages ne peuvent être utilisés que dans des applications de niche. Cependant, les IPMSM modernes tirent déjà parti du couple de réluctance en façonnant leurs aimants, en plus de produire un couple de réaction, et la combinaison de ces deux types de couple peut être une approche prometteuse.

En résumé, ce travail souligne l'importance de la tolérance aux pannes dans les applications critiques pour la sécurité. De plus, les véhicules aériens multirotors se sont avérés être une application très difficile. Cependant, le système d'actionnement du moteur SR conçu a atteint des performances satisfaisantes et un degré élevé de tolérance aux pannes. Combiné à une commande tolérante aux pannes, il peut donner lieu à un véhicule hautement résilient et sûr. Bien que le niveau actuel de la technologie SR ne puisse pas concurrencer le BLDC ou le PMSM dans cette application, il est intéressant d'étudier les principes du couple de réluctance et de l'indépendance de phase et leur application à d'autres machines électriques. Cependant, les systèmes d'actionnement SR peuvent être intéressants pour les eVTOLs, car les contraintes de poids sont un peu plus souples. Les avantages de la tolérance aux pannes et la diminution progressive de l'efficacité avec l'augmentation des incertitudes sont beaucoup plus importants, car il y a des passagers à bord.

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List of Abbreviations

BLDC	Brushless Direct Current
DC	Direct Current
DoD	Depth of Discharge
DoF	Degree of Freedom
DSSRM	Double Stator SRM
DT	Digital Twin
EASA	European Union Aviation Safety Agency
ESC	Electronic Speed Controller
ESR	Equivalent Series Resistance
EV	Electric Vehicle
eVTOL	electric Vertical Take-Off and Landing (Vehicle)
FC	Flight Controller
FEM	Finite Element Method
FPMH	Failures Per Million Hours
FPV	First Person View
ICAO	International Civil Aviation Organization
ID	Inside Diameter
IGBT	Insulated Gate Bipolar Transistor
IMU	Inertial Measurement Unit
LiPo	Lithium-Polymer
LOE	Loss Of Effectiveness

MCSR	Mutually Coupled SRM
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
MTOW	Maximum Take-Off Weight
OD	Outer Diameter
PAV	Personal Air Vehicle
PCB	Printed Circuit Board
PM	Permanent Magnet
RC	Radio Controlled
RMSE	Root Mean Square Error
RPM	Revolutions Per Minute
SMC	Surface Mounted Component
SoC	State of Charge
SPPO	Short Period Pitch Oscillation
SR	Switched Reluctance
SR-SRM	Segmental Rotor SRM
SRM	Switched Reluctance Motor
UAM	Urban Air Mobility
VTOL	Vertical Takeoff and Landing
WOT	Wide Open Throttle

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Chapter 1

Introduction

Multicopter air vehicles produce lift with multiple (typically 4 or 8) rotors driven by corresponding electric motors and powered by a battery. This is known as the actuating system. This study proposes a **multicopter actuating system based around switched reluctance (SR) motors**. It is motivated by inherent fault-tolerance of such system against certain faults, specifically open phase faults. This system is evaluated in terms of performance, reliability and fault-tolerance, as it is assumed to be able to achieve similar performance to currently adopted solutions, while possessing high safety capabilities (Laudensack, Polonskiy & Gerling, 2014). The work started with a literature review and a pre-study on sizing consumer-grade multicopter air vehicles. The findings are then used for the development of actuating system design methodology, SR motor geometry optimisation and actuating system modelling and simulation. The system is then validated, through simulation, in terms of performance and reliability. Loss of Effectiveness metric is used to make the results compatible with studies on fault-tolerant flight control. Due to intended application in multicopters, the designed system is constrained in terms of total weight and temperature during operation. The project concludes with the manufacture of a complete prototype SR motor actuating system, although with a relaxed limit on motor controller (including power stage) weight due to financial and time constraints. Also due to these constraints, flight-testing of a complete vehicle (due to cost of manufacturing a light-

weight motor controller unit) and a reference actuating system simulation (due to time required for an in-depth identification) are not included.

Within the scope presented, this research work has achieved several contributions to the knowledge:

- an approach for multirotor actuating system sizing, utilising system's dynamical model to offer three approaches of increasing model complexity,
- a methodology of SR motor actuating system optimisation for specific torque and speed, with weight and current density constraints, and the motor geometries generated using this approach,
- a direct comparison of SR and BLDC motor actuating systems performance (in terms of thrust) using simulation and measured data, and
- a fault-tolerance evaluation of SR motor actuating system against faults and uncertainties, including open circuit in motor phases, current and position sensors issues.

These contributions combine to validate SR motor actuating systems as a candidate for multirotor air vehicle propulsion, characterised by adequate performance to be used in place of BLDC motor based systems and with a high degree of fault-tolerance.

Throughout the thesis, a number of tools and approaches were used to allow this work to be used in future research and development efforts, as well as provide value to the business sector. The specific components of the project's impact are:

- a vehicle size range suitable to be outfitted with SR motor actuating system, identified based on the feasibility of generated motor designs for a range of weight and thrust requirements,
- an SR motor geometry optimised for a 8 kg quadrotor vehicle application, and the manufactured 4-phase motor unit to be used in testing,
- design optimisation results confirming that a purely reluctance torque motor is sufficient for use in multirotor air vehicle propulsion,

- simulation results confirming the benefit of phase separation for fault-tolerance, specifically in case of open circuit faults, and
- loss of effectiveness (LOE) scores for different types of faults injected into the SR motor actuating system and effectiveness scores for different types of uncertainties (parameter deviations) in the system.

When combined, these findings provide a value of an SR motor actuating system design that can be easily combined (thanks to used metrics) with already available fault-tolerant control schemes to create a highly resilient air vehicle. Such a vehicle has the potential to meet the requirements of safety critical missions and offer an alternative to current solutions.

1.1 Context

The transport sector is a big contributor to green house gas (including CO₂) emissions (IPCC, 2018). The aviation sector alone produced 914 million tonnes of CO₂ in 2019, which accounts for about 2% of all human-induced CO₂ emissions (Air Transport Action Group, 2020, p. 34). This has led to re-think the concept of air transportation in search of ways to reduce reliance on fossil fuels and greenhouse gases emissions. New paths pursued include concepts of more electric, hybrid and full-electric aircraft to be introduced into general aviation. However, there are also completely novel vehicle designs, centred around the Urban Air Mobility (UAM) concept (NASA, 2020; Sharma, 2020).

Multicopter air vehicles are one of such designs, characterised by a distributed electrical vertical propulsion system. At large sizes, these are proposed to carry passengers over short distances in densely populated urban areas. But even at small and medium sizes, they have become immensely popular as unmanned air vehicles (UAV), with applications ranging from sports and recreation, through surveillance systems to package delivery. Mechanical simplicity, flexibility of operations and low cost are the key factors behind the prognosed market growth from 1.86 billion USD in 2019 to 8.49 billion USD by 2027

(Emergen Research, 2020).

With the introduction of more and more of such vehicles into the public airspace, the question of safety becomes vitally important. Although small unmanned multirotors have relatively low kinetic energy, thus being unlikely to damage large structures, they still pose a threat to humans on the ground or other vehicles in the air. This risk escalates when passenger-carrying vehicles are considered and the possible consequences of a failure worsen. Therefore, there is benefit in researching multirotor vehicle systems (specifically actuating systems) of enhanced robustness and fault-tolerance to ensure the ability of safely landing in case of a fault or failure.

1.2 Aims and objectives

In this work, switched reluctance (SR) motors are considered to be used in place of the currently used brushless DC motor in the actuating system, as they potentially offer a higher level of fault-tolerance. BLDC technology is a popular choice for electric propulsion vehicles due to its benefits of high torque at low motor weight and wide speed range. However, there may be missions where enhanced fault-tolerance is desired. Therefore, the aim of the study can be formulated as follows:

Propose SR motor actuating systems as a highly fault-tolerant solution with sufficient performance for safety-critical applications.

Of course, this work is not about proving that one technology is better than the other, but rather contributing to the continuous improvement in the areas of safety and performance of air vehicles. Therefore, secondary aims are also defined:

Evaluate potential increase of reliability and fault-tolerance of multirotor air vehicles in safety critical applications coming from reluctance torque and motor phase independence.

Decrease multirotor air vehicle weight by removing the need for redundancy in commercial applications.

The commercial multirotor market is currently dominated by machines using BLDC-based actuating systems and vehicles using switched reluctance technology are unavailable for purchase. Therefore, this work is concerned more with the design and validation of such system, rather than in-flight performance. The research objectives realised for this project are the following:

1. Determine feasibility of SR motors for air vehicle actuation and identify a suitable vehicle size range for its application,
2. Design an SR motor actuating system for a commercial-grade multirotor vehicle,
3. Verify, through simulation studies, performance and fault-tolerance of the designed actuating system,
4. Manufacture designed actuating system and acquire demonstrator vehicle,
5. Compare static and dynamic performance between BLDC-based (ground testing) and SR-based (simulation) actuating systems.

1.3 Research methodology

The list of objectives given in the previous section is very general and result-driven. It does not account for the workload required. Therefore, this section will detail specific tasks and approaches needed to progress the work. It is important to note, that the project was started with a specific end-goal in mind - test-flight of a multirotor demonstrator with SR-based actuating system - and the workflow follows that. Specific results, however, are a product of this process and together form a picture that achieves set objectives.

The literature review in Chapter 2 provides background on the state-of-art in the areas of multirotor air vehicles, faults, reliability and electric motors. The application vehicle is presented with its specific advantages, uses and challenges. With one of the major challenges being safety, it is reviewed in the context of faults and preventive measures, specifically those in the actuating system. It is investigated how faults arise and develop

and how they are related to components used. Alternative actuating system technologies are also considered, with the electric motor being the defining element. Different available motor technologies are reviewed. It is seen that SR motor seems to be positioned between Induction and BLDC in terms of performance (efficiency, torque density) (Harris & Miller, 1989) and above BLDC in terms of reliability and ruggedness T. J. E. Miller (2002). Thus making it a viable choice for multirotor air vehicles. However, no operational examples of such vehicles were found.

Complete, off-the-shelf, SR motor driven multirotor platforms are not currently available. The majority of the commercial solutions utilise exclusively Brushless DC motors. The alternative being Permanent Magnet DC motors, which are used mostly in vehicles under 100 g. Therefore, it is clear that at least some components in the actuating system would need to be custom designed.

Another issue connected with the lack of SR motor-based vehicles is the unavailability of a reference point in terms of feasibility. It is obvious that SR motors are different from its direct competition (BLDC, PM DC, Induction, etc.) due to the required geometry of the stator and rotor, thus the possible torque vs. weight ratio that can be achieved at different scales also varies. The question that needs answering is **whether the motor can generate enough torque** (and therefore thrust) **while keeping the weight of the whole system low** enough to make it effective.

The multirotor actuating system, although with a simple structure, has quite complex dependencies between its elements, especially when placed within the application. Therefore, a design methodology needs to be used to ensure all design goals are achieved. There are multiple methodologies available (Budinger, Reyssset, Ochotorena & Delbecq, 2020; Dai, Quan, Ren & Cai, 2019a; Gatti, 2017), but they are fairly general. As a pre-study, a multirotor sizing methodology is developed, that uses component databases to size the actuating system and estimate flight time. As it uses only commercially available parts, it is not suitable for the use with SR motor technology, but rather serves as a study on characteristics of each actuating system element. The study is described in Chapter 3.

The fact that the designed system is supposed to replace another system can be used to the advantage. By keeping the same structure, inputs, and outputs the workload can be significantly reduced, especially when it comes to test-bench design and fitting the system in a vehicle. To take advantage of this property, an actuating system design methodology is extrapolated and generalised from the sizing methodology. Similarly, it is based on the actuating system's dynamical model and allows enough flexibility to be used for development of digital twin-ready digital model for simulation purposes. This approach is described in detail in Chapter 4.

The design methodology provides for three levels in complexity of the models used, as described in Sections 4.4 and 4.5. The highest level describes a dynamic model that is the cornerstone for an SR motor actuating system simulator. Its development and capabilities are described in Section 6.1. It is used for validation of SR motor performance and fault-tolerance, thus partially extensively completing the third research objective. In addition, it supports control solution development and power stage design.

The approach adopted allows to model actuating systems for different sizes. Thrust requirements are decoupled from the vehicle configuration with **two intuitive parameters** - lifting ratio l_r and thrust-to-weight ratio. A set of motor designs is optimised for a range of thrust requirements typical for small and medium sized multirotors. Optimisation methodology and results were presented in Chapter 5. This completes the first research objective.

Specifically, a single design was selected to be manufactured. After simulation using 3D models, the expected performance significantly decreased due to phenomena not included in 2D models, which use FEM to calculate electromagnetic properties of motor geometry on a plane and then multiply the results by stack length. As these issues stem from simplification and certain assumptions in methodology - using 2D models instead of 3D to reduce computation time - they cannot be eliminated by simply changing optimisation parameters. Re-designing the methodology was deemed too time consuming, so mitigation approaches - material change, design modification, battery change and

step-up converter - are investigated in Section 5.4.1. Out of 4 methods analysed, manual modification of geometry was selected and the motor manufactured. This completes the second research objective. In addition, this design is analysed under varying battery State of Charge (SoC), battery internal resistance and rotor speed. Thermal and vibrational properties are also investigated. Results are shown in Section 5.5.

The design methodology and motor optimisation process decouple the number of rotors from actuating system requirements to simplify calculations. However, selection of rotor configuration is required when choosing a demonstrator vehicle. At the vehicle size (and weight) considered, the typical configuration is an octorotor, with two motor-propeller units per arm, for increased safety and payload capabilities. However, SR motor actuating system is designed as a quadrotor (one motor-propeller unit per arm), while using the same chassis and foregoing payload to achieve suitable weight. Removal of system redundancy was motivated by increased reliability and fault-tolerance of SR motors. This has eased weight constraints on newly designed components, while simplifying the vehicle and completing the fourth research objective.

The SR motor is verified in two ways: static performance validated against the design, and dynamic performance compared to BLDC motor data. Section 6.4 describes the design of the SR motor power stage and controller and summarises possible experiments of manufactured motor on ground test-bench. The validation procedures and results are described in Section 7.1. Thus, the third and fifth research objectives are achieved.

As shown in Section 2.2, there are numerous possible faults that can occur in even a simple system, such as multirotor air vehicle. Many of which lead to loss or degradation of control authority, resulting in crashing. In Section 7.2.2 some of these faults are simulated to showcase predicted SR motor behaviour. The simulations include faults as pre-existing conditions or occurring at different points of operation. Influence of uncertainties in specific parameters is also analysed, as described in Section 7.2.1. This allows for judging of the adaptability to different actuating system components (specifically ro-

tors) and resilience against manufacturing defects.

In summary, the workflow, and consequently tasks and milestones follow an organised progression starting with studying multirotor's actuating system and ending with analysis of the designed SR drive. The topics included in this work can be listed as:

- Design methodology,
- Feasibility at different sizes,
- Design of an SR motor,
- Simulator software,
- Performance comparison,
- Fault-tolerance analysis.

Through work being done in these areas the research objectives are realised. SR motor actuating systems are presented in all aspects relating to operation in multirotor air vehicles, keeping in mind the state of art, maturity of technology and possible advancements.

1.4 Publications

There are two publications arising from this thesis:

- (Biczyski, Sehab, Whidborne, Krebs & Luk, 2020) proposed a multirotor actuating system sizing methodology that uses propeller and motor databases, that is presented here as the pre-study in Chapter 3. It allows for sizing based on relatively few input parameters, the main one being vehicle MTOW, and provides results with specific component names, parameters and estimated flight time for a given operating point. The method achieves results in line with components used in popular consumer-grade products.

- (Biczyski, Sehab, Krebs, Whidborne & Luk, 2021) describes the approach of designing small-sized SR motors using 2D models and the associated problem of the influence of 3rd dimension effects leading to decrease in produced torque. To address this, the paper proposes four mitigation methods, described in this work in Section 5.4.1.

Chapter 2

Literature Review

The increased environmental awareness and the push for cleaner fuels is leading to accelerated research in terms of fully electric, hybrid and hydrogen fuel cell-powered aircraft (Grand et al., 2021). Benefiting from this changing landscape is a subset of VTOL air vehicles - multirotors. During the last 20 years they saw an evolution from being merely a curiosity, through becoming the main tool for aerial photography to being proposed for transporting goods and even humans (Mazur, Wiśniewski & McMillan, 2016).

2.1 Multirotor air vehicles

Multirotors can be essentially considered a subset of helicopters with more than 2 main rotors (Sledge, Taha & Liebeck, 2021). Therefore, another common name for this type of vehicle is *multicopter*. Additionally, depending on the number of main rotors, specific names can also be given, such as quadrotor (4) or octorotor (8) (Stevens, Lewis & Johnson, 2015). Throughout this work, the name multirotor will be used to highlight the difference that helicopters typically use variable-pitch propellers, while multirotors rely on fixed-pitch propellers. This is mainly because of the lower assembly weight and the fact that multiple rotors can achieve the same actuator disc surface with lower diameter per rotor, which enables them to spin faster and avoid the problem of rotor stalling (Federal Aviation Administration, 2012). Similarly, although very similar to fixed-wing aircraft's

propellers in terms of design, rotors primarily serve to provide lift to the vehicle instead of pushing it forward, hence the difference in naming convention (Stevens et al., 2015).

The following multirotor dynamics description uses a body axis system - the ox axis is plotted from the centre of mass (o) through the front of the vehicle, the oy axis goes to the right hand side and the oz axis points downwards. As the name suggests, this axis system is tied to the vehicle body and moves with vehicle manoeuvres. Therefore, along these axes we can plot forces X, Y, Z and linear velocity U, V, W , and around the axes we have moments L, M, N , angular velocity p, q, r and angular position ϕ, θ, ψ . These are illustrated in Figure 2.1.

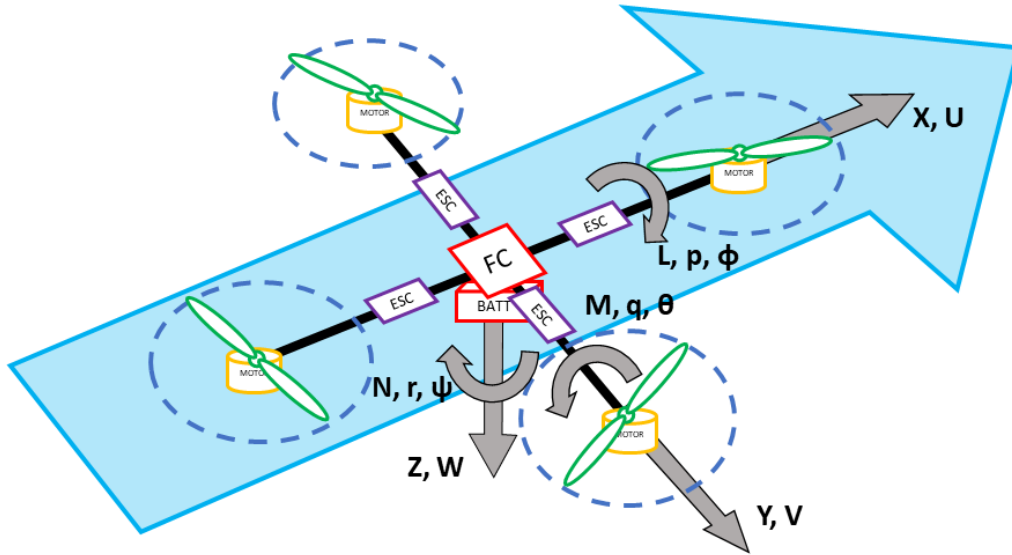


Figure 2.1: Quadrotor schematic.

Multirotor flight dynamics can be best explained with an example of a ‘+’-configuration quadrotor, illustrated in Figure 2.1. It has one rotor in the front (in reference to flight direction), one in the back and one at each side. This makes it simpler to control (on the flight controller level), as opposed to the more popular ‘x’-configuration with rotors placed diagonally, which offer faster response in basic manoeuvres (and do not obscure camera view). Each of these rotors $k = 1 \dots 4$ (as a part of its respective actuating system) produces a thrust force T_k and a moment τ_k , offset from the centre of mass. During stable

hover, all these forces point upwards, while moments depend on rotor spinning direction, as shown in Figure 2.2. Vehicle is in the state of equilibrium:

$$T_1 = T_2 = T_3 = T_4 = \frac{mg}{4}, \quad (2.1)$$

$$\tau_1 + \tau_3 = \tau_2 + \tau_4, \quad (2.2)$$

where Q is vehicle weight, m is vehicle mass and g is gravitational acceleration.

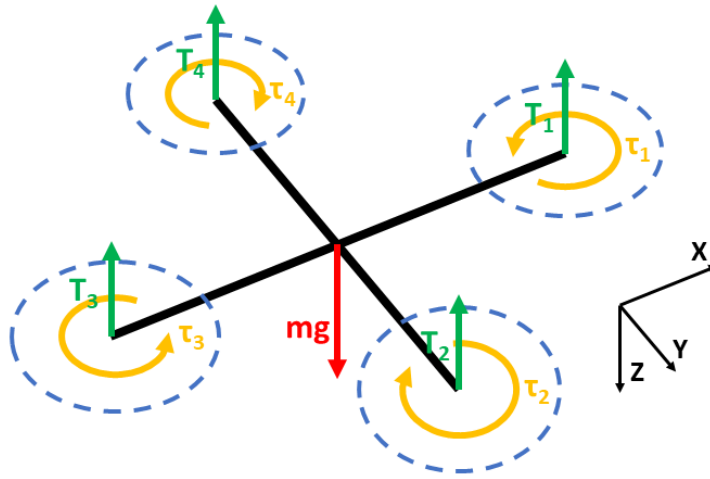


Figure 2.2: Forces and moments in a quadrotor.

From the state of hover simple motions can be performed, as explained in Figure 2.3. These manoeuvres can be performed only by changing the respective motor speed, which in turn changes the force and moments (as these are proportional to each other (Magnussen, Ottestad & Hovland, 2015)). In particular (assuming body axis centre in CG):

- heave (translation along Z axis) - RPM decrease of motors 1 - 4,
- roll (rotation around X axis) - RPM decrease of motor 2, RPM increase of motor 4,
- pitch (rotation around Y axis) - RPM increase of motor 1, RPM decrease of motor 3,

- yaw (rotation around Z axis) - RPM decrease of motors 1 and 3, RPM increase of motors 2 and 4.

Therefore, it is possible to directly control 4 Degrees of Freedom (DoF) out of 6, rendering the vehicle under-actuated. However, the vehicle is fully controllable, hence the remaining DoF can be achieved by combining the directly controllable motions:

- surge (translation along X axis) - negative pitch and heave,
- sway (translation along Y axis) - roll and heave.

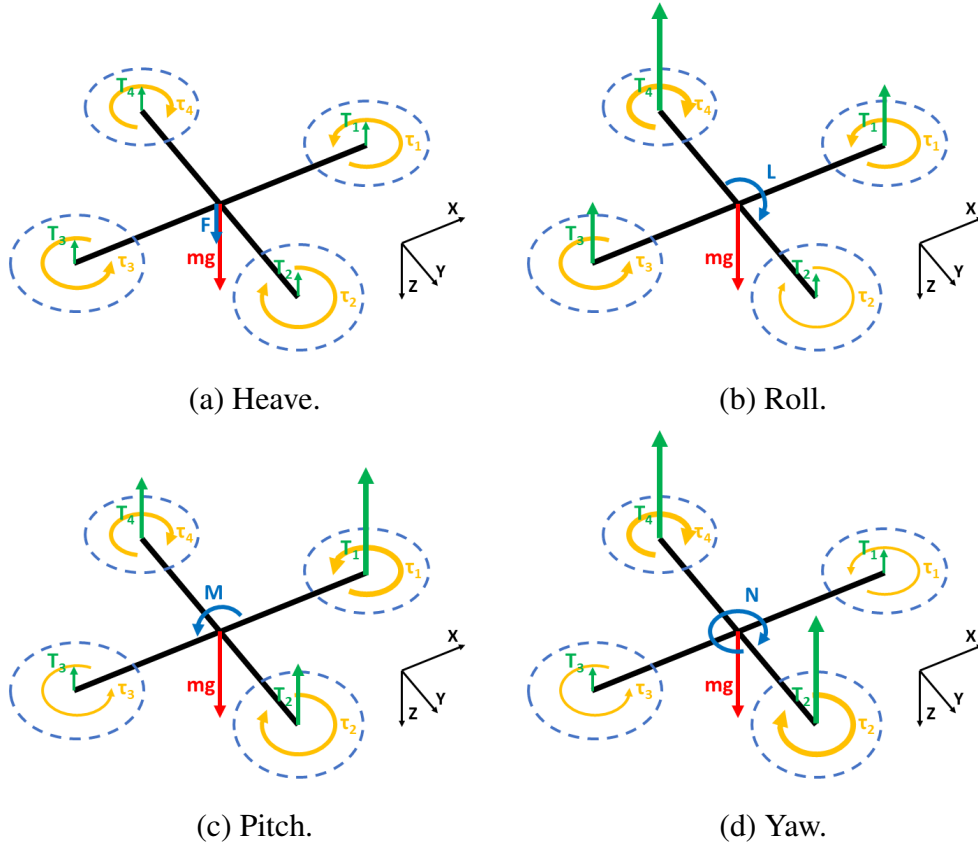


Figure 2.3: Basic translational and rotational movements of a multirotor.

It is important to note that due to usually low aerodynamic coefficients of a multirotor's body, especially at low speeds, the dynamic modes (SPPO, phugoid, dutch roll, spiral mode, etc.) typically present in fixed-wing aircraft are negligible. Therefore, the vehicle is able to easily hold input attitudes (roll, pitch, yaw). Of course, additional control schemes

can be used to reinforce that capability and protect from disturbances. Because of that capability, from the operator's point of view, there are multiple control modes (schemes) that can be used, each with more assistance from the vehicle's controller (Hochstenbach, Notteboom, Theys & De Schutter, 2015; Lim, Park, Lee & Kim, 2012). Three notable ones are:

- rate mode - the operator controls rolling rate p , pitching rate q and overall thrust T ,
- angle mode - the operator controls roll angle ϕ , pitch angle θ and overall thrust T ,
- GPS-assisted mode - the operator controls surge, sway and heave.

In all of these modes, yaw rate r is controlled directly. This allows for versatility in adjusting the control scheme for application.

2.1.1 Applications

In the commercial sector, unmanned aerial vehicles are marketed as a solution in and of itself (CHC Navigation, 2021; USAID Global Health Supply Chain Program-Procurement and Supply Management, 2017). However, multirotors, like all vehicles, are merely a tool, capable of moving certain mass (payload) from point A to point B or loiter in place. However, even as a tool they possess a few unique qualities that set them apart from other air vehicles:

- wide weight range and scalability (Budinger et al., 2020),
- ease of control,
- mechanical simplicity, hence low maintenance costs,
- low manufacturing cost,
- low noise and vibrations (Stevens et al., 2015),
- ability to operate unmanned or autonomously,

- fully electric propulsion,
- vertical takeoff and landing.

Of course, specific disadvantages are also present (Shafiee et al., 2021):

- inherent instability,
- inability to glide,
- auto-rotation only possible with fault-tolerant control,
- susceptibility to wind gusts,
- low flight-time and range,
- small payload capability.

Bearing these quantities in mind, multirotors lend themselves to a subset of jobs, where they can be used as a part of a solution. Of course, they can be also further tailored for a job within this subset, for example by choosing frame size or motors of specific power. Therefore, depending on the application, multirotors can be designed by balancing four aspects: power, endurance, safety, and cost. Power is needed for the vehicle to be fast, agile and be able to carry high payload. It is mainly dependent on the number and size of rotors (and their respective motors). Endurance encompasses the ability to stay in the air for a long time, be it hovering, flying in a straight line or on a set path patrolling. It is of course determined by power usage in relation to battery size, but also - to a much lesser extent - vehicle's aerodynamics, which contribute to available range. Finally, as cost is self-explanatory, safety covers two areas: reliability and fault-tolerance. They correspond respectively the vehicle's ability to operate without any fault and the operational capabilities retained during and after a fault has occurred.

Due to the relatively low production cost and simple structure, multirotors can be developed quickly and for a specific applications, even custom built for the job. This is in opposition to general aviation, where one design is exploited (with minor improvements)

for many years and in an array of use cases. That is why multirotor applications can be defined in more detail.

The application that sees the most rapid developments is, sport and recreation. The ongoing competition leads to inventing more and more ways to reduce weight or increase output power, as the vehicles are oftentimes built by the operators themselves. Those machines are stripped of everything but the bare necessities to reduce the weight as much as possible, often at the risk of crashing the drone in case of any faults. The flagship discipline is drone racing in multiple weight categories¹, where operators (also called pilots) use First Person View (FPV) vision systems to navigate multirotors through a special track in the shortest time possible. Other categories also exist, such as Freestyle (multirotor aerobatics), Drone Soccer (Fédération Aéronautique Internationale, 2021), or automated/autonomous flight competitions (Drobots Company, 2022).

A step up in complexity would be multirotors used in entertainment, such as for ‘dancing’² or ‘flying screen’ displays (Intel Corporation, 2022). Vehicles used in those applications must be sufficiently robust to be able to maintain constant position in the air or move on a very specific path and avoid collision with other objects. That is why additional equipment allowing for collision detection or vehicle-to-vehicle communication is used (Bürkle, Segor & Kollmann, 2011; Shraim, Awada & Youness, 2018). That being said, the focus is mostly placed on the collective behaviour of the group, rather than on individual performance, so the reliability requirements are somewhat reduced, especially considering these displays are meant to be viewed from a distance, so the flying happens far from populated areas.

Package delivery is an application that, by its definition, requires operation in close proximity to humans, therefore requiring additional safety measures. Even if the routes for regular deliveries could be plotted away from settlements (Pourtakdoust & Karimi,

¹<https://thedroneracingleague.com/>
<https://www.tinywhoop.com/>
<https://www.multigp.com/>

²<https://dancingwithdrones.com/>



Figure 2.4: Example multirotor used for drone racing - iFlight Cidora SL5 V2.1 HD (iFlight, 2021)



Figure 2.5: Formation of multirotors during a ‘flying screen’ performance at the Olympic Games Tokyo 2020 opening ceremony (Intel Corporation, 2022).

2017), the delivery point is still someone’s home or workplace³. Still, as already proven, the best use of multirotors seems to be in time-critical deliveries in densely populated (or otherwise inaccessible) areas, such as transporting first-aid equipment or health testing

³https://www.youtube.com/watch?v=MXo_d6tNWuY

supplies (Mazur et al., 2016; Neate, 2020; USAID Global Health Supply Chain Program-Procurement and Supply Management, 2017). As already mentioned, safety is paramount, but the ability to carry substantial payload is as important. Not only the weight of the transported object needs to be considered, but also the whole mounting system and packaging, as often it contains environment-control systems, such as temperature control when transporting samples or sensitive electronic sensors (Tanda, 2020).

More rounded set of requirements is required for one of the most popular jobs as of now - aerial photography. Due to the variety of environments the vehicle would be operating in - mountains, seaside, caves, inside of buildings, etc. - the design must be as versatile as possible. In addition, it often would be operated by personnel with only basic training (Federal Aviation Administration, 2021), so there is merit in adding additional safety measures like parachutes (Terkildsen, Schultz & Jensen, 2021), propeller guards, geo-fencing (ST Microelectronics, 2018) or obstacle avoidance systems (Sanchez-Lopez, Wang, Olivares-Mendez, Molina & Voos, 2019). Of course, enough power for steady flight with, sometimes sizeable, camera payload is another requirement. This being said, there is a subset of small photography-oriented multirotors with enclosed rotors (Liang, 2022), that are used for steady video capture while in close proximity to the filmed object (moving or static), such as a race-car or a person⁴.

Similar applications, but with much higher focus on flight endurance (and therefore battery capacity), are surveillance and inspection. These use cases can be grouped together on the functional basis of gathering data (mainly visual) from a high point (Mazur et al., 2016; Zaheer, Usmani, Khan & Qadeer, 2016). The specific examples might be aircraft part inspection (Malandrakis et al., 2018), animal surveillance (Landeo-Yauri, Ramos, Castelblanco-Martínez, Torres & Searle, 2020) or smoke cloud analysis (Daniel, Dusza, Lewandowski & Wietfeld, 2009). Multirotor's agility and the ability to quickly change direction make it easy to get multiple views of the object in question.

Finally, multirotors might be employed to solve Urban Air Mobility (UAM) (Sharma,

⁴<https://www.youtube.com/watch?v=iCY3X-Rd8Sc>

2020) challenges of reducing congestion by employing 3-dimensional transportation. Specifically, multirotors are seen as a candidate for short-distance travel (Air Taxi) (Ploetner et al., 2020) due to their vertical takeoff and landing (VTOL) capabilities and limited energy density of batteries. However, to reach the state where humans are safely allowed as passengers in such a vehicle, many developments still need to be made, that is why all attempts made so far are only prototypes, while the industry awaits guidance on possible certification for such vehicles (European Union Aviation Safety Agency, 2019; Straubinger et al., 2020). However, this leaves a wide design space to explore new concepts, such as tilting actuating surfaces (Joby Aviation, 2022), addition of wings (Boeing, 2022) or unconventional placement of rotors (Urban Aeronautics, 2022). Figure 2.6 shows some Personal Air Vehicle (PAV) concepts currently being developed.



Figure 2.6: Personal Air Vehicle examples.

The wealth of applications with their own requirements invites specialised vehicles,

but also serves as a good test-bed for new designs. There is a constant need of pushing performance or safety further, even at the cost of the other one. However, some of the unconventional designs have already found their way into prototyping or production stage. This technology is far away from maturity, though, and some challenges still need to be solved before the full potential can be realised.

2.1.2 Challenges

As with the introduction of every new major technology, the number of issues needed to be solved is tremendous. Of course, recent years have brought substantial progress in terms of realisation of the vehicles themselves. Small, consumer-grade multirotors started as RC toys, but as the research and design optimisation effort continued, they have become reliable tools in numerous professions, such as photography, surveying or farming. However, at least as many issues need reliable solutions before they become common in the surveillance or UAM sectors. These challenges can be roughly divided into three categories: performance, safety and operations.

Performance

The performance of multirotors is tightly related to what missions they need to carry out. In surveillance applications high endurance is needed, for package delivery - high payload capacity and long range. However, to achieve any of these things, considerable amount of energy is needed. Currently, this energy is stored in batteries as specifically as electrical energy, but due to low charge density (Boulais, 2021), the batteries tend to be quite heavy, constituting around 20% of the vehicle mass (Budinger et al., 2020). Therefore, constant effort is being made to improve battery power density, improve actuating system's efficiency (Agarwal, 2018; Budinger et al., 2020; Dai, Quan, Ren & Cai, 2019b) or use a different storage medium (Marzougui, Neuhaus, Boukal, Labracherie & Scalabrin, 2021).

With high endurance, flight missions become longer, so more heat is generated and

needs to be properly dissipated to avoid temperature rise to dangerous levels. Due to weight and reliability considerations, no additional cooling system can be taken on-board. Therefore, motors and electronics need to be cooled passively or with forced air generated by the rotor. This becomes an issue with heavier vehicles, as larger propellers require more torque to drive them, more torque means more current and more current results in increased heat generation. Excessive temperature results in reduction of component lifespan or even faults (Jeong, Shi, Lee & Kang, 2020). For short flights this might not pose a threat, but missions with duration of over an hour will certainly benefit from increased efficiency of the hardware, energy-efficient mission path planning (Di Franco & Buttazzo, 2015), improved passive cooling or even active cooling methods (Nowacki, Dar & Austrin, 2006).

In the previously mentioned problems, there is a tight constraint on weight. Similarly, it applies to the multirotor as a whole and each of its components. Indeed, lower mass of the vehicle leads to lower power needed to operate it and the increase of all performance metrics. A possible source of this saving might be novel lightweight materials (Callicot, Gaeta & Jacob, 2014; ElFaham, Mostafa & Nasr, 2020; Hatfield et al., 2016). However, it needs to be noted, that lighter materials are more susceptible to damage or vibration, which might result in structure failure, as demonstrated in (Gururajan, Mitchell & Ebel, 2019), (Rattanagraikanakorn et al., 2018) and (Sledge et al., 2021).

Even though much smaller than in a conventional rotorcraft, the rotors on a multirotor occupy a sizable area, especially when considering the total volume (above and below the rotor disc) required for efficient operation. This can prove problematic when trying to increase the rotor count for additional reliability or performance or when minimising vehicle footprint to be operated in tight spaces (indoors, forests, urban airspace). In those cases, the rotors might have to overlap. Unfortunately, little is known about the behaviour of such systems with only a few works specific to this application, such as (Theys, Dimitriadis, Hendrick & De Schutter, 2016). However, a specific case of overlap - concentric rotors - has proven to be a popular choice for octorotors, and its characteristics

were studied in more detail in (Saied et al., 2015) and (Khan, Shah, Javed, Qadri & Hus-sain, 2021).

Safety

Technological challenges in the area of safety are mainly related to the management of crash situations - crash prevention (avoiding the situation) and crash mitigation (prevent-ing damage) (Littell, 2019). These, of course, apply to the whole mission, but their effect and probability of occurrence might differ depending on the phase of flight the multirotor is in. Therefore, a lot of effort needs to be put into targeting the possible vul-nerabilities. Specifically, reliability and fault-tolerance of vehicle's systems play a crucial role in dealing with issues of internal nature, such as faults. Unfortunately, the data on fault occurrence and severity is scarce due to the number of flight hours being relatively small, as most flights are not logged. Therefore, even literature on this subject uses simple models and assumptions (Gururajan et al., 2019; Stansbury, Gillespie, Robbins & Geraci, 2019), because the data available is insufficient for statistical methods.

Another issue comes from the weight constraint. One approach to increasing reli-ability is to increase durability - making wires thicker, increasing the width of the arms and frame, or over-sizing the electronics - but this is rarely possible. Another way is to introduce redundancy by duplicating actuating systems, thus creating hexarotors and oc-torotors, which have the ability to fly (although reduced) after shutting down some of its motors (Du, Quan & Cai, 2015; Saied et al., 2015; Y. Zhang et al., 2013).

Improvement of safety without increasing the weight can be achieved by complex control algorithms. Development in this area is quite rapid and new approaches are pro-posed regularly, allowing for predicting, sensing, and managing actuating system faults (Ducard, 2009; Izadi, Zhang & Gordon, 2011; Sadeghzadeh & Zhang, 2011; Saied et al., 2015). In addition, it is now becoming possible to temporarily operate with certain sensor faults (L. Cork & Walker, 2007; Rafaralahy, Richard, Boutayeb & Zasadzinski, 2008) and even with damaged rotors (Li, Zhang & Gordon, 2013).

Operations

Even though multirotor technology has been around for decades, it is only recently that certain missions have been regulated (Tsiamis, Efthymiou & Tsagarakis, 2019). However, for vehicles of higher size, especially those to carry passengers, regular flights are still not viable. The main focus areas leading towards a safe introduction into the regulated airspace were listed by Gimenes et al. (2013, p. 996), adapted from ICAO Circular 328 (International Civil Aviation Organization, 2011):

- *licensing,*
- *rules of the air,*
- *aircraft operation,*
- *aircraft airworthiness,*
- *aeronautical telecommunications,*
- *security (...),*
- *the radio frequency spectrum.*

Since then, constant efforts in the area of certification have resulted in the creation of two new Special Conditions by EASA (EASA Staff & Solar, 2021). VTOL Special Condition (European Union Aviation Safety Agency, 2019) details person-carrying VTOL aircraft with powered lift and control (including PAV multirotors), while Special Condition E-19 (European Union Aviation Safety Agency, 2021) governs electric and hybrid propulsion systems.

Aside from certification issues, there are other unsolved issues stemming from the fact that multirotors and their applications are different from conventional aircraft. Dalmagkidis, Valavanis and Piegler (2012, chap. 7.1) highlight some of the current concerns relating to UAV, which can also be extended to multirotors as one of its types. One of

these issues is the area of operations, as UAV due to their shorter range and planned introduction into UAM, will spend much more time over congested areas. Therefore, current safety procedures of general aviation might be inadequate. However, for missions carried over water, forests or fields, with limited human population, these regulations may be excessive.

An unique characteristic of unmanned vehicles is the easy replaceability. Vehicles are relatively cheap, easy to make and a lot of parts can be salvaged even after a destructive crash. Therefore, non-passenger-carrying UAVs might be intentionally crashed ('sacrificed') in case of a loss of control, if it reduces the risk harm to people (Dalamagkidis et al., 2012, chap. 7.1.3). However, the challenge here stems from being able to discern situations where sacrifice is beneficial and prepare specific procedures, so it can be done also in a safe manner.

Control authority is an aspect that stems from removing the pilot from the cockpit. The operator on the ground only receives information sent from the vehicle, which might be limited in terms of quantity (depending on available sensors) and quality (depending on connection strength) (Bürkle et al., 2011; Costello, 2017), as well as be significantly delayed. Therefore, it might be possible to move the operator to a supervisory role (Valavanis, 2017), with the aircraft being semi- or fully-autonomous. This might allow one operator to control more UAVs, but also introduces additional points of failure, therefore requiring specific procedures. Challenges come from ensuring reliability and robustness while reducing operators' workload (Jahanpour, Berberian, Imbert & Roy, 2020).

It is easy to notice that multirotors provide a unique approach to transportation with multiple possible advantages. Multiple applications already profit from their benefits, with further use cases being considered. However, disadvantages stemming from inherent instability of the vehicle and relative immaturity of the technology create a wealth of challenges that need solving. Most of these issues are heavily related to maintain the safety of both the vehicle, as well as surrounding environment. Therefore, only with continuous improvement of reliability and fault-tolerance, can multirotors be safely introduced into

public airspace and bring the full extent of benefits to the society.

2.2 Air vehicle faults and preventive measures

Isermann (2006, chap. 2) differentiates between faults, failures and malfunctions. Specifically:

- ‘A **fault** is an unpermitted deviation of at least one characteristic property (feature) of the system from the acceptable, usual, standard condition.’
- ‘A **failure** is a permanent interruption of a system’s ability to perform a required function under specified operating conditions.’
- ‘A **malfunction** is an intermittent irregularity in the fulfillment of a system’s desired function.’

Based on these definitions, fault is a state that, depending on severity, may lead to one of two events - temporary interruption of operation (malfunction) or complete cease of operation (failure). Of course, a single fault does not necessarily result in disruption of operation, while a specific malfunction/failure may manifest itself only in the presence of combination of faults. Therefore, this section attempts to list and provide links between possible faults, malfunctions and failures.

Currently, a significant portion of research work in the area of UAV faults focus on elements of fault-tolerance: fault identification and fault-tolerant control. Surveys on the topic, such as (Sadeghzadeh & Zhang, 2011), (Y. Zhang et al., 2013) and (Furlas & Karras, 2021), identify multiple works specifically on the topic of multirotors and their faults (as compared to single rotor and fixed-wing vehicles). The three main categories considered are: sensor, actuating system and plant (frame, mounting, electronics, etc.) faults (L. R. Cork, Walker & Dunn, 2005). These can be traced to the elements of a closed-loop system, as shown in Figure 2.7, although only physical components are considered for the influence of faults.

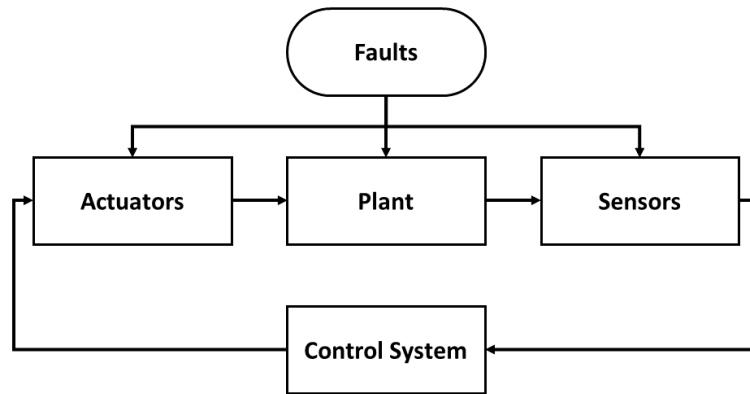


Figure 2.7: Representation of fault locations in a closed-loop system (L. R. Cork et al., 2005)

2.2.1 Fault classification

In a typical UAV there are 3 sensor systems: inertial measurement system (IMU) - X , Y , Z ; gyroscope - p , q , r ; and magnetometer (Heredia, Ollero, Bejar & Mahtani, 2008; Tanwani, Galdun, Thiriet, Lesecq & Gentil, 2007). GPS unit is rarely considered, as it is not required for control of the vehicle and often plays only a supporting role due to low measurement frequency. The faults can take multiple forms with zero output, constant bias, additive type (drift), multiplicative type and random noise being the most common (L. R. Cork et al., 2005; Heredia & Ollero, 2009). Detection methods include model-based (L. Cork & Walker, 2007; Freddi, Longhi & Monteriu, 2009; Rafaralahy et al., 2008) and knowledge-based (Sun, Cheng, Wang & Ochieng, 2017). Berbra, Lesecq and Martinez (2008); Nguyen et al. (2009) in their detection methods include a detailed model of the sensor unit to allow accurate estimation of dynamics, which even allows for some degree of fault-tolerant control through switching strategy,

Similar to sensors, detection and identification methods of actuating system faults can also be divided into:

- model-based (Izadi, Gordon & Zhang, 2010; Izadi et al., 2011; Saied et al., 2015; N. Zhang, Drouin, Doncescu & Félixo, 2008),
- knowledge-based (Younes, Noura, Rabhi & Hajjaji, 2019).

Although actuating systems are a major risk factor in an UAV, the majority of analysed literature treats them either as a complete loss of actuator or as a loss of effectiveness (usually given in percent). These represent the worst case scenarios. In a quadrotor (and to some extent - hexarotor), a loss of effectiveness fault changes the dynamics of the vehicle. The extreme case being the loss of an actuator, where the now 3-rotor vehicle loses its stable equilibrium point and needs to be heavily controlled to stay in the air. Nonetheless, this is still possible, as studies have demonstrated with multiple approaches, such as adaptive control (Chamseddine, Zhang, Rabbath, Fulford & Apkarian, 2011; Dydek, Annaswamy & Lavretsky, 2010b; X. Zhang, Zhang, Su & Feng, 2010; Y. Zhang et al., 2013), control allocation (Xulin & Yuying, 2018; Zhou, Zhang, Rabbath & Theilliol, 2010) and machine learning-based methods (Allahverdy, Fakharian & Menhaj, 2021). Some of these have even been validated on real vehicles (Chamseddine et al., 2011; Dydek, Annaswamy & Lavretsky, 2010a; Mueller & D'Andrea, 2014; Sadeghzadeh, Mehta & Zhang, 2011). Fault-tolerant control has also been developed for vehicles with actuator redundancy for increased safety (Sadeghzadeh, Chamseddine, Zhang & Theilliol, 2012; Saied et al., 2015).

Tanwani et al. (2007) did investigate faults related to motor backlash, but multirotors nowadays rarely use gearing systems, so the results are of limited usability. Milhim, Zhang and Rabbath (2010) proposes a fault-tolerant control scheme for a curious vehicle - one that can vary the orientation of each of its 4 rotors, as well as their speed. Similarly, this is of limited interest, due to scarcity of such vehicles.

Although in some cases, from the mathematical point of view these can be considered equal to the general/motor loss of effectiveness faults, some works are dedicated specifically to rotor faults. These may fail from collisions, propagating cracks, excessive vibration or accelerating over allowed limits. Mueller and D'Andrea (2014) designed controller for cases of rotor loss, taking into consideration propeller inertia. Chamseddine et al. (2011); Dydek, Annaswamy and Lavretsky (2013); Li et al. (2013); Sadeghzadeh et al. (2012) present the results of experiments involving damage to propeller during flight and control

strategies allowing for continued operation.

Limited studies exist on the topic of faults that occur in the control system. Tanwani et al. (2007) investigates the influence of embedded networks and the delays they can cause by comparing CAN and Ethernet networks. Sadeghzadeh et al. (2012) simulate actuator fault through PWM signal limit and propose a control allocation strategy to address that.

2.2.2 Risk Assessment

Malfunction and failure describe only the system's ability to operate. The consequences of the loss of function can vary greatly, but from the safety point of view it is more important to classify their severity (and frequency of occurrence) through the effects on environment and the aircraft. Leung and Rife (2017) use a 5-level classification (Table 2.1) based on FAA System Safety Handbook (FAA, 2000) with similar definitions available from other agencies. It needs to be noted that this classification was developed for general aviation and, in the case of UAVs, the loss of the aircraft has much less severe consequences, thus the focus should be on damage to people or property.

Table 2.1: Classification of fault severity (FAA, 2000; Leung & Rife, 2017).

No failure	Has no effect on safety
Minor	Does not significantly reduce system safety
Major	Major occupational illness and/or major environmental damage and/or major property damage
Hazardous	Fatal injury to ground personnel and/or general public
Catastrophic	Results in multiple fatalities and/or loss of the system

This classification, associated maximum allowed occurrence frequency and knowledge of specific faults and their combinations can be used to compute reliability estimates. They allow to judge relative safety of the vehicle and areas that need improvement. Leung and Rife (2017) have compared three methods of calculating risk probability in order to showcase that incorporation of additional knowledge about the situation, such as environment data or the use of additional sensor systems, does reduce the risk factor across all categories. In turn, it allows to relax some reliability constraints on less severe

faults, giving greater flexibility in the design.

Hammer, Murray and Lowman (2017) present a detailed safety analysis of a complete UAS operation, dividing the top-level event ‘loss of flight for any reason’ into 5 categories (reasons):

- ‘loss of controlled flight due to compromised airframe’,
- ‘...due to technical failure’,
- ‘...due to operating out of envelope’,
- ‘...due to weather phenomenon’,
- ‘...due to aerial collision’.

The median probability achieved for the whole tree was around 2×10^{-3} , which validates the systems for use in rural (all vehicle sizes) and urban (sizes < 2 kg) areas (Hammer et al., 2017). However, this probability is mostly influenced by the *technical failure* branch with the probability of any technical failure having the highest importance score. In this branch, the *control system mechanical failure* and *propulsion system mechanical failure* events have the highest contributions, effectively pinpointing actuating systems and their faults as paramount to the vehicle’s safety.

2.3 Electric motors used in actuating systems

The majority of critical faults that lead to the loss of control happens within the actuating system. As explained in the previous section, the current approach is to independently develop fault-tolerant control systems and introduce redundancy in sensors and mechanical components. However, a large number of these methods increase the system’s weight, which in turn increase the required power to keep the vehicle in flight and decrease manoeuvrability. Therefore, even if it is the most popular approach now, as the technology

evolves, due to lowering rate of contribution (The MITRE Corporation, 2014), a different technology may become more favourable.

Typically, a multirotor actuating system requires four elements: rotor, motor, power system for the motor and a controller. A power source (usually battery) is omitted in this chapter, as its development can be semi-independent from the actuating system. That is, parameters like capacity or cell technology are of little concern at this stage and can be modelled as an ideal voltage source. The rotor is strictly a mechanical element, so its faults come mainly from physical damage due to collisions (Gururajan et al., 2019). Therefore, only three elements are left to consider: motor, power system and controller. Out of those the motor is the most important, as it is responsible for the conversion between electrical and mechanical power. It also defines the technology of the power system and the control algorithm. Therefore, changing motor technology has a large impact on the whole actuating system and may serve as a way of increasing the system's reliability and fault-tolerance without impacting weight.

When considering electric motor technologies, it must be noted that they are in different levels of maturity, as their development was not always consistent. T. J. E. Miller (2019) has created the 'Periodic Table of Electric Machines' (Figure 2.8) showcasing the current industrial focus on specific technologies. It incorporates not only the maturity of the technology itself, but also its popularity and importance in the industry. That is why the induction machine is in the centre with designs such as DC and brushless permanent magnet (PM) machines to the right, with prominent future ahead of them.

The following sections describe induction, DC and PM brushless motors, as well as two less popular designs (synchronous reluctance and switched reluctance). Each of the motors is discussed in terms of principle of operation, control, power electronics, advantages, and disadvantages. In addition, possible speed, power and torque ranges and typical applications are presented. Finally, safety considerations and possible usage in multirotor air vehicles is discussed.

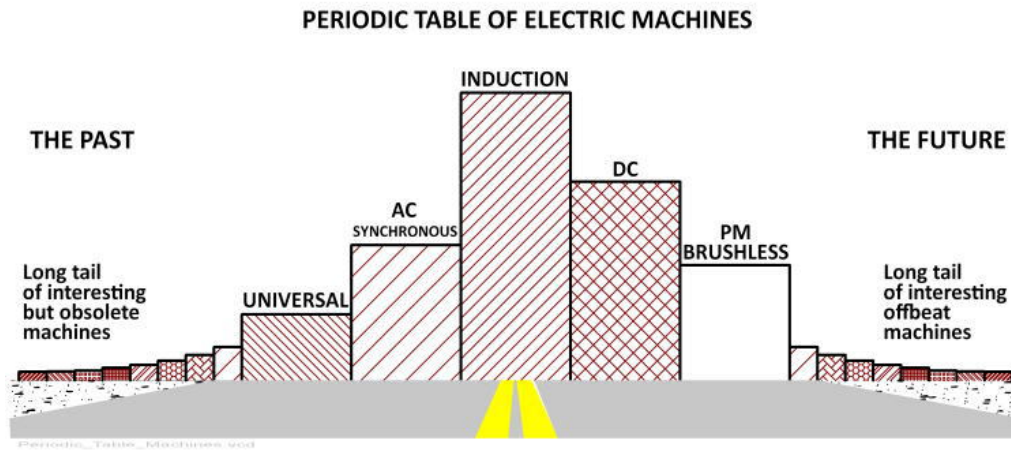


Figure 2.8: Periodic Table of Electric Machines (T. J. E. Miller, 2019).

2.3.1 Induction machine

Induction machines by some (Hughes, 2006) are considered extremely important due to their elegance and simplicity. Others (Gieras, 2008) note their low cost and suitability for constant speed applications. However, it is a fact that integral power (> 1 hp) induction motors drive a major part of the industrial equipment today (Choudhary, Goyal, Shimi & Akula, 2019; Gieras, 2008), making them one of the most influential designs of the 20th Century.

The functional principle is simple: windings placed in slots throughout the stator are energised with AC current to create a rotating magnetic field (or ‘the flux wave’) in the airgap. This results in an electromotive force (e.m.f.) and rotor rotation. At the same time, in the rotor’s conductors a voltage is induced that creates another e.m.f. of a lower frequency. Through the interaction of these forces, the motor speed is stabilised at a level primarily dependent on number of stator poles, AC supply frequency and voltage and the slip parameter:

$$s = \frac{N_s - N}{N_s} \times 100\%, \quad (2.3)$$

where s is slip (in %), N is rotor speed and N_s is the speed of synchronous magnetic field. Typical operating characteristic can be seen in Figure 2.9.

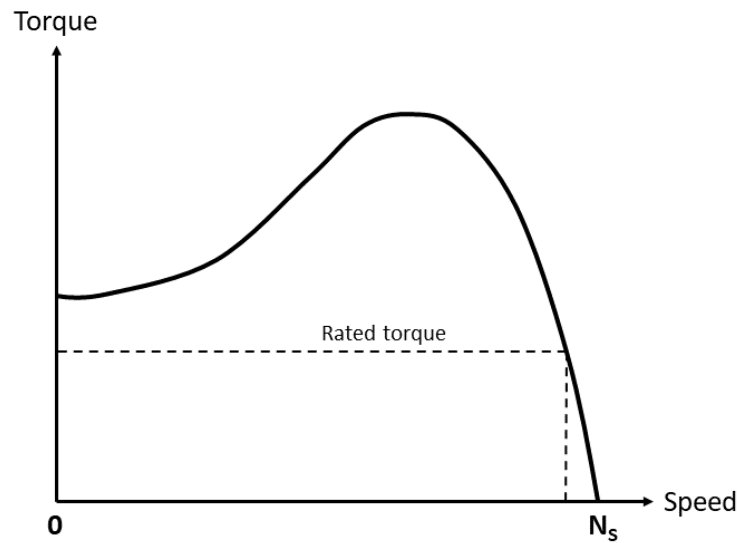


Figure 2.9: Induction motor operating characteristic.

Because the motor speed does not depend on the rotor configuration, the same rotor can be used in multiple machines, which significantly reduces costs and simplifies maintenance. Rotors used in induction machines can be divided into two categories - (squirrel) cage rotors and wound rotors, both are shown in Figure 2.10 alongside a typical stator. The cage rotor is made from long conductors connected at the ends with end-rings, which makes them very cheap, rugged and easy to scale. Wound rotors are manufactured similarly to stators, as windings in slots, but the connection between specific coils is made outside of the rotor allowing the control of windings' resistance or the frequency of rotor currents, thus the control of rotor speed. However, this solution requires brushes to make the connection from the rotor to the outside, which are prone to faults and wear, significantly increasing the price of manufacture and operation. Therefore, although wound rotors were previously popular, cage rotors now dominate the market both in constant-speed and variable-speed applications due to the advent of digital inverter technology (Saïdi, Taleb, Mansour & Midoun, 2015; Saleh & Rahman, 2007).

Typical induction motors can range from as little as 70 W, through 500 kW, up to 19 MW for machines specially designed for ship propulsion (Gieras, 2008). Assuming standard 50 Hz AC supply, the synchronous speeds can range from 500 to 3000 RPM

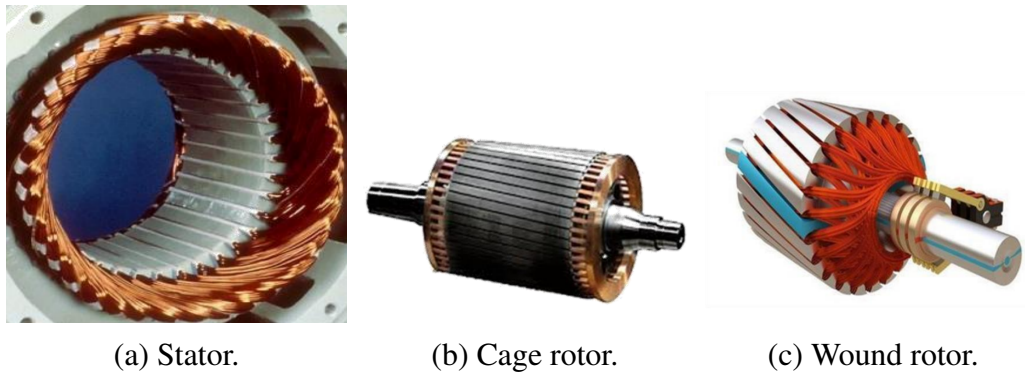


Figure 2.10: Induction machine elements (Alkadhim, 2020).

(Hughes, 2006) and for constant speed applications no additional equipment is needed. For higher speeds or variable speed applications additional inverters can be used. These can also make it possible to operate on DC supply.

The immense popularity of induction machines is thanks to their numerous advantages (Gieras, 2008):

- simple construction,
- low price,
- availability of materials,
- easy maintenance,
- lack of commutator or slip rings (in case of cage rotors),
- low torque ripple,
- relatively quiet operation.

However, induction machines of classical designs have also distinct disadvantages, limiting their use in certain applications:

- small airgap,
- poor performance at low speeds,

- high starting currents,
- torque proportional to the square of voltage,
- risk of overheating when operating high-inertia loads,
- sensitivity to voltage drop,
- low power factor,
- loss of performance when scaling down.

Induction motors are very simple and elegant machines, which combine low cost, robustness and satisfactory efficiency with high versatility for both constant- and variable-speed applications. Although very popular in industrial setting or for ship propulsion, they are rarely used in aerial vehicles. This is due to insufficient power density, requirement of high voltage, possibility of overheating and excitation issues at small sizes.

2.3.2 Direct Current (DC) machine

The induction machine is extremely simple from the mechanical point of view and slightly more complicated with regards to electromagnetic characteristics, DC motors are the opposite. They work by placing an energised winding in a magnetic field and letting it move due to the magneto-motive force (Zaccarian, 1998):

$$T_M = K_\Phi \Phi i_a, \quad (2.4)$$

$$T_M = K i_e i_a, \quad (2.5)$$

where T_M is motoring torque, K_Φ and K are constants specific to the motor, Φ is the magnetic flux flowing through the rotor, i_a and i_e are rotor (armature) and stator currents respectively. To keep the sign of the force constant, the current's polarity is switched based on the rotor position. At the same time, an electro-motive force (e.m.f.) is generated

in the rotating conductor due to Faraday's law of induction, generally known as the back-e.m.f. e :

$$e = K_{\Phi}\Phi\omega, \quad (2.6)$$

$$e = Ki_e\omega, \quad (2.7)$$

where ω is the rotor angular speed. In general, the rotor dynamics of a DC motor can be described by a simple set of equations - one electric and one mechanical:

$$v_a(t) = L_a \frac{di_a}{dt} + R_a i_a + e, \quad (2.8)$$

$$T_M = J \frac{d\omega}{dt} + F\omega + T_L, \quad (2.9)$$

where v_a and i_a are armature voltage and current, L_a and R_a are rotor coil inductance and resistance, F is viscous friction coefficient and T_L is load torque. Typical operating characteristics of a DC motor are shown in Figure 2.11.

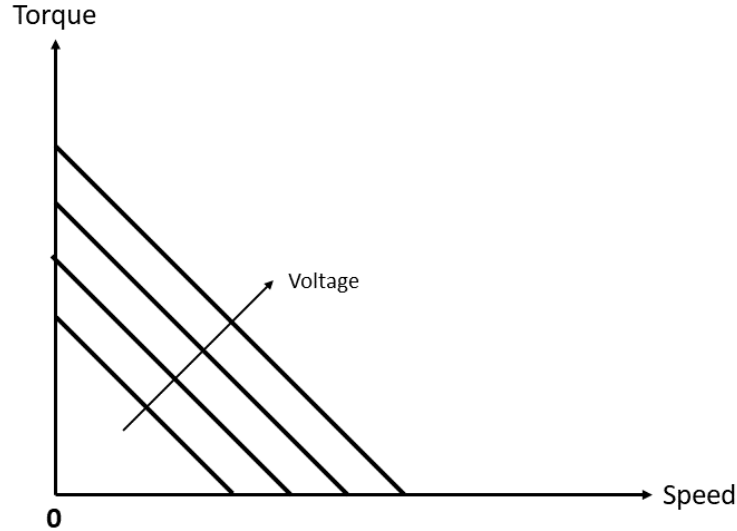


Figure 2.11: Permanent Magnet DC motor operating characteristic adapted from (Bullock, 1995).

Depending on the type of connection between windings in the stator (or the use of

permanent magnets), different characteristics can be observed. Traditionally, there are shunt (parallel), series and compound DC motors (Pillai, 2015). Of course, wound stators can also be powered by a separate power supply or converter. However, in recent years, Permanent Magnet DC (PMDC) machines became popular for their small size (and low weight), although with less options for control (Rahman, Patterson, Cheok & Betz, 2018). This is the only type currently used in multirotor actuating systems (Liang, 2021), therefore will be the focus of this section.

The limiting factor of DC machines is the way of supplying current to rotor windings. It has to be done through a physical commutator that uses brushes (thus the common name ‘brushed DC machine’) to connect supply circuit with specific windings on the rotor and switch the current direction throughout the rotation. An example of a DC machine with an exposed commutator is shown in Figure 2.12. Having to rely on physical contact reduces longevity and increases maintenance cost. The commutator is also highly prone to sparking and other mechanical faults (Shakweh, 2018).

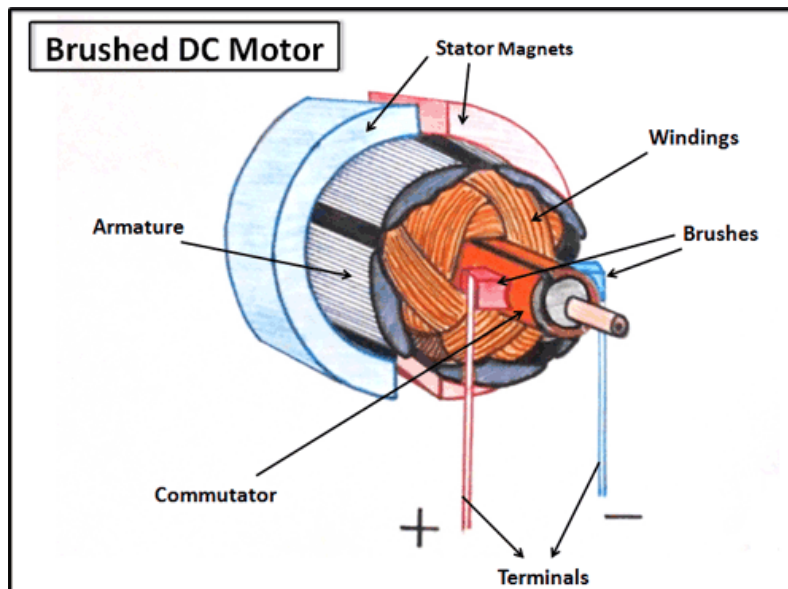


Figure 2.12: DC machine with a brushed commutator (Clemson Vehicular Electronics Laboratory, 2022).

As mentioned previously, PMDC machines are popular in small size applications, such as toys, home appliances, automotive auxiliaries (T. J. E. Miller, 2019) and aerial

vehicles from the micro category (<100 g) (Liang, 2021). Their power ranges from a few watts to a few kilowatts, while speed can reach up to 12000 RPM (Hughes, 2006). Wound machines for industrial applications start at about 100 W and can reach megawatt outputs, although usually keeping the rated speed under 3000 RPM. These are, however, being steadily replaced by induction machines.

DC motors have positioned themselves to make up for induction machines shortcomings - they excel at low speeds, high loads and at small sizes. In particular, their advantages are (Gieras, 2008; Hitchins, 2022; T. J. E. Miller, 1989; Shakweh, 2018):

- low cost of manufacture,
- generally smaller size,
- easy maintenance,
- good low-speed performance,
- high starting torque,
- variety of control solutions,
- ability to operate on DC supply without additional controls,
- ability to be operated above rated speed,
- free from issues related to harmonics.

Due to the need for a physical commutator and the presence of back-e.m.f., these machines have also a range of disadvantages:

- low lifespan,
- frequent maintenance,
- inability to be operated in explosive atmospheres,
- torque loss at speeds above rated,

- cogging at low speeds,
- temperature limitations when using permanent magnets.

Control and associated power electronics depend mainly on application and the type of motor used. Although they can be run directly from a DC supply (like a battery), the use of variable-voltage DC/DC (AC/DC in case of AC supply) converter is recommended for variable speed applications (Bullock, 1995). In addition, an H-bridge needs to be used to control the polarity of the voltage to reverse the direction of rotation, although this is rarely used in multirotors.

DC machines are simple in operation and naturally suited for use in battery operated devices. Their low lifespan and the need for maintenance is not a barrier for the use in aerial vehicles, where, especially at very small sizes, the low weight of PMDC motor and its simple voltage control (reducing the amount of electronics) are an asset. However, an additional point of failure from the commutator prevents them being used in larger and more expensive vehicles.

2.3.3 Brushless Direct Current (BLDC) and Permanent Magnet Synchronous (PMS) machine

To address the shortcomings of a physical commutator, in ‘brushless’ machines the current needs to be delivered only to the stator, while the magnetic field on the rotor is achieved using permanent magnets. An example 3-phase BLDC motor schematic is shown in Figure 2.13. This topology removes the need for physical connection between the stator and the rotor and the switching of current direction is achieved using specialised controller, thus often called a ‘digital commutator’ (Krumov, 2009). Therefore, even if the principle of operation is very similar to PMDC machines (with swapped rotor and stator), brushless DC machines always require an additional system to obtain the rotor position (physical or virtual) and to energise the stator windings based on it. In multirotor air vehicle applications this is called the Electronic Speed Controller (ESC), which con-

sists of the DC/DC converter, speed controller and sensorless positioning system in one package. Such an unit can be used with any 3-phase BLDC motor of adequate voltage and current ratings.

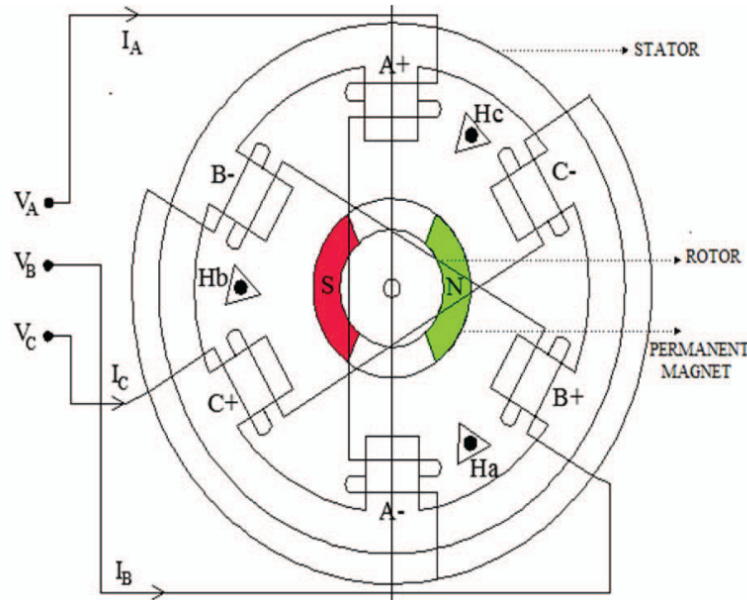


Figure 2.13: 3-phase Brushless DC (BLDC) motor schematic (Poovizhi et al., 2017).

Permanent Magnet Synchronous Machines (PMSM) are also the focus of this chapter, because even though being AC machines, they are almost identical in their construction to DC counterparts. Essentially, the difference lies in the shape of e.m.f. generated by the stator - in BLDC it is trapezoidal and in PMSM it is sinusoidal (Jain & Kumar, 2018). Of course, it is much easier to generate trapezoidal excitation current (as square waves (Derammelaere, Haemers, De Viaene, Verbelen & Stockman, 2016)), so the converters tend to be smaller and lighter, thus more suited for aerial vehicles (and generally aerospace) applications. In addition, with 3-phase machines it is possible to obtain the rotor position without the need for an external sensor (Ahmad, 2010, chap. 5.11), further reducing weight. Therefore, PMSMs are usually used only in larger vehicles that can accommodate more advanced inverters and sensors.

The market growth of DC brushless machines in recent years has been significant, rising from about 300 million USD in 2003 to 1300 million USD in 2008 (Gieras, 2008). Now, with the electrification of automotive and general aviation sectors it is expected

to jump from over 12 billion USD in 2020 to over 23 billion USD by 2028 (Vantage Market Research, 2021). This is mainly thanks to particular suitability to transportation applications with power ranging from a few watts up to 750 kW and excelling in the 10-15 kW range (Gieras, 2008). Specifically, the following advantages are of interest (Emadi, 2005; Gieras, 2008; Yedamale, 2003):

- high power density,
- very high efficiency (even higher in PMSM),
- high torque-to-weight ratio at small sizes,
- minimum maintenance,
- reliability,
- low noise,
- wide speed range,
- good heat dissipation (through stator),
- good performance at low speeds,
- easy and accurate speed control (due to closed-loop operation).

At the same time, the disadvantages restrict their use in industrial settings:

- expensive to manufacture,
- high cost of the magnet material,
- limited sustainability of rare earth magnet material,
- issues of demagnetisation,
- limited range of field weakening operation,
- requirement of power electronics converter,

- significant torque ripple (lower in PMSM),
- limited operating temperature due to permanent magnets,
- induction of voltage during rotation with unpowered windings (Laudensack et al., 2014),
- cogging at low speeds.

Typically, the motors used in RC applications have the rotor on the outside (so called out-runner). It consists of surface-mounted permanent magnets and a simple tube (bell) to close the magnetic circuit. Therefore, stator is located in the centre, reducing the lengths of end-windings. This configuration allows the increase of airgap length without significantly affecting weight, therefore improving torque-to-weight ratio. The drawbacks of this arrangement is leaving the rotor unprotected from external damage and the possibility of the magnets detaching (they are glued to the bell) during operation. Due to these issues this type of motors is most popular for RC toys, where performance is more important than safety, but in recent years they have also found use larger vehicles and even manned aircraft⁵.

Excellent performance at small sizes, high torque throughout the speed range and availability of specialised converters in the form of ESCs make the BLDC motor a good candidate for aerial vehicle propulsion. Therefore, it is of no surprise that the majority of commercial multirotors nowadays use this technology. However, for applications requiring a higher degree of safety, such as manned aircraft, the disadvantages prove to be a challenge. That being said, the technology continues to develop, slowly overcoming these obstacles with every day.

2.3.4 Less common technologies

To the right side of the graph in Figure 2.8 is the ‘long tail of interesting offbeat machines’. As T. J. E. Miller (2019) notes, some of those are already obsolete, but others

⁵<https://store.tmotor.com/goods.php?id=891>

have managed to find their niche and are steadily manufactured, although still in small numbers. Two of such examples might be the Synchronous Reluctance (SyncRel) and Switched Reluctance (SR) machines.

These are of particular interest, as they rely on **reluctance torque**, as opposed to reaction torque of induction, brushed DC and brushless DC machines (Bostanci, Moallem, Parsapour & Fahimi, 2017). However, PMSM machines with internally mounted magnets can utilise reluctance torque in case of magnet failure, but they are still designed mainly with reaction torque in mind (Dwivedi, 2019, chap. 5.4).

That being said, reluctance machine is, at the same time, a century old idea (Ahn & Lukman, 2018; T. J. E. Miller, 2001) with first modern attempt at synchronous reluctance motor being Kostko's design from 1923 (Kostko, 1923). Similarly, the name switched reluctance motor was first used by Nasar (1969), with similar principle being used in the phonic wheel by La Cour (1878) and Rayleigh (1899) as far back as 1878. Having been overshadowed by AC and DC machines for many years (T. J. E. Miller, 2001), these designs might as well have become obsolete if not for the reemergence of interest in the 1980s (Ahn & Lukman, 2018). In recent years, the advancement of high-speed electronic commutation made control easier and more accurate, increasing efficiency and speed ranges.

Although not as popular in industrial or transportation applications, still being manufactured in small quantities, reluctance machines are starting to be treated with similar interest to induction or brushed-DC machines. A good sign of this is dedication of chapters in books on the matter (Ahmad, 2010; Emadi, 2005; Gieras, 2008; Hughes, 2006; T. J. E. Miller, 1989), as well as numerous studies directly comparing them to popular technologies (Ahn & Lukman, 2018; Bilgin et al., 2020; De Almeida, Ferreira & Baoming, 2014; Harris & Miller, 1989; Hashemnia & Asaei, 2008; Lebsir, Bentounsi, Rebbah & Belakehal, 2013; Ramadhan, Asfani, Negara & Nugraha, 2021; Sayed et al., 2021). There are even whole books dedicated solely to these machines (Krishnan, 2001; T. J. E. Miller, 2001; Pellegrino, Jahns, Bianchi, Soong & Cupertino, 2016).

Synchronous Reluctance (SyncRel) machines

Magnetic reluctance is the measure of magneto-motive force in regards to magnetic flux:

$$\mathcal{R} = \frac{\mathcal{F}}{\Phi}, \quad (2.10)$$

where $\mathcal{R}$ is magnetic reluctance in $\frac{\text{At}}{\text{Wb}}$, $\mathcal{F}$ is magneto-motive force in At (Ampere-turns), and Φ is magnetic flux in Wb. This equation bears similarity to the Ohm's Law and is, in some cases, treated as its analogue in magnetic circuits (Heaviside, 1894). Therefore, magnetic reluctance, similar to resistance, depends on the geometry and material (or rather its magnetic permeability μ) of the object in question, with vacuum and air having high reluctance and ferrous materials like soft iron having low.

Magnetic flux always tries to take the path with lowest reluctance, therefore special paths of high and low reluctance must be constructed. This is shown in Figure 2.14. This allows to maximise the reluctance torque T_M (Oprea, Dziechciarz & Martis, 2015):

$$T_M = p \frac{U^2}{\omega_s} \left(\frac{1 - \frac{X_q}{X_d}}{X_q} \right) \sin 2\delta, \quad (2.11)$$

where p is pole pair number, U is stator phase voltage, ω_s is angular speed of rotating field, X_q and X_d are reactance in quadrature and direct axes, and δ is current angle. For that reason, synchronous reluctance machines' rotors tend to have air-filled barriers, as shown in Figure 2.15a (more common), or have saliency as in Figure 2.15b (Kolehmainen, 2010). Their purpose is to increase reluctance in the quadrature axis, so that the rotor will turn and follow the rotating field of the stator. What is more, a common inverter-fed stator, as found in induction motor, can be used effectively reducing the cost of the drive. However, the synchronous reluctance machine, as the name suggests, is synchronous, so a position sensor needs to be used in most applications (Dwivedi, 2019, chap. 5.6). However, with modern solid state electronics, variable or constant speed operation is not an issue.

Due to their simplicity and the lack of conductive material in the rotor, synchronous

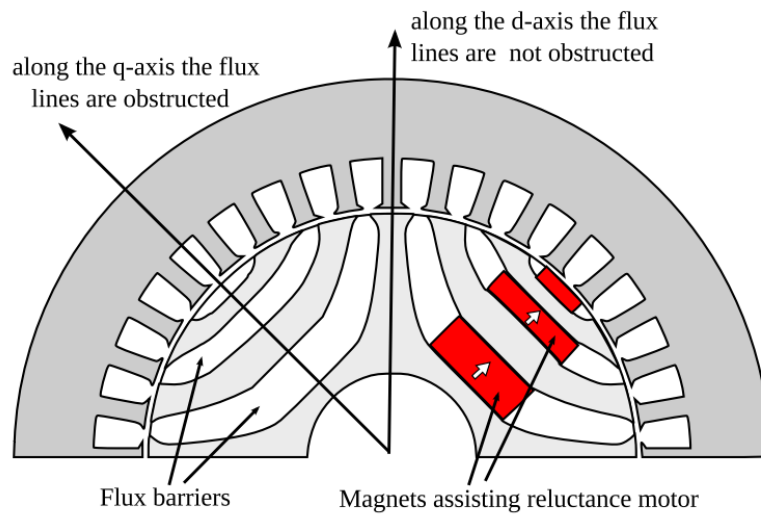


Figure 2.14: Synchronous Reluctance (SyncRel) motor schematic with optional assisting magnets (Bianchi et al., 2016).

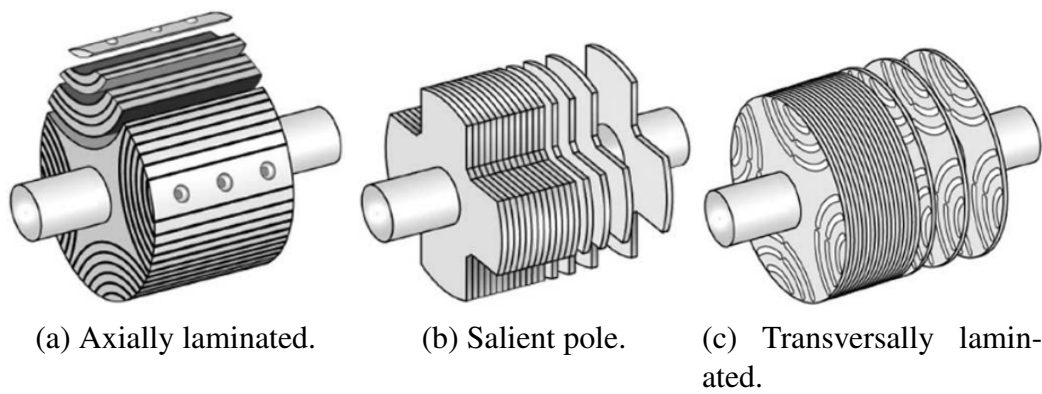


Figure 2.15: Example rotors of a synchronous reluctance machine (Kolehmainen, 2010).

reluctance machines boast multiple advantages over its competitors (especially the induction machine) (Chau, 2016; Deng et al., 2020):

- low material cost (Z. Zhang, 2020),
- simple rotor structure
- ease of control in flux weakening region,
- no losses during idle operation (only stator excitation),
- low bearing working temperature,

- no breaking torque during short-circuit faults,
- can be assisted with permanent magnets for increased performance (Dwivedi, 2019; Mohanarajah, Rizk, Hellany & Nagrial, 2019).

However, the following disadvantages need to also be considered:

- low specific torque density (due to solid rotor),
- low power factor,
- requirement of inverter and position sensor,
- susceptibility to harmonic fields,
- significant windage losses in case of salient rotors (Figure 2.15b),
- mutual coupling between phases due to overlapping windings,
- low production volume - high manufacturing cost.

It is hard to estimate typical power ranges of synchronous reluctance motors, mainly due to low production numbers. However, research is being done comparing them with cage rotor induction machines, so it can be assumed the operating ranges are also similar, although with wider speed range and higher efficiency (J. M. Miller, 2010a; Santiago et al., 2012). Moreover, some units have become available in manufacturers' catalogues. ABB is offering two categories of products: IE5 ultra-premium efficiency machines with 5.5 - 315 kW output; and high output machines with power between 1.1 and 350 kW⁶. Oemer (2022) has in its range motors as small as 2.8 kW, 1000 RPM (88.7% efficiency), as powerful as 436 kW, 1800 RPM (96.9% efficiency) and as fast as 86 kW, 2600 RPM (96.0% efficiency).

These ranges fit well with the historical applications of SyncRel machines, such as textile mill process line (Pellegrino et al., 2016) or synchrolifts for lifting ships

⁶<https://new.abb.com/motors-generators/iec-low-voltage-motors/process-performance-motors/synchronous-reluctance-motors>

(T. J. E. Miller, 2001), where the fact was exploited that, if driven from the same inverter, numerous machines could be operated exactly synchronised. Recently, however, this technology has become seriously considered for the drivetrain of electric vehicles, both with traditional rotors (Oprea et al., 2015), as well as permanent magnet-assisted ones (Bianchi et al., 2016). Similarly, research is being carried on use of these machines in aerospace, although focus has been more at multiple kW power examples for driving actuators (Amin & Abdel Aziz, 2019). That being said, some research has also been done towards electric propulsion in small traction vehicles (such as electric scooters) (Inte, Jurca & Martis, 2019; Jurca, Mircea, Martis, Martis & Florin, 2014), which share similar power, speed and torque requirements as multirotors.

Synchronous reluctance machines, although with roots in very old designs, only recently have been brought to the general attention. Therefore, it is still a relatively young technology with a lot of potential for further improvement. However, even now it has been proven to offer advantages in terms of performance (higher efficiency than IM) and safety (simple and rugged rotor, lack of permanent magnets). What is more, it has been shown to be a viable solution at sizes encountered in multirotor applications.

Switched Reluctance (SR) machine

While synchronous reluctance motor combines a salient rotor with a conventional slotted stator, switched reluctance motor is a machine of double saliency (T. J. E. Miller, 2001) - both in rotor and stator, as shown in Figure 2.16. Therefore SR motors are characterised not only by the number of phases, but also by the number of poles (teeth) on each side, with 6/4 (3-phase machine with 6 teeth in stator and 4 teeth in rotor), 12/8 (3-phase) and 8/6 (4-phase) configurations being the most common (T. J. E. Miller, 2001). Because of the double saliency, it is easy to distinguish two specific positions - aligned (Figure 2.17a) with the highest value of self-inductance and unaligned (Figure 2.17b) with the lowest. Torque is generated through the tendency of the rotor to minimise the reluctance by minimising the airgap thickness. Therefore, when the winding becomes energised,

the rotor moves from the unaligned to the aligned position where the winding gets de-energised (to avoid generating negative torque) and the next one in sequence becomes energised. Hence the name switched reluctance.

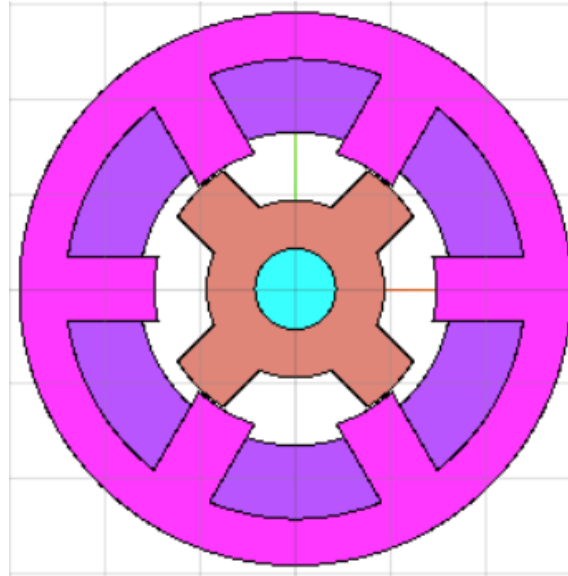


Figure 2.16: 3-phase 6/4 switched reluctance motor schematic.

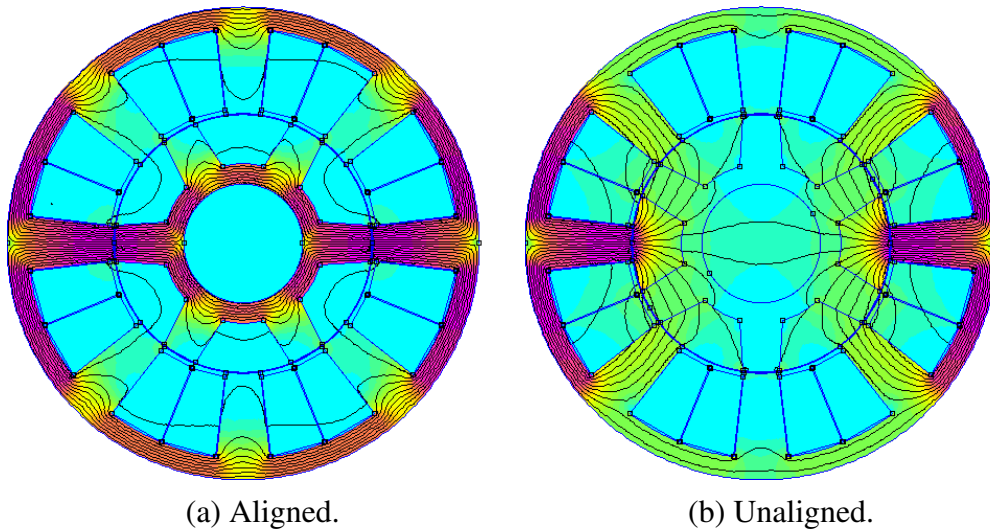


Figure 2.17: Extreme rotor positions in a switched reluctance motor.

To be able to discern which windings need to be energised and when, a rotor position needs to be obtained. However, multiple techniques have been developed to estimate this position (Cai & Deng, 2013; Kuai, Zhao, Heng & Cui, 2017; T. J. E. Miller, 2001), hence removing the need for a physical sensor. That being said, a current sensor for each

phase is also required, as the self-inductance changes with rotor position, so the winding current needs to be monitored and appropriately adjusted. The angles for energising and de-energising windings also change with speed (because of current rise and fall times (Hamouda & Számel, 2017)), so additional motor data is required for efficient operation. Because of that, switched reluctance motors require an (electronic) controller with a control solution developed for the specific machine, thus lacking universality of induction or DC motors. However, due to the windings being excited sequentially, the converter leg for each phase is also independent, greatly improving reliability (Indira & Venmathi, 2021; Narain, 2020).

It is easy to see that switched reluctance motors require different approach. On one hand they are very simple mechanically, made only of soft iron and copper (or aluminium) windings, but on the other they rely heavily on finely-tuned control and sensing. However, due to these differences, they boast quite a few advantages (Atkinson et al., 2010; Jain & Kumar, 2018; T. J. E. Miller, 2001; Rahman et al., 2018; Zabihi & Gouws, 2016):

- simple and robust construction,
- wide speed range,
- good heat dissipation,
- high level of fault-tolerance,
- wide constant power region,
- electrical and mechanical decoupling of phases,
- low material cost,
- sustainable - highly recyclable.

At the same time some disadvantages need to be considered:

- acoustic noise,

- significant vibrations,
- high torque ripple,
- complex control (nonlinear characteristics),
- need for sensors,
- uncommon converter topology,
- prone to magnetic saturation,
- high manufacturing cost due to low production numbers.

Even in 1993 a number of SR motors was successfully in operation (T. J. E. Miller, 1993), from small machines for kitchen appliances, through traction drives and high-speed starter-generators, up to 35kW heavy-duty machines. Since that time, multiple advancements have been made, such as the development of alternate topologies - Double Stator SRM (Abbasian, Moallem & Fahimi, 2010) and Modular Rotor SRM (Ullah, McDonald, Martin, Benarous & Atkinson, 2019) being two of them. One of the most influential events, however, is the 2009 unveiling by Dyson (Ahn & Lukman, 2018; Brandon, 2009) of a 104000 RPM motor operating on the switched reluctance principle (although augmented with rare earth magnets), for the use in handheld vacuum cleaner. Another promising area for SR machines are hybrid and electric vehicles (Bilgin et al., 2020; Saadi, Sehab, Chaibet, Boukhnifer & Diallo, 2017a; Takeno, Ogasawara, Chiba, Take-moto & Hoshi, 2011).

Conventional rotor design of SR motor does not use conductors nor magnets, so not only it is efficient, but also reliable. Independence of motor phases, in regards to windings and converter, provides a high degree of fault-tolerance. It has been shown that a complete loss of one phase does not degrade performance (up to certain loading of course) and the recovery time after fault is minimal (Dúbravka, Rafajdus, Makyš & Szabó, 2017; Tursini, Villani, Fabri & Di Leonardo, 2017). However, between the small ultra-high-speed machines and large high-power ones, small high-torque designs, that might be of

interest for multirotor propulsion. Laudensack et al. (2014) have explored this application, although only from theoretical point of view.

Switched reluctance motor is the most researched reluctance machine as of now, although still relatively uncommon in the consumer market. However, its high degree of fault-tolerance and power density surpassing inductance motors make it an interesting technology that seems to balance safety and performance. Recent popularity only plays to its advantage as the potential for further developments has already been shown, perhaps bridging the gap towards brushless DC motors in applications of electric propulsion, both for traction and aerial vehicles. This serves as a sufficient incentive to study them in more detail.

2.4 SR motor electromagnetics

The doubly salient structure of SR motors hints at their connection with electromagnets. This is true, as the principle of torque production in an SR motor follows that of the electromechanical energy conversion in a solenoid (Krishnan, 2001, chap. 1.4). The electrical input energy W_e is defined as:

$$W_e = \int e i dt = \int i dt \frac{dN\Phi}{dt} = \int N i d\Phi = \int F d\Phi, \quad (2.12)$$

where e is the induced back-electro-motive force (back-e.m.f.), i is current, N is the number of coil turns, Φ is flux, and F is the magneto-motive force (m.m.f.). This energy is equal to the sum of the energy stored in the coil W_f and the energy converted into mechanical work W_m , $W_e = W_f + W_m$. When considering incremental changes between positions 1 and 2, it is written as $\delta W_e = \delta W_f + \delta W_m$ and is shown in Figure 2.18.

The area between the curves at incremental rotor positions $\delta\theta$ is directly proportional

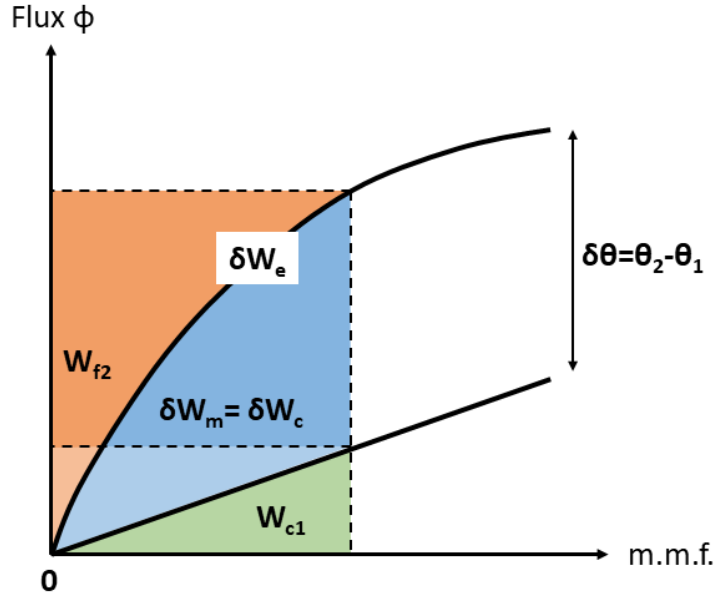


Figure 2.18: Flux-m.m.f. characteristics of SR motor pole pair when treated as a solenoid.

to mechanical work δW_m , therefore electromagnetic torque in such machine is:

$$\delta W_m = T_e \delta \theta, \quad (2.13)$$

$$T_e = \frac{\delta W_m}{\delta \theta}. \quad (2.14)$$

Assuming a case of constant excitation, incremental mechanical work δW_m is equal to the rate of change of co-energy δW_c given by:

$$W_c = \int \Phi dF = \int \Phi d(Ni) = \int (N\Phi) di = \int \lambda(\theta, i) di = \int L(\theta, i) di, \quad (2.15)$$

where λ is flux linkage and L is inductance. During rotation, each rotor tooth shifts between the unaligned and aligned positions, as previously illustrated in Figure 2.17.

The change of energy between two positions θ_1 and θ_2 can be expressed as:

$$T_e = \frac{\delta W_m}{\delta \theta} = \frac{\delta W_c}{\delta \theta} = \frac{\delta W_c(i, \theta)}{\delta \theta} \Big|_{i=\text{const.}}, \quad (2.16)$$

$$T_e = \frac{dL(\theta, i)}{d\theta} \frac{i^2}{2}, \quad (2.17)$$

where

$$\frac{dL(\theta, i)}{d\theta} = \frac{L(\theta_2, i) - L(\theta_1, i)}{\theta_2 - \theta_1} \Big|_{i=\text{const.}} \quad (2.18)$$

and assuming inductance is linearly varying with rotor position for a given current, i.e. no magnetic saturation occurs.

Equation (2.17) was also be derived from the voltage equation by T. J. E. Miller (2001, chap. 3.2). For a single phase, terminal voltage v is given by:

$$v = Ri + \frac{d\lambda}{dt} = Ri + \omega_m \frac{d\lambda}{d\theta} = Ri + \omega_m \frac{d(Li)}{d\theta} = Ri + L \frac{di}{dt} + \omega_m i \frac{dL}{d\theta}, \quad (2.19)$$

where R is the phase resistance and ω_m is the rotor angular velocity. The last term $\omega_m i \frac{dL}{d\theta}$ is the back-e.m.f. e found in (2.12). The rate of change of magnetic stored energy δW_f is given by:

$$\frac{d}{dt} \left(\frac{Li^2}{2} \right) = \frac{1}{2} i^2 \frac{dL}{dt} + Li \frac{di}{dt} = \frac{1}{2} i^2 \omega_m \frac{dL}{d\theta} + Li \frac{di}{dt}. \quad (2.20)$$

Combining (2.19) and (2.20) and keeping in line with the law of conservation of energy, we get:

$$T_e = \frac{p}{\omega_m} = vi - Ri^2 - \frac{d\left(\frac{1}{2}Li^2\right)}{dt}, \quad (2.21)$$

$$T_e = \frac{1}{2} i^2 \frac{dL}{d\theta}, \quad (2.22)$$

which confirms the approach of Krishnan (2001).

Equation (2.17) showcases many interesting properties of SR machines, as catalogued by Krishnan (2001). Direction of flowing current has no influence due to the i^2 component, but positive torque can only be produced with rising inductance slope. Therefore, in motoring operation, the winding should be energised only between the unaligned and aligned positions, effectively demanding current pulses for control. Idealised variation of inductance and torque production process is shown in Figure 2.19.

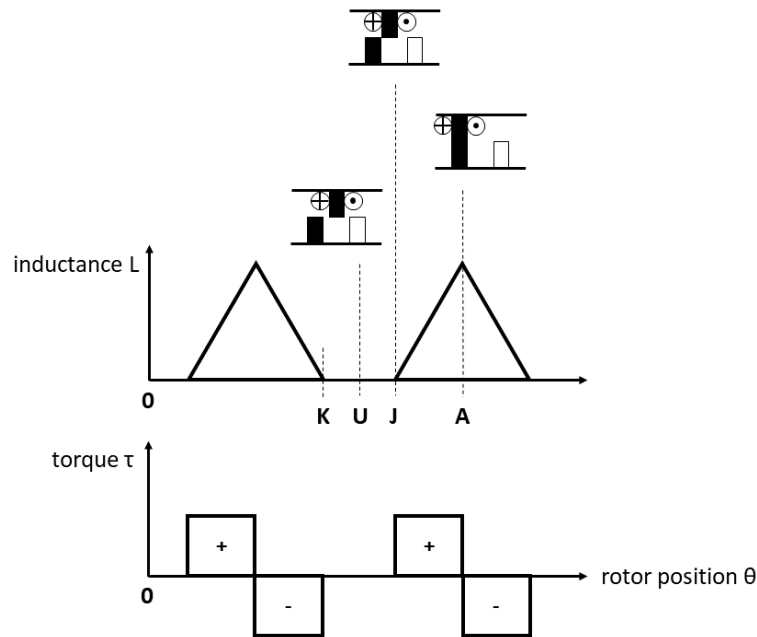


Figure 2.19: Idealised inductance and torque production process of an SR motor pole.

The torque equation (2.17) derived previously is applicable only to operation in the linear region due to undertaken assumptions ((2.18) and linear variation of inductance with position). Figure 2.20a shows inductance characteristics typically found in real motors, which is highly non-linear. As the term $\frac{dL(\theta,i)}{d\theta}$ can be effectively considered the torque constant, the torque produced, as shown in Figure 2.20b, is also non-linear and varies with current. Therefore, switched reluctance motors cannot be modelled with simple equivalent circuits.

It is evident from (2.17) that at unaligned and aligned positions torque production is zero. Moreover, useful (unidirectional) torque can only be produced over a limited angle. Therefore, to ensure continuous torque production and self-starting capability, multiple

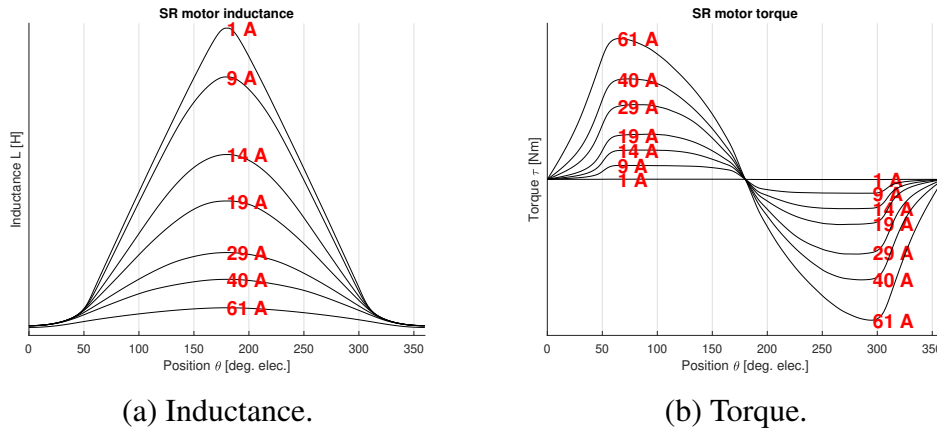


Figure 2.20: Inductance and torque characteristics of a real SR motor.

phases are needed. Although inductance profiles of specific phases can be considered independent in the typical machine design (short-pitched windings and single phase excitation), the produced torque is combined on the same rotor, as shown in Figure 2.21. However, real torque profile rarely has a perfectly rectangular shape, therefore substantial torque ripple is present in high-speed or high-torque operation.

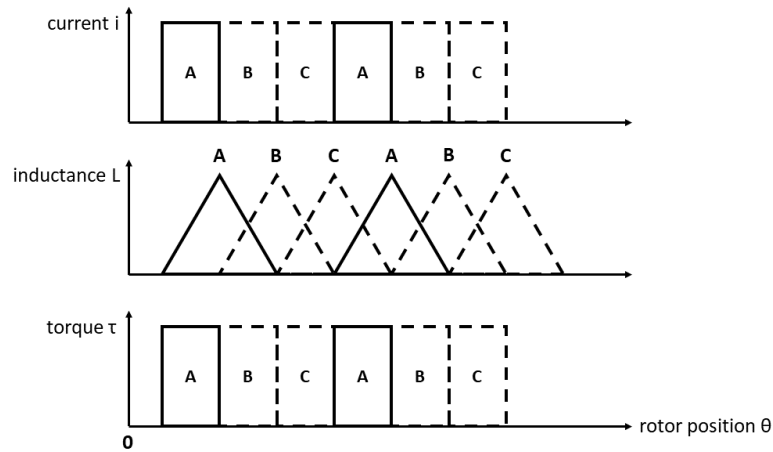


Figure 2.21: Idealised current, inductance and torque waveforms in a 3-phase SR motor.

One cycle of torque production is called a stroke and is given by:

$$S = mN_r, \quad (2.23)$$

$$\varepsilon = \frac{2\pi}{S}, \quad (2.24)$$

where S is the number of strokes per revolution, m is the number of phases, N_r is the number of rotor poles and ε is the stroke angle. With higher S the amount of torque-producing events increases, but at the same time it is offset by lower rotor pole arc, thus reduction in inductance ratio $\frac{L(\theta_A, i)}{L(\theta_U, i)}$ and energy-conversion area. Therefore, 3- and 4-phase configurations with $N_r = N_s \pm 2$ rotor poles, where N_s is the number of stator poles, are the most popular. One exception is the 12/8 configuration, which is essentially 6/4 topology multiplied by two.

2.4.1 SR motor control

As shown in Figure 2.19, to produce a rectangular torque waveform, a rectangular current pulse needs to be present in the stator winding. Typically, in low-speed and medium-speed operation, the current of each phase is controlled by a simple converter, such as the one shown in Figure 2.22. The circuit chops the voltage to vary the current in the winding. There are two common techniques: voltage-PWM and current-hysteresis control (T. J. E. Miller, 2001, chap. 5.3.3). In voltage-PWM the voltage is switched at constant frequency with variable duty cycle, without the closed-loop current control. Current-hysteresis switches voltage asynchronously, to keep the current value within a specified range based on the reference value. Both methods are shown in Figure 2.23. The period of negative voltage after passing a specified angle is to reduce current in the coil as quickly as possible. It is not required, but recommended in most cases, as it helps to avoid negative torque generation that would increase torque ripple and reduce efficiency of the drive. It is worth noting that both control methods can be used with both uni- and bipolar voltage, depending on the converter configuration.

The previous methods are well suited for low- and medium-speed operation, however, as the speed increases, so does the back-e.m.f. up to a point that it is impossible to maintain flat-topped current shape. The transition speed is known as the base speed. Above base speed, the pulse control strategy is used, which is shown in Figure 2.24. It uses a continued voltage pulse and controls only the switch-on (firing) angle θ_0 and switch-

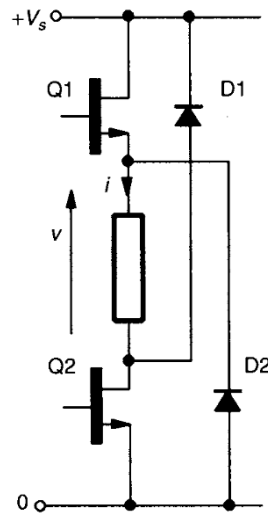


Figure 2.22: One leg of asymmetric bridge converter (T. J. E. Miller, 2001).

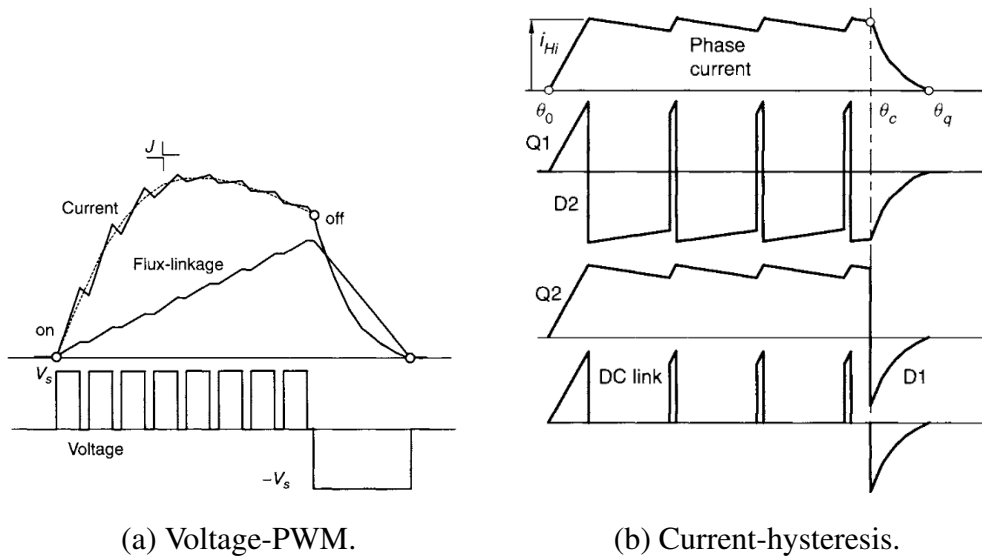


Figure 2.23: Common current control techniques (T. J. E. Miller, 2001).

off (commutation) angle θ_c . After commutation zero voltage (freewheeling), negative voltage, or a combination of these two can be supplied, depending on the transistor rating and required performance, to bring the current to zero. As the speed increases the angle required for current to rise (or fall) to a specified value also increases, thus control angles need to be constantly adjusted in regards to speed and torque demand.

As has already been established and is evident from Figure 2.20b the polarity of the produced torque is dependent almost exclusively on angles at which the phase winding is

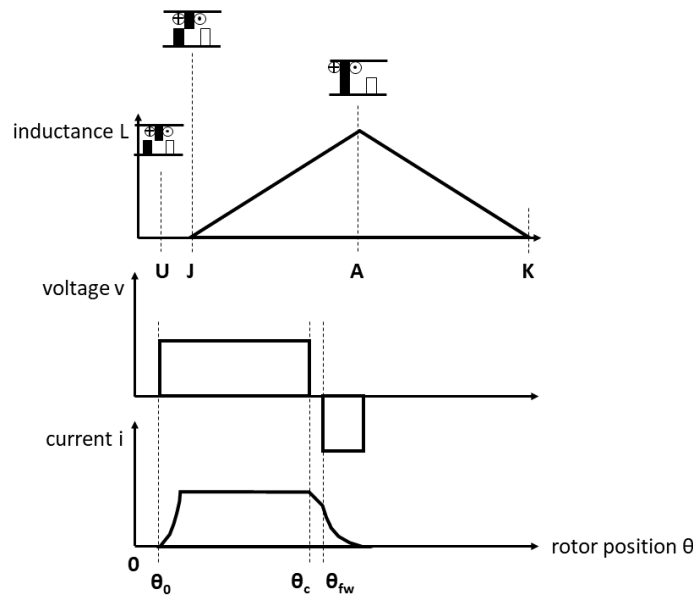


Figure 2.24: Pulse control technique.

energised and de-energised. In addition, spinning direction is determined by the order in which the phases are energised. Assuming typical converter architecture and electronic control, any modern conventional SR motor is capable of four quadrant operation, at least from the control perspective. However, that may be limited by the parameters of the power stage.

Although SR motor electrodynamics and control may seem complicated, basic drive systems are actually easy to realise thanks to high-speed control units and smart sensors. However, it needs to be noted that this technology lacks universality, as controllers are tied to motors due to the need of accurate switching based on commutation angle data, which is unique to every motor design. In addition, modern control techniques require even more specific motor data to ensure high-efficiency and reliable operation.

2.4.2 Topology

As said in Section 2.3.4, SR motors generally have lower power density than currently used solutions. This disadvantage can be, to some extent, offset by some alternative topologies available. Similarly, improved fault-tolerance or lower torque ripple may also

be achieved with specific motor geometry.

The conventional SR motor design - in-runner, with short-pitched windings (Figure 2.25a) - has already been explored for aerospace applications by Tursini et al. (2017). They highlight the high degree of fault-tolerance due to the use of concentrated windings. Unfortunately, due to power electronics limitations no tests were carried at full power.

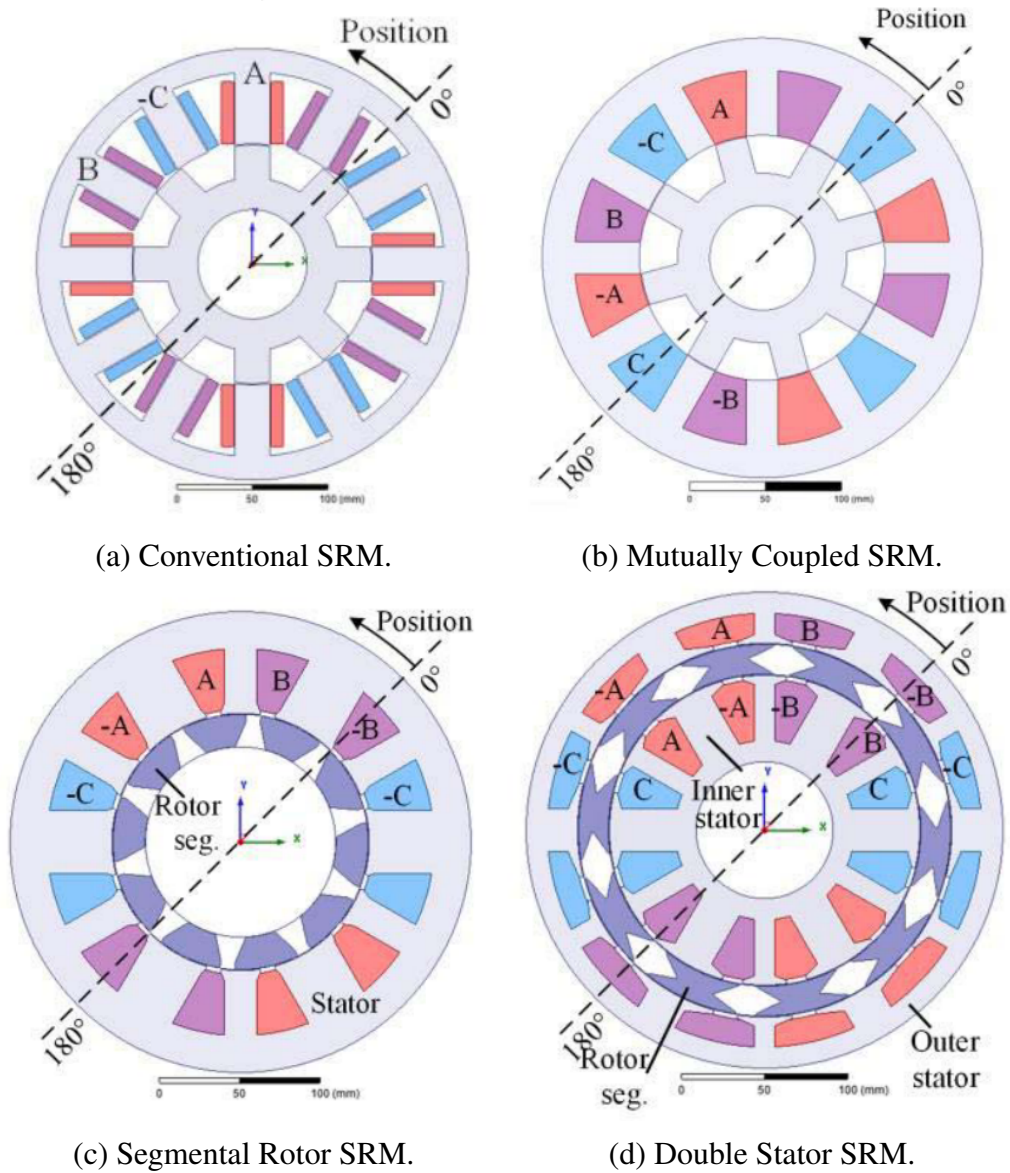


Figure 2.25: Different SRM geometries (Bostanci et al., 2017)

Bostanci et al. (2017) carry out a comparative study of SR motor topologies focused on ground Electric Vehicles, but the findings can safely be extended onto Aerospace ap-

plications too. One of the geometries investigated is the Mutually Coupled SRM (MC-SRM), as seen in Figure 2.25b. This topology retains the conventional iron shape, but changes the way coils are wound. This leads to an increase in torque and power density, but is balanced by the fact that phases are no longer independent from each other, therefore reducing reliability and fault-tolerance. Another disadvantage of this approach is a substantial increase in end-winding length, thus copper weight.

An approach allowing to keep the short-pitched windings while increasing torque density is the Segmental Rotor SRM (SR-SRM), as shown in Figure 2.25c. Bostanci et al. (2017) argue that through the introduction of short flux paths and more active surface in the airgap, the offered torque density is higher than with conventional geometry, but at the same time the machine suffers from being more prone to magnetic saturation. Another issue is the increased complexity of the rotor, which relies on another structure for support of the segments.

Building upon the design of SR-SRM is the Double Stator SRM (DSSRM), as shown in Figure 2.25d. It has two stators, which was enabled by the use of a segmental rotor. This allows for possible reduction in vibration, as the radial forces now act from two sides, balancing each other. In addition, according to Abbasian et al. (2010), the motional force is substantially increased leading to a drastic increase in energy conversion efficiency over conventional SRM. This is confirmed by Bostanci et al. (2017) who compare its performance to IPMSM and achieve comparable results both in terms of maximum torque and efficiency.

2.5 Electric drive reliability

Continuing from section 2.2, in this section it makes sense to formally define this vehicle as safety critical. According to the definition of Ertugrul, Soong, Dostal and Saxon (2002): ‘A *safety critical system is the system whose failure may cause injury or death, which should have the ability (...) to respond to an unexpected hardware or software*

failure.' There are two parts to this definition: the application of the system (which multicopters fulfil, as even unmanned vehicles can crash into humans on the ground), and the design requirement (which current vehicles complete through redundancy).

This work considers two aspects of critical safety: reliability and fault-tolerance. White (1995) defines reliability as the measure of '*how often will this component (or system) malfunction*' and fault-tolerance as a state in which '*no single failure will cause the system to malfunction*'. Although the definitions can be slightly modified to suit the applications, for example in commercial aviation a fault-tolerant system may be required to tolerate multiple faults. Still, a distinction needs to be made that reliability is a measure of time (Ertugrul et al., 2002), while fault-tolerance is an ideal (usually unattainable) state.

Following this principle reliability of the system can be easily calculated from reliability of each component using various techniques, as shown in a set of studies by Shu et al. (2020) (2021). The novelty is consideration of the whole motor system, composed from the drive motor and motor controller (although the cooling system was not investigated). This is important, as the motor controller was found to be much more unreliable than the drive motor, lowering the reliability estimate of the whole system.

The most common drive motor faults were found to be related to bearings (oil seal), sensors (position and temperature) and winding (rotor and stator). This data is in line with estimates based on induction motors used by Terec, Ruba, Szabó and Ernő (2010), who suggested extrapolating the data to SRM also. Although it needs to be noted that SR machines are not subject to rotor winding faults and in the multicopter actuating system considered in this study the temperature sensor is not included due to particularity of the operational cycle and weight constraint. Therefore, most common motor failures to investigate are bearing oil seal (0.447 FPMH - failures per million hours), position sensor (0.375 FPMH) and stator winding (0.252 FPMH). According to Zaiets and Kondratenko (2019) in non-stop manufacturing applications winding faults are even more prevalent, while Galea, Giangrande, Madonna and Buticchi (2020) argue that faults of winding in-

sulation are largely due to outdated design methods.

Two groups dominate motor controller faults: surface mounted components (SMCs) of control module (1.653 FPMH) and SMCs of drive module (1.391 FPMH). The failure rates are visibly higher than in the case of drive motor components. This seems to be due to the sheer amount of SMCs in these modules (553 in control module and 368 in drive module). Next in term of failure rate is the block of three IGBT switches (0.420 FPMH) followed by the rest of SMC components. Considering the commonalities in construction (Dodge, 2003) and failure mechanisms (Yang et al., 2010), the fault rates of MOSFETs used in motor systems are considered similar to that of IGBTs.

In the follow-up study Shu et al. (2021) look at the degradation of reliability of the motor controller and its component over a vehicle's lifespan. SMCs in all analysed modules are subject to significant drop in reliability ranging from 7-8% (discharging and communication modules) through 30% (driver module) to 35% (control module) after 250000 hours of service. Printed Circuit Boards (PCBs), on the other hand, degrade very little, less than 5% with suggestions on improving this value through increasing track width and decreasing the number of through holes. IGBTs also exhibit a significant drop of about 10%, which is more than DC-link capacitor (5%) and current sensor ($<2\%$). While the reliability drop of modules and components is linear, the reliability of the complete motor controller is highly nonlinear reaching about 77% of the original value after 50000 hours, 49% after 150000 hours and 29% after 250000 hours. This is a drastic drop, rendering the system highly unsafe. However, it is almost impossible for a multirotor vehicle to operate for such a long time.

An SR motor-centred reliability assessment is presented by Chen, Yang, Chen and Iu (2016). That study also considers a whole drive system including the motor and the converter, which is only right considering the close link between these two. On the component level, components are divided according to their function and common fault modes selected. A novelty, and an SR drive-specific characteristic, is the inclusion of phase deficient operation under five different kinds of faults. System-level reliability is calcu-

lated based on analysed fault modes using two methods in an attempt to reflect the fault-tolerance of SR drives. The resulting reliability metrics show a **considerable increase of reliability when considering the possibility of phase deficient operation**. However, the authors point out that this work aims to showcase and popularise the approach, rather than provide numerical results.

Reliability analysis as shown above provides convenient numerical metrics, which are, unfortunately, not very useful in this work due to difference in applications. Focus on weight reduction, outdoor operation and relatively short operation times introduce additional fault modes that have not been well explored. For example, water droplets may get inside the motor assembly (due to the need of cooling with air), high humidity may lead to corrosion or frequent heating and cooling of components may damage transistors. Moreover, changing environmental conditions may also influence the rates of already investigated faults. Therefore, Section 2.5.1 includes an attempt to identify possible points of failure and their causes.

White (1995) states that **when dealing with a fault-tolerant (or close to fault-tolerant) system, reliability is of secondary importance**. This seems to be confirmed by aforementioned study (Chen et al., 2016), where the ability to operate without one phase resulted in a significant reliability increase. Fault-tolerance definition, its requirements and relation to the multicopter vehicle application is discussed in Section 2.5.2.

2.5.1 Possible points of failure

Combining the works of Chen et al. (2016); Ertugrul et al. (2002); Garcia, Cusidó, Rosero, Ortega and Romeral (2008); Jack, Mecrow and Haylock (1996); Krishnan and Bharadwaj (1991); Terec et al. (2010); Valentine, Das and Pecht (2015), we get the following list of common faults:

- bearing - oil seal, outer and inner race, rolling element, cage,
- winding - open circuit, short circuit between turns, short circuit at terminals, short

circuit between phases, short circuit bridging winding,

- power MOSFET - open circuit, short circuit, shoot-through, parameter drift,
- freewheeling diode - open circuit,
- DC-link capacitor - open circuit, short circuit
- current sensor - omission, offset, gain,
- position sensor - omission, offset, gain,
- control system fault,
- supply - battery voltage drop, battery failure,
- combination of the above faults.

Naturally, many of these faults have been discussed in the previously mentioned studies, However, there are also new additions such as shoot-through and parameter drift of power transistors, or battery faults. Gopalakrishnan, Omekanda and Lequesne (2006) discuss in depth possible faults in the SR motor electrical system, focusing specifically on short and open circuit faults. Control system faults are not investigated in more detail due to the sheer amount of possible faults, which is outside of scope of this study.

Terec et al. (2010) also comment on possible sources of winding faults: mechanical vibration, heat, age, damage during installation, and power converter failure. Similarly, bearing fault causes are also provided: inadequate lubrication, asymmetric loading, and misalignment.

Valentine et al. (2015) list IGBT fault causes, but in general case these can be extrapolated to MOSFET also. In particular: high temperature, over-voltage, high current densities, and power (thermal) cycling. The last case is particularly interesting, as the study has shown that frequent heating and cooling cycles (as is the case in multirotor operation) can significantly reduce the reliability and lifespan of the transistor.

In addition, SRM-specific faults can be also identified (Chen et al., 2016; Terec et al., 2010):

- uneven airgap thickness - rotor eccentricity, vibration,
- phase deficient operation,

As SR machine's performance depends heavily on the airgap thickness and its uniform surface, uneven airgap can cause increased torque ripple and vibration. Resonance is also possible between two sources, some of which have been identified by Sarrazin, Anthonis, Van Der Auweraer, Martis and Gyselinck (2014): unbalance, misalignment, looseness and distortion, defective bearings, gearing and coupling inaccuracies, resonances, rotor/stator misalignment, and bent rotor shafts.

To complete the study, some less common faults can also manifest (Sarrazin et al., 2014; Zaiets & Kondratenko, 2019):

- detachment of motor from the frame - due to excessive vibration,
- rotor failure (breakage, detachment) - due to excessive vibration or contact with obstacles,
- faults from improper use,
- faults from improper maintenance,

As can be seen from the fault descriptions and possible causes, it is possible for one failure to cause another. This can happen multiple times causing a chain. Therefore, certain requirements need to be met by fault-tolerant systems to prevent such situations.

2.5.2 Fault-tolerance requirements

Along with the definition of fault-tolerance quoted earlier, White (1995) (later repeated in (Atkinson et al., 2010)) has also proposed four fundamental requirements:

- *redundancy and partitioning*,

- *fault isolation,*
- *fault detection and annunciation, and*
- *on-line repair.*

All of these requirements aim to increase availability (time spent in operation) of the system. However, these were thought to be used for power systems in industrial application, and not for transportation, where conducting repairs of a moving vehicle is much harder (never mind if the vehicle is in the air). Therefore, Mecrow et al. (1999) has adapted this set for aerospace applications by changing the fourth requirement. The modified criteria are as follows:

- *Partitioning and redundancy*
- *Isolation between units,*
- *Fault detection and reporting*
- *Continued operation until next service opportunity.*

Partitioning is a way to divide a system into ‘*Failure Groups*’, which are independent subsystems in such a way, that a fault in one subsystem will not completely disrupt system operation. Redundancy is the property of having ‘spare’ subsystems that are able to take over operation in case of failure. Partitioning in an SR multirotor actuating system is realised through independent phases in the motor and the converter. Redundancy can be achieved by including both physical position sensor and implementing sensorless control methods (Kuai et al., 2017; Tursini et al., 2017), or implementing methods using limited amount of current sensors, such as (Ali & Gao, 2021). However, due to the weight constraint, redundancy of physical components (such as converter legs) is heavily limited.

With the system divided into partitions, the next step is to ensure the faults do not propagate into other modules. Jack et al. (1996), Atkinson et al. (2010) and Deng et al. (2020) point out that SR machine’s phases are de-coupled electrically and mechanically,

but with slight magnetic and thermal coupling. This might be somewhat alleviated by the use of a spacer tooth between phase winding or adding new thermal paths (Gerada, Galea & Kladas, 2015). In addition, end-windings do not overlap reducing the probability of a phase-to-phase fault, and no current is driven into a phase without excitation.

Fault detection comes quite easily in SR actuating systems, as means to detect or estimate current and position are required, so already the control system has a lot of information about the drive. As mentioned previously, faults in sensors can be also detected by comparing their output with results of sensorless methods. In addition, Terec et al. (2010) proposes multiple simple sensor architectures that can be used, although it is also subject to the weight constraint. Similarly, vibration sensors can also be used for early fault detection - Ugwiri, Mpia and Lay-Ekuakille (2020) discuss it in the context of the electric machine, while Bondyra, Gasior, Gardecki and Kasinski (2018) present an approach in terms of the whole multirotor vehicle.

Finally, as has already been proven by numerous studies (Castellini, Cuscinetti, Lucidi & Villani, 2016; Chen et al., 2016; Saadi, 2019; Terec et al., 2010; Tursini et al., 2017), SR drivers are perfectly capable of continuing operation in case losing one or more phases, although with decreased performance. Gopalakrishnan et al. (2006) also show operation during certain short circuit faults. Combined with previously mentioned properties, this makes it a technology inherently suited for fault-tolerant, safety critical actuating systems. This being said, still the area of reliability in application (outdoor, in-flight) requires further research.

Technology of electric propulsion is changing very rapidly and multirotors are no different. For example, in the past 18 years Draganfly company progressed from being barely able to lift a low-resolution camera for 15 min (Heer, 2004), to 25 minute missions with dual camera (20MP + FLIR) payloads (Draganfly Innovations Inc., 2020). Therefore, it would be safe to estimate that the vehicles would be operated for only a few years before they are exchanged for a newer model. This would also be in line with the expected 5-year lifespan (Galea et al., 2020) of electric machines in transport applications. Therefore, it

makes sense to favour fault-tolerance over reliability, as ultra-long fault-free operation periods are simply not needed. That being said, some older models may be kept as a backup, therefore some degree of reliability is still needed.

2.6 Summary

Multirotors have proven themselves to be an interesting concept for air vehicles, combining mechanical simplicity with high agility and great scalability. Usability and versatility is shown through numerous application in different settings - from sport, through photography and surveillance, finishing with manned vehicles in UAM context. However, one of the main factors halting the development of multirotors in current and new applications is safety. As inherently unstable systems, they rely on well-designed actuating systems and control algorithms to keep them in the air.

Table 2.2: Summary of typical parameters of electric motor actuating systems (Bostanci et al., 2017; Gieras, 2008; Yildirim et al., 2014).

Parameter	Cage IM	DC	BLDC	SyncRel	SRM
Power density	satisfactory	low	highest	satisfactory	high
Efficiency	high	low	highest	high	high
Controllability	highest	highest	high	highest	satisfactory
Reliability	highest	satisfactory	high	highest	highest
Technological maturity	highest	highest	high	satisfactory	high
Power factor	high	low	highest	satisfactory	low
Lightweightness	high	low	highest	high	highest
Cost effectiveness	highest	high	satisfactory	high	high

Fault is a state of the system that might lead to failure or malfunction of the vehicle. Typically, in a multirotor faults can occur in sensors, actuating system or in vehicle's structure. The worst case scenarios are the loss of effectiveness or the complete loss of an actuator, which can change dynamics of the vehicle leading to instability. Most faults leading to critical consequences happen in the actuating system and conventional preventive measures add excess weight leading to decrease in performance. Therefore, electric

drive-specific faults are also investigated, with the focus on SR motor faults. Reliability of such drives is investigated, but a conclusion is reached that in the safety-critical application fault-tolerance is of more importance than reliability. In addition, the ability to operate with certain faults (like phase deficiency) significantly increases reliability. Therefore, a list of requirements for achieving fault-tolerance was presented and discussed in the context of SR drives.

Actuating system architecture is mainly determined by the motor technology used. The two most popular motor technologies currently are the induction motor and brushed DC motor. The first one, although reliable is not powerful enough at sizes considered for multirotor propulsion. The second is used only in toys due to low reliability because of physical commutator. Most multirotors nowadays use brushless DC motors due to their high power density and reasonable reliability. However, reliance on rare earth magnets is not suitable for safety-critical applications such as UAM. A solution might lie in reluctance machines. Out of two designs analysed - synchronous reluctance motor and switched reluctance motor - the latter is more promising, as shown in Table 2.2.

From the electromagnetic point of view, the SR motor behaves similar to a solenoid, which makes its control simple from the conceptual point of view. Unfortunately, due to a high degree of non-linearity and dependence on rotor position, precise control requires accurate sensors and high-speed electronics. While most of the theoretical discussion applied to the most popular SR motor topology with short-pitched windings, there exist also alternative topologies improving upon specific parts of the design, such as creating short flux paths.

Chapter 3

Multirotor Sizing Methodology

The previous chapter have established the principles of operation and mathematical models of SR motors. However, in application they are a part of the actuating system. Therefore, the following two chapters will present a methodology of sizing of such system in regards to the whole multirotor vehicle. This chapter is a pre-study that develops the sizing methodology using databases of off-the-shelf components (propellers and BLDC motors) to simplify the design process. Therefore, it is not linked to any research objective as such, but helps establish approaches, concepts and vocabulary for further discussion. The next chapter (Chapter 4) is therefore devoted to the evaluation of the approach and extending it to custom components (SR motors and controllers).

Multirotors as a category of flying vehicles cover a lot of variants differing not only in the number of rotors, but also their placement. Currently, the most popular configuration seems to be *quad x* with four parallel rotors placed diagonally from the centre, as shown in Figure 3.1. One of the characteristic properties of most multirotors is their symmetry and the fact that every arm is the same, except for the rotor spinning direction. This makes it easy to analyse the propulsion system for the general case by analysing only one arm (one propulsion chain). The Flight Controller (FC) is responsible for control strategy for the whole platform and preparing a set point for each arm, but it does not participate in the propulsion chain as such.



Figure 3.1: Multirotor in *quad X* configuration with visible components of the propulsion chain. (i) Flight Controller, (ii) ESC (under arm), (iii) BLDC Motor, (iv) propeller, (v) battery connector.

3.1 Multirotor propulsion chain

In most cases Brushless DC (BLDC) motors are used for multirotor propulsion, but sometimes, usually for toys under 100 g, DC motors are also used. This pre-study focuses only on BLDC, however most concepts shown apply to both types. The main components of the propulsion chain are identified to be: *propeller*, *motor*, *ESC* and *battery*, as shown in Figure 3.1. In addition, Figure 3.2 shows that there is one input of a set point (given by FC) and one output, namely the thrust generated by the propeller. Therefore, the propulsion chain can be identified as a open-loop Single Input Single Output (SISO) system, which makes it relatively easy to size components one at a time. In the next part of this section, each component will be described in detail.

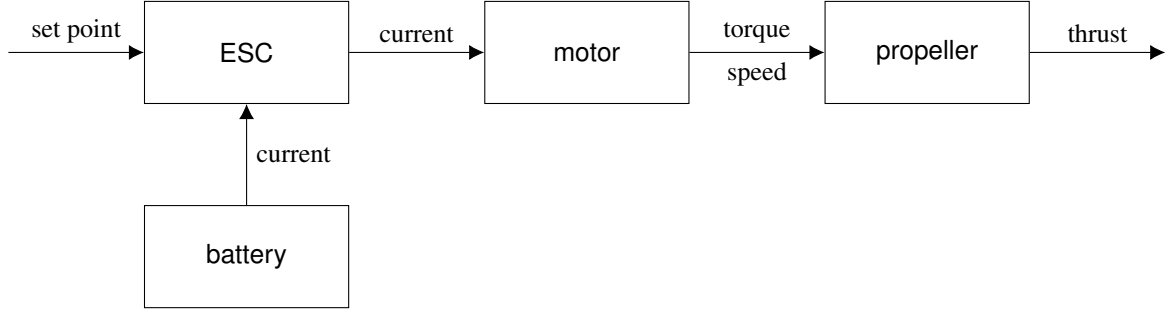


Figure 3.2: Multirotor propulsion chain diagram.

3.1.1 Propeller

Aircraft propellers are characterised by 3 main parameters: diameter, pitch and the number of blades. Generally, the higher these are, the higher the thrust generated, but also higher torque is exerted on the motor. However, long, slowly-spinning, 2-bladed propellers are known to be more aerodynamically efficient than small, fast-spinning, multi-bladed ones (Bershadsky, Haviland & Johnson, 2016). Propeller characteristics are mainly a function of its rotational speed and the speed of incoming air (Brandt, Deters, Ananda, Dantsker & Selig, 2020):

$$C_T = \frac{T}{\rho \omega^2 d^4}, \quad (3.1)$$

$$C_P = \frac{P}{\rho \omega^3 d^5}, \quad (3.2)$$

$$J = \frac{V}{\omega d}, \quad (3.3)$$

$$\eta = \frac{C_T J}{C_P} = \frac{TV}{P}, \quad (3.4)$$

where C_T, C_P are thrust and power coefficients, T, P are thrust and power (in Nm and W), ρ is the air density (in $\frac{\text{kg}}{\text{m}^3}$), ω is revolutions per second, d is the propeller's diameter (in m), J is the advance ratio, V is the velocity (in $\frac{\text{m}}{\text{s}}$), and η the is propeller's efficiency. However, if we consider air density to be constant and the air to be static (at hover in still air), thrust, torque, power, and efficiency depend only on propeller speed. Additionally, there are secondary parameters such as mass and geometry template expressed as

manufacturing series (e.g. ‘Multirotor’, ‘Slow Flyer’, ‘Carbon’, etc.).

3.1.2 Motor

In a multirotor, the motor’s main objective is to drive the propeller reliably and with high acceleration (and deceleration), so the speed can be changed quickly. The main limitations of a BLDC motor are in terms of speed and current. Maximum current is often stated by the manufacturer and maximum speed in no-load conditions ω_0 can be calculated from the speed constant KV (in $\frac{\text{RPM}}{\text{V}}$) multiplied by the applied voltage U :

$$\omega_0 = \text{KV} \times U. \quad (3.5)$$

With a constant voltage, when current is applied, the motor starts exerting torque on the shaft accelerating it until its torque equals the load torque, assuming the mechanical losses are neglected. At low speed, far from the motor constraints, it is assumed that the relation between motor torque and current is constant and expressed with motor torque constant (K_T). Therefore, the applied current is transformed into the torque based on the motor characteristic, then the torque is transformed into speed based on the propeller torque-speed characteristic, and finally the speed is transformed into thrust using the propeller thrust-speed characteristic, an example of which is shown in Figure 3.5. This sequence makes the propulsion chain easy to calculate analytically as a SISO system.

3.1.3 Electronic Speed Controller

Although Electronic Speed Controllers (ESCs) serve a very important purpose in the real-life multirotor, in the propulsion chain model it has very little importance. In the model, its function is reduced to transferring current from the battery to the motor under constant voltage. However, when designing a multirotor, ESC still needs to be sized according to the maximum current flowing to the motor.

3.1.4 Battery

When it comes to lightweight aerial vehicles, Lithium Polymer (LiPo) batteries currently dominate the market due to their high energy density and high current discharge capabilities (Gatti, 2017; J. M. Miller, 2010b). These batteries are composed of several cells connected in series (rarely in parallel). Cell voltage changes according to the state of charge with 4.2 V being at 100%, 3.85 V at 50% and 3.7 V (nominal) at 20%. However, discharging a LiPo cell under 3 V leads to permanent damage to the battery. Therefore, it is recommended to only discharge the batteries to about 20%, which grants a Depth of Discharge (DoD) of 80%. The cells can be connected in series or in parallel, denoted by *S* or *P* respectively, so for example, *4S1P* is a 4 cell battery with 14.8 V nominal voltage. Additionally, the batteries are characterised by their capacity in mAh and a C-rating (r_C), which specifies the maximum current that can be drawn continuously, for example $35C \times 5.2Ah = 182A$ (the unit being C and not Coulomb). It is evident that maximum discharge current is not dependent on battery capacity.

3.2 Sizing methodology

In Figure 3.2, by tracing the path from battery voltage to propeller thrust and inverting it - a new model can be obtained allowing to estimate battery voltage based on thrust generated, as shown in Figure 3.3. This allows for an iterative approach in order to determine the time required to deplete the battery at constant power draw, which effectively serves as a flight time estimate. Thus, two distinct sub-systems can be distinguished in the system model: the actuating system and the power system. This manifests itself in the sizing methodology, which is also divided into two parts. Figure 3.4 shows a simplified view of the methodology. Although it is based on the diagram in Figure 3.3, it also shows the separation between battery sizing and battery simulation (flight time simulation).

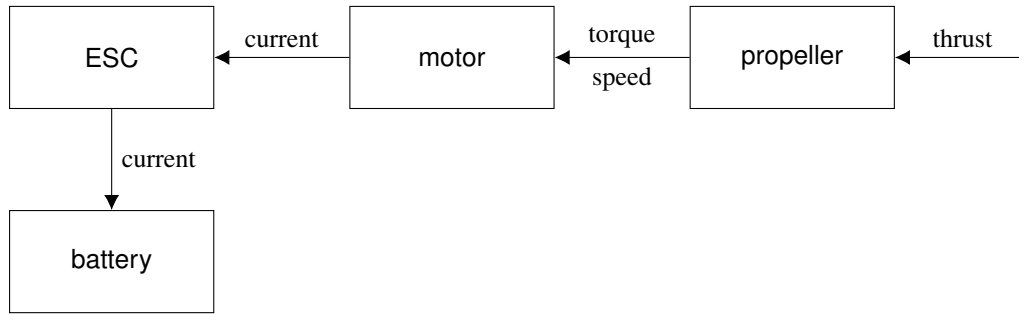


Figure 3.3: Inverted multirotor propulsion chain diagram.

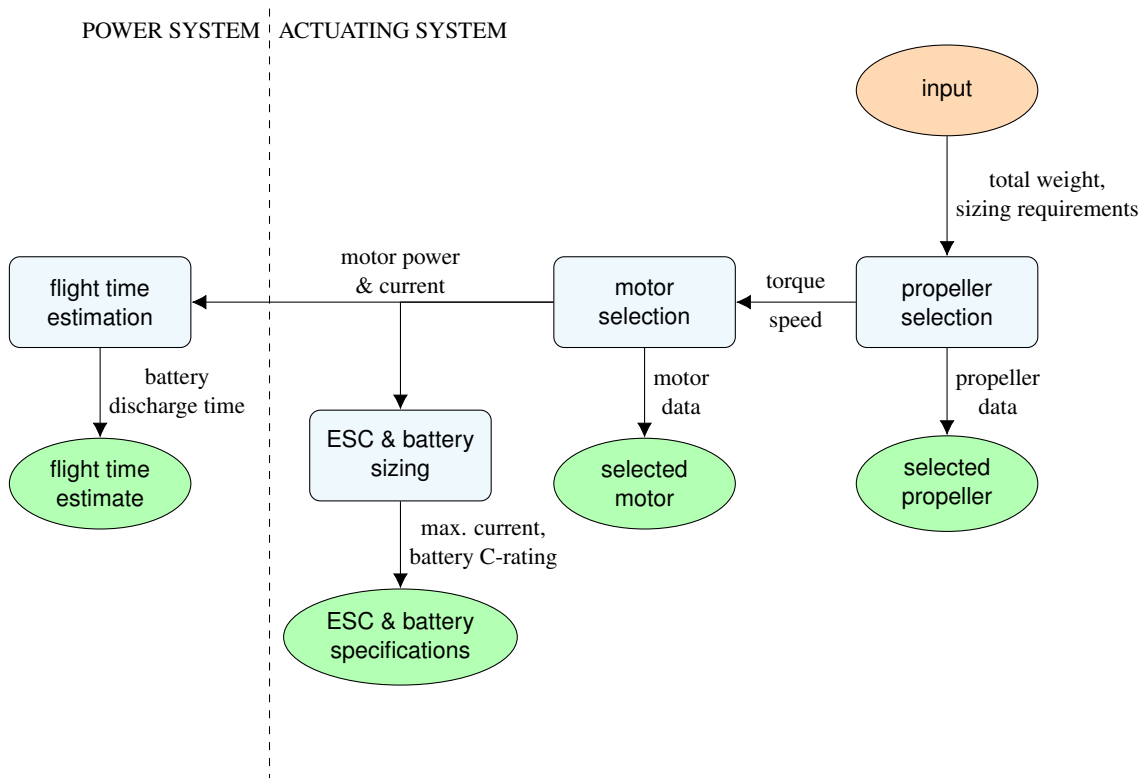


Figure 3.4: Simplified sizing methodology flowchart with division into two sub-systems.

3.2.1 Actuating system

The actuating system provides the thrust propulsion to the vehicle and consists of the propeller, the motor, an ESC to control the motor and a battery to power the motor. The propeller sizing and selection is performed first, the motor sizing being dependent on the propeller properties. Finally, specifications for the ESC and the battery are produced.

The propulsion system model used here is only applicable in static conditions and at constant speed. Modelling a multirotor in flight is much more complicated due to

the presence of aerodynamic effects such as variable angle of attack, reduction of thrust coefficient with advance ratio and additional frame drag. However, an approximation of the required performance for full controllability in flight is made using the model only in static conditions of operation. It uses a state of equilibrium achieved at hover (in no-wind conditions), where thrust generated by the propellers is equal to the multirotor's weight. This thrust can be multiplied by a constant thrust-to-weight ratio to achieve a value of static thrust that guarantees specific performance in the air depending on the application. This approach appears imprecise, however, during the years of use of similar methods in the community of radio controlled aircraft modellers, the values of thrust-to-weight ratio required for different applications have been validated with many test flights. A quick summary of typical values can be found in Table 3.1, which is based on (Half Chrome Drones, 2017) and (Liang, 2019). Additionally, in static conditions there is no influence of rotor inertia on motor performance, so the propeller and motor selection can be decoupled, further simplifying the process.

Table 3.1: Typical applications for multirotors of different thrust-to-weight ratios.

Thrust-to-weight ratio	Application
2	slow flight (minimum)
3	payload transport; photography
4	surveillance
5+	aerobatics; high-speed video
7+	racing

Propeller sizing and selection

The propeller sizing and selection process starts by defining a propeller database represented as a set of available propellers

$$\mathcal{P} := \{\mathbf{p}_i : i = 1 \dots n_p\} \quad (3.6)$$

where the i th propeller $\mathbf{p}_i$ is defined by the pair

$$\mathbf{p}_i := (\mathbf{f}_{pi}, \mathbf{g}_{pi}) \quad (3.7)$$

where $\mathbf{f}_{pi}$ denotes the i th propeller performance, which will be defined later, and $\mathbf{g}_{pi}$ denotes its physical properties expressed as a 4-tuple

$$\mathbf{g}_{pi} := (d_i, \theta_{pi}, m_{pi}, s_{ni}) \quad (3.8)$$

where d_i is the i th propeller diameter, θ_{pi} is its pitch angle, m_{pi} is its mass and s_{ni} is a discrete parameter representing the propeller series name. The propeller set $\mathcal{P}$ is then filtered to obtain a set of propellers $\mathcal{P}_p \subseteq \mathcal{P}$ that satisfy a requirement 4-tuple

$$\mathbf{g}_{pr} = (d_{\min}, d_{\max}, m_{p_{\max}}, \mathcal{S}_{nr}) \quad (3.9)$$

where $d_{\min}$ is the minimum diameter, $d_{\max}$ is the maximum diameter, $m_{p_{\max}}$ is the maximum mass, and $\mathcal{S}_{nr}$ is a set of preferred series names

$$\mathcal{S}_{nr} := \{s_{nk} : k = 1 \dots n_s\}. \quad (3.10)$$

Thus

$$\mathcal{P}_p = \{\mathbf{p}_i : d_i \in [d_{\min}, d_{\max}], m_{pi} \in (0, m_{p_{\max}}], s_{ni} \in \mathcal{S}_{nr}\}. \quad (3.11)$$

This helps save time when evaluating the performance data and calculating operating points that is done next.

The performance of the i th propeller $\mathbf{f}_{pi}$ is denoted as a triplet of bijective mappings

$$\mathbf{f}_{pi} := (\omega \mapsto T(\omega), \omega \mapsto \tau(\omega), \omega \mapsto P_p(\omega)) \quad (3.12)$$

where ω is the rotor speed, T is the thrust, τ is the torque and P_p is the propeller power. Let $T_r^{(k)}$ denote a required thrust. For each $\mathbf{p}_i \in \mathcal{P}_p$, we determine a set of n_o operating points $o_{pi} = \{o_{pi}^{(k)} : k = 1 \dots n_o\}$ where

$$o_{pi}^{(k)} := (T_i^{(k)}, \omega_i^{(k)}, \tau_i^{(k)}, P_{pi}^{(k)}), \quad (3.13)$$

and where

$$T_i^{(k)} = T_r^{(k)}, \quad (3.14)$$

$$\omega_i^{(k)} = T^{-1}(T_r^{(k)}), \quad (3.15)$$

$$\tau_i^{(k)} = \tau(\omega_i^{(k)}), \quad (3.16)$$

$$P_{pi}^{(k)} = P_p(\omega_i^{(k)}). \quad (3.17)$$

An example of the mapping triplets for two propellers (APC 12x4.5MR and APC 12x5.5MR) is shown in Figure 3.5 along with an illustration of obtaining o_{pi} from T_r .

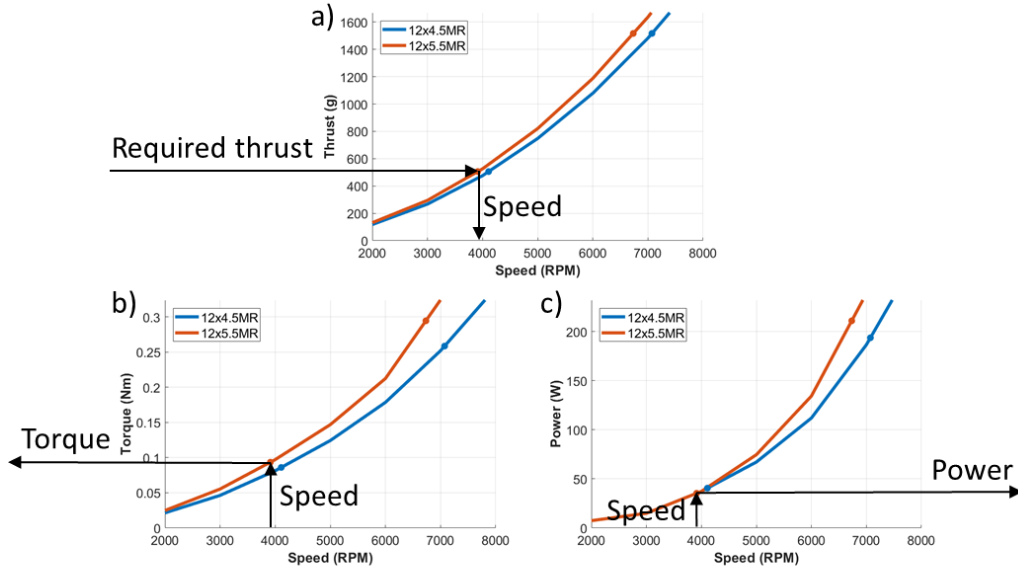


Figure 3.5: Example of obtaining a propeller operating point based on required thrust. a) Obtaining speed from required thrust. b) Obtaining torque from speed calculated in a). c) Obtaining power from speed calculated in a).

Usually $n_o = 2$ operating points are calculated: the operating point at hover $o_{pi}^{(1)}$, and

the Wide Open Throttle (WOT) operating point $o_{pi}^{(2)}$. These signify the lower and upper boundaries of the flight performance respectively. A third operating point ($k = 3$) can also be defined that corresponds to the propeller limit speed designated by the manufacturer; this can be used for checking the feasibility of the other operating points. The thrust requirements, $T_r^{(1)}$ for the hover condition and $T_r^{(2)}$ for the WOT condition, can be calculated from

$$T_r^{(1)} = \frac{W_{\text{total}}}{n_{\text{rot}}}, \quad (3.18)$$

$$T_r^{(2)} = r_T \times T_r^{(1)} \quad (3.19)$$

where W_{total} is the estimated total weight of the multirotor, n_{rot} is the number of rotors and r_T is the thrust-to-weight ratio. Except for the propeller (and motor) set filtering purposes, the methodology uses only the total estimated weight of the multirotor, as it is presumed that the frame, battery size, payload and control modules are pre-selected from the ones available to the user and suited for the application. As only static conditions are considered (multirotor inertia not considered), the weights of those components are of lower importance as opposed to the estimated weights of propellers, motors and ESCs, which are multiplied by the number of rotors

$$W_{\text{total}} = n_{\text{rot}} (W_{\text{prop}} + W_{\text{motor}} + W_{\text{ESC}}) + W_{\text{frame}} + W_{\text{battery}} + W_{\text{payload}} + W_{\text{FC}} + W_{\text{other}}. \quad (3.20)$$

In practice, due to the fact that the propeller characteristics mappings defined by (3.12) are often given in the form of sample points, interpolation must be used for the calculations. This introduces errors. Therefore, although in theory $P_p = \tau\omega$, often in practice (dependence on k removed for notational simplicity)

$$P_{pi} \neq \tau_i \omega_i, \quad (3.21)$$

due to errors associated with interpolating the data, hence an average of those two values is taken

$$P_{pi_{\text{avg}}} = \frac{1}{2}(P_{pi} + \tau_i \omega_i). \quad (3.22)$$

To choose the propeller, various selection criteria are available. If $n_o > 1$ then determining the minimum power solution is a multiobjective problem, and some user interaction is then helpful in making the selection. However, it is often possible to reduce the problem to the simplest case for $n_o = 1$, where the lowest power at hover operating point can be computed as follows

$$\mathbf{p}_{\text{selected}} := \arg \min_{\mathbf{p}_i \in \mathcal{P}_p} P_{pi_{\text{avg}}}^{(1)}. \quad (3.23)$$

In this case the minimisation can be quickly carried out through exhaustive search, thanks to the small set size due to the filtering in previous steps.

Motor sizing and selection

In a similar manner as for the propeller, let $\mathcal{M}$ be the set of available motors

$$\mathcal{M} := \{\mathbf{m}_j = (\mathbf{f}_{mj}, \mathbf{g}_{mj}) : j = 1 \dots n_m\} \quad (3.24)$$

where $\mathbf{f}_{mj}$ is the motor model described by the triplet of mappings

$$\mathbf{f}_{mj} := (I \mapsto P_m(I), I \mapsto P_e(I), (P_m, P_e) \mapsto \eta(P_m, P_e)) \quad (3.25)$$

where I is the current, P_m is the mechanical power, P_e is the electrical power, η is the efficiency and where $\mathbf{g}_{mj}$ denotes the motor properties expressed as a triplet

$$\mathbf{g}_{mj} := (I_{\max j}, \omega_{0j}, m_{mj}) \quad (3.26)$$

where $I_{\max_j}$ is the maximum allowable i th motor current, ω_{0j} is its maximum no-load speed and m_m is its mass.

Unlike the process for the propeller selection, the performances of the motors must be evaluated first. The required motor power is set to be $P_r = P_{p_{\text{selected}}}^{(k)}$. Then for each $\mathbf{m}_j \in \mathcal{M}$, we determine n_o motor operating point triplets

$$o_{mj}^{(k)} := (I_j^{(k)}, P_{ej}^{(k)}, \eta_j^{(k)}), \quad (3.27)$$

where (dependence on k removed for simplicity):

$$I_j = P_m^{-1}(P_r), \quad (3.28)$$

$$P_{ej} = P_e(I_j), \quad (3.29)$$

$$\eta_j = \eta(P_r, P_{ej}). \quad (3.30)$$

It should be noted that the mapping $I \mapsto P_m(I)$ is not bijective in terms of motor characteristics, because at high current values most of the energy is dissipated as heat. However, considering the domain only up to the maximum current specified by manufacturer, the function is almost always monotonic. Therefore, in practice, over the domain $[0; I_{\max_j}]$ the inverse of power function P_m^{-1} can almost always be evaluated.

Knowledge of o_{mj} for all $\mathbf{m}_j \in \mathcal{M}$ allows for filtering of the motor set in regards to maximum current, speed and mass, thus obtaining $\mathcal{M}_p \subseteq \mathcal{M}$ that satisfies maximum current requirement on each motor $I_j \leq I_{\max_j}$ and a requirement pair

$$\mathbf{g}_{mr} = (\omega_{\max}, m_{m_{\max}}) \quad (3.31)$$

where $\omega_{\max} = \omega_{\text{selected}}^{(2)}$ is the propeller speed at WOT and $m_{m_{\max}}$ is the maximum motor mass. Thus

$$\mathcal{M}_p = \{\mathbf{m}_j : I_j \leq I_{\max_j}, \omega_{0j} \geq \omega_{\max}, m_{mj} \leq m_{m_{\max}}\}. \quad (3.32)$$

Like in the propeller's case, various selection criteria could be used to choose the motor. In the simple example for $n_o = 1$ it could be the lowest electrical power

$$m_{\text{selected}} := \arg \min_{\mathbf{m}_j \in \mathcal{M}_p} P_{ej}^{(1)}. \quad (3.33)$$

Again the filtering operation in (3.32) makes it possible to use exhaustive search for the minimisation purpose.

ESC and battery sizing

The Electronic Speed Controller is sized mainly in regards to the maximum current it can handle. As it is assumed that the multirotor will never need more thrust than achieved at WOT operating point, the current should also not go over the calculated value. Therefore, it can be said that

$$I_{\text{ESC}} = I_{\text{selected}}^{(2)} \quad (3.34)$$

where I_{ESC} is the rated (maximal) ESC current and $I_{\text{selected}}^{(2)}$ is the motor current at WOT operating point.

A substantial part of battery specification needs to be provided by the user to realise flight time estimation as described in the Subsection 3.2.2. However, the methodology allows to complete the battery specification by sizing the C-rating parameter

$$r_C = \frac{I_{\text{ESC}} \times n_{\text{rot}}}{C} \quad (3.35)$$

where r_C is the minimal required battery C-rating and C is the battery capacity.

The whole actuating system sizing methodology is depicted by the data flow chart shown in Figure 3.6. It shows the dependence of motor sizing on propeller specification and ESC and battery sizing on motor specification. The light cyan blocks correspond to the methodology stages, the dark blue blocks show requirements and constraints and

the orange ellipses signify points of database access. The output data in green ellipses includes specification parameters for sizing all of the major components of the propulsion system (namely propeller, motor, ESC and battery) and the calculated propeller and motor operating points that can be used for calculating additional data, such as estimated flight time. The data corresponding to each of the outputs can be found in Table 3.2.

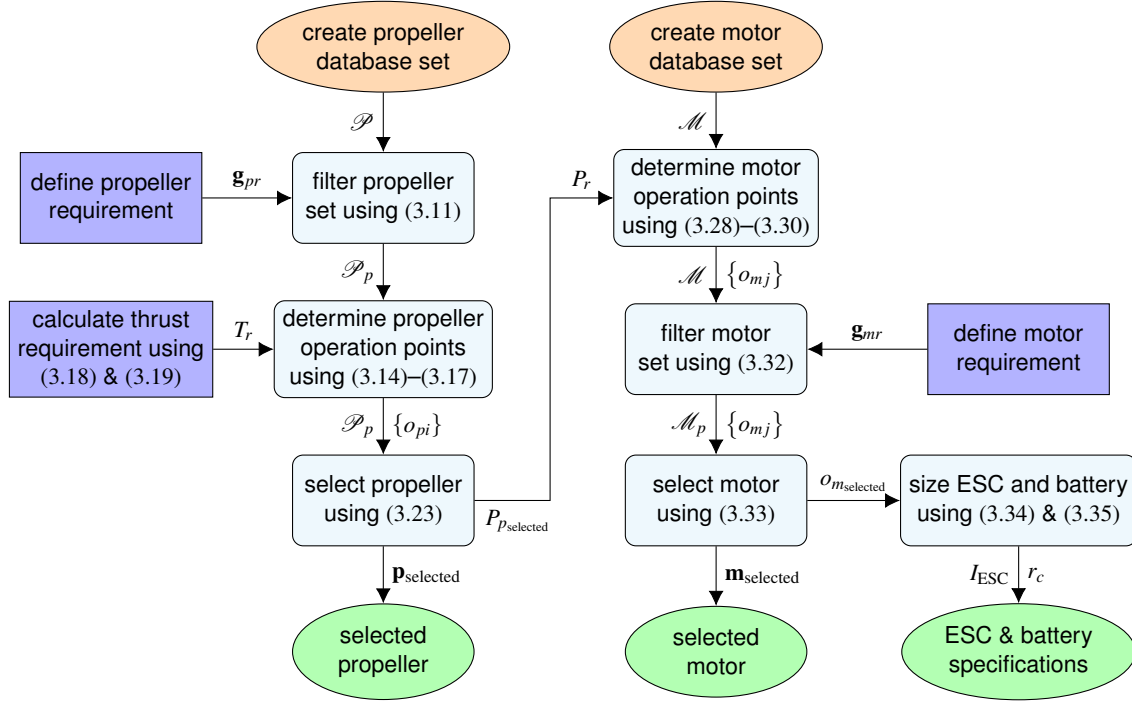


Figure 3.6: Actuating system sizing methodology information flow diagram.

Table 3.2: Data contained in sizing methodology outputs

Output name	Data contained
Propeller specification	name; diameter d ; pitch θ_p ; series s_n
Motor specification	name; KV rating; rated speed $\omega_{\text{selected}}^{(2)}$; rated torque $\tau_{\text{selected}}^{(2)}$; rated mech. power $P_{m_{\text{selected}}}^{(2)}$; rated el. power $P_{e_{\text{selected}}}^{(2)}$; rated efficiency $\eta_{\text{selected}}^{(2)}$; nominal voltage U
ESC specification	maximum current I_{ESC}
Battery specification	cell number n_C ; minimum C rating r_C ; capacity C

In Figure 3.6 a substantial impact of estimated total drone weight can be also seen - it is used to calculate required thrust T_r that plays a key role in selecting the propeller, and

consequently the motor. Due to the discrete nature of propeller and motor parameters, the relationship is highly nonlinear, so it needs to be analysed numerically. However, it is easy to implement the methodology in a loop to plot the characteristics of flight time versus weight, which may be used in a payload sizing application.

3.2.2 Power system

The power system section of the methodology focuses on flight time estimation by modelling the battery. The model is based on the iterative approach presented by Traub (2011). It features two important phenomena - decrease of capacity with the increase of current and drop in voltage due to discharge. Additionally, the power demand can be varied throughout the simulation, however, in the base version of the methodology this is not used, as the operating points are constant. A block diagram of the calculations for one operating point can be seen in Figure 3.7.

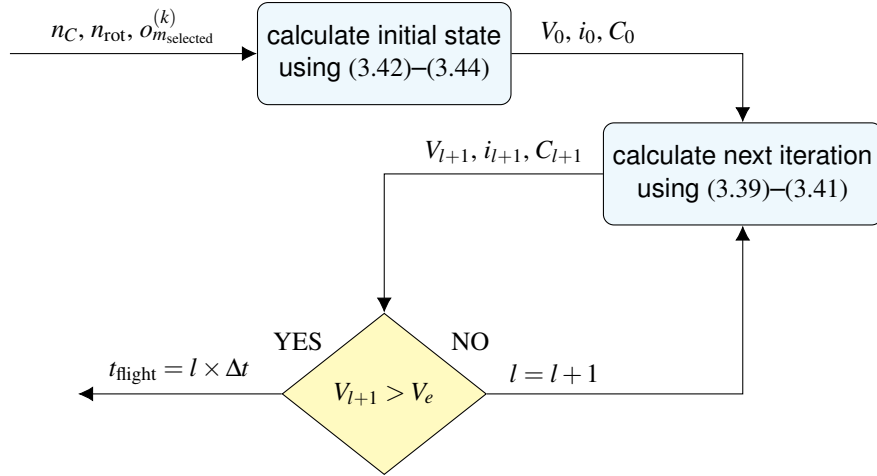


Figure 3.7: Power system calculation flowchart for k^{th} operating point.

Modelling of the battery capacity varying with drawn current is done through modified Peukert's equation in the form of:

$$t = \frac{Rt}{i^n} \left(\frac{C}{Rt} \right)^n \quad (3.36)$$

where Rt is battery hour rating (1 hour in case of small packs) and n is Peukert's constant

(1.3 for LiPo) dependent on battery type and temperature.

Measuring battery voltage is one of the main ways of measuring remaining charge in-flight. Typically, Lithium Polymer (LiPo) cells used in drones have 4.2 V when at full charge and drop to 3.7 V when at 20% charge. The voltage drop curve is nonlinear, but for the model it has been linearised and is expressed through

$$U(t) = U_0 - k_1 [C_0 - C(t)], \quad (3.37)$$

$$k_1 = \frac{4.2\text{V} - 3.7\text{V}}{\text{DoD} \times C_0 \times n_C}, \quad (3.38)$$

where U_0 is the initial voltage, k_1 is the voltage drop coefficient, C_0 is the initial battery capacity, DoD is the maximal Depth of Discharge and n_C is the number of battery cells. Based on Traub (2011) the battery model can be defined with a set of iterative equations:

$$U_{l+1} = U_0 - k_1 [C_0 - C_l], \quad (3.39)$$

$$i_{l+1} = \frac{P_e}{U_{l+1}}, \quad (3.40)$$

$$C_{l+1} = i_{l+1}^{1-n} R t^{1-n} C^n - \sum_{m=1}^{l+1} i_m \Delta t \quad (3.41)$$

with the initial state defined as

$$U_0 = 4.2\text{V} \times n_C, \quad (3.42)$$

$$i_0 = \frac{P_e}{U_0}, \quad (3.43)$$

$$C_0 = i_0^{1-n} R t^{1-n} C^n. \quad (3.44)$$

The information flow in the model is visualised in Figure 3.7.

As time passes, the voltage decreases, therefore increasing current draw to achieve the same power, and consecutively decreasing available battery capacity due to Peukert's

effect, as can be seen in Figure 3.8. The simulation is stopped when voltage reaches

$$U_e = 3.7V \times n_C \quad (3.45)$$

or when capacity reaches 20% of initial capacity (only works when power drawn is constant). The output is simply the simulation time, calculated as the product of the time step value and the number of iterations.

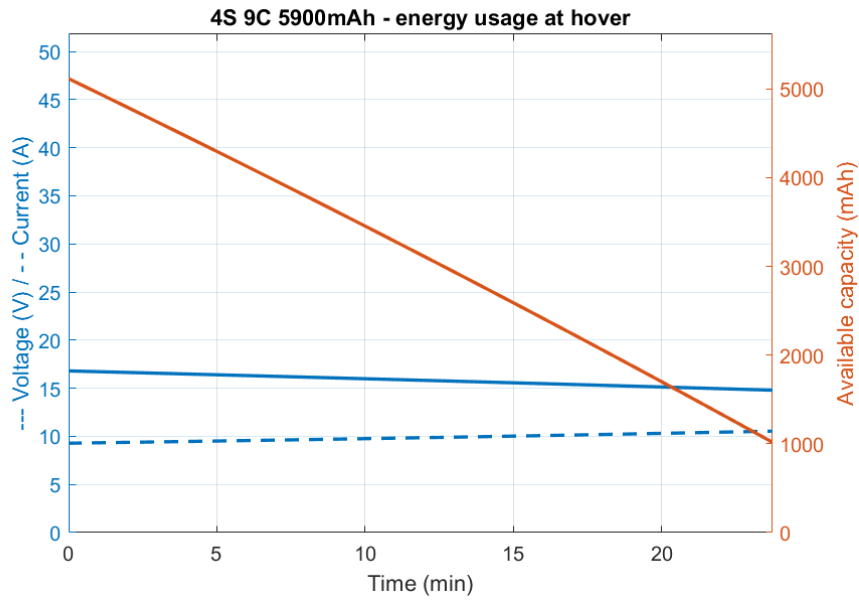


Figure 3.8: Example battery behaviour during hover.

3.3 Example results

The methodology presented has been implemented as a MATLAB script. This allows to easily process large quantities of data from propeller and motor databases and to plot component characteristics on every stage of the selection process.

In this example, performance data published by APC Propellers (2019) will be used for the propeller database. It contains static and dynamic performance obtained through analytical methods of all products currently manufactured by the company. Due to the reliance on external computer software, airfoil drag (and consequently, torque) may be

under-predicted at low speeds. Additionally, wind tunnel measurements of selected propellers (Brandt et al., 2020) show over-prediction of thrust coefficient (and consequently, thrust) of around 12% on average across all tested propellers. A summary of mean relative errors is shown in Figure 3.9. Therefore, an easily adjustable parameter called *Safety Factor* (SF) was introduced that increases required power at the WOT operating point to reduce the impact of mentioned inaccuracies and guarantee that the chosen motor will be able to reach the expected speed

$$I_j^{(2)} = P_m^{-1}(P_r \times SF), \quad (3.46)$$

$$\eta_j^{(2)} = \eta(P_r \times SF, P_{ej}). \quad (3.47)$$

There is no need to include *Safety Factor* in the ESC sizing, as the WOT operating point at which it is sized, in typical operating conditions, is achieved only for a few seconds at a time, not enough to damage the unit. The inclusion of the *Safety Factor* parameter in the battery sizing is recommended, as LiPo batteries are prone to ageing, which increases their internal resistance. Hence, with time at high currents more and more heat is generated, eventually leading to battery damage. What is more, cheap batteries are known for parameters varying between each unit, further justifying the need for an additional safety measure. Therefore, (3.35) becomes:

$$r_C = \frac{I_{ESC} \times n_{rot} \times SF}{C}. \quad (3.48)$$

For the motor database, a database bundled with DriveCalc software (Persson, 2019) was used. It is based on measurements done and uploaded by its users, so it is impossible to accurately measure the discrepancies with real products, but they are estimated to be around 5-10% overall. However, a significant inaccuracy is introduced with the simplified motor model used to calculate characteristics based on scarce data. The model, applicable both to BLDC and DC motors, considers only two sources of losses: copper losses,

calculated using winding resistance

$$P_{\text{Cu}} = R_m I_{\text{motor}}^2, \quad (3.49)$$

and iron losses, calculated using no-load current

$$P_{\text{Fe}} = U \times I_0, \quad (3.50)$$

where P_{Cu} are copper losses, R_m is the windings resistance (of all simultaneously working phases), I_{motor} is the current delivered to motor windings, P_{Fe} are iron losses, U is the nominal voltage and I_0 is the no-load current. As the no-load measurement is usually done through an ESC, the iron losses also incorporate losses from the controller. The model, based on (Radio Control Info, 2019), is calculated as follows:

$$P_{\text{prop}} = \tau_{\text{prop}} \times \omega_{\text{prop}} \times SF, \quad (3.51)$$

$$I_{\text{motor}} = \frac{U - \sqrt{U^2 - 4R_m(P_{\text{Fe}} + P_{\text{prop}})}}{2R_m}, \quad (3.52)$$

$$P_{\text{motor}} = U \times I_{\text{motor}}, \quad (3.53)$$

$$\eta_{\text{motor}} = \frac{P_{\text{prop}}}{P_{\text{motor}}} \times 100\%, \quad (3.54)$$

where P_{prop} - is the power delivered to the propeller, τ_{prop} is the propeller torque, ω_{prop} is the propeller speed, P_{motor} is the motor electrical power and η_{motor} is the motor efficiency.

3.3.1 Example results

For the ease of validation, the input parameters of the methodology were set to match those of the DJI Phantom 4 Pro V2.0, as indicated in Table 3.3. This enables easy comparison of the vehicle's published specification (DJI, 2019) with the sizing method's results in terms of flight time and propeller dimensions, as the manufacturer does not provide motor data. It should be noted here that the Phantom 4 uses LiHV (High Voltage LiPo)

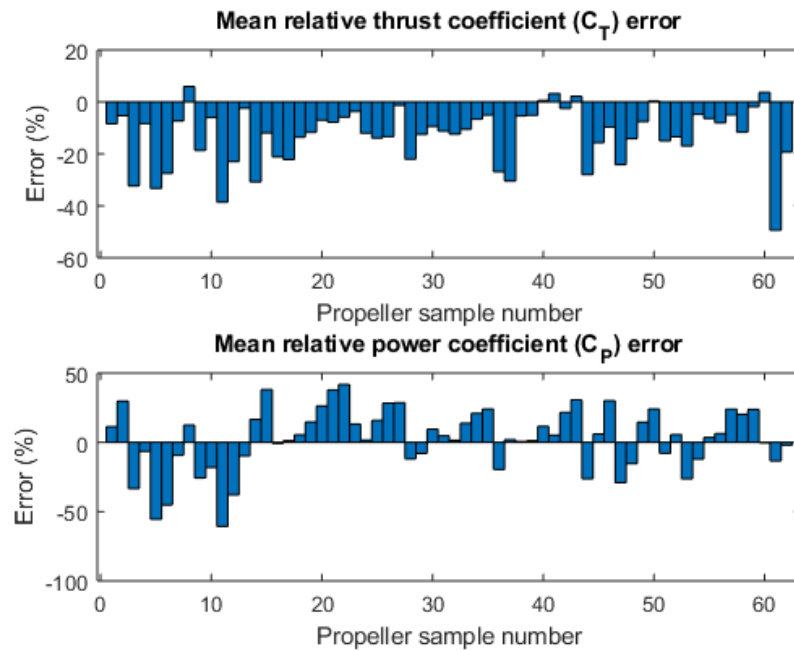


Figure 3.9: Relative errors between measured and simulated propeller coefficients.

batteries rated at 3.8 V per cell, however in the calculations the more popular LiPo batteries, rated at 3.7 V per cell, are used. Additionally, V2.0 uses FOC-enabled drivers, which generate sinusoidal signals instead of the usual trapezoidal. However, the manufacturer advertises it as a means to reduce noise instead of improving performance, so it can be assumed that in this case the difference can be neglected.

Table 3.3: Basic DJI Phantom 4 V2.0 parameters.

Number of rotors	4
Diagonal size	350 mm
Total weight	1375 g
Battery weight	468 g
Battery capacity	5870 mAh
Battery nominal voltage	15.2 V
Battery type	LiHV 4S
Propeller diameter	9 inch
Propeller pitch	5.5 inch

The MATLAB script¹ has been run considering two operating points: hover and WOT. The goal was to reduce energy usage at hover, as the platform's main purpose is photo-

¹<https://github.com/mbiczyski/Multirotor-Sizing-Methodology>

Table 3.4: Additional methodology parameters used in small drone sizing.

Thrust-to-weight ratio r_T	3
Min. propeller diameter $d_{\min}$	8 inch
Max. propeller diameter $d_{\max}$	9 inch
Safety Factor SF	1.05
Preferred propeller series $\mathcal{S}_{n_r}$	MR, E, E-3, E-4
Max. propeller mass m_{pr}	24 g
Max. motor mass m_{m_r}	100 g

graphy. For the thrust the unit of gram-force (gf), which corresponds to the force acting on 1 gram of mass in a standard gravitational field, is used due to intuitiveness in this application. Additional sizing parameters are listed in Table 3.4. The results are below:

Results For a 4-rotor drone with estimated AUM of 1375 g:

- APC 9x4.5E propeller should be chosen for the highest specific thrust of 9.69 gf/W per motor at hover.
- Hacker B20 26L (2080 KV) motor should be selected with 0.15 Nm torque at maximum speed of 9600 RPM.
- One motor uses 35 W of electrical power at hover and 237 W of electrical power at WOT.
- The drive should be controlled by a 16 A ESC per motor.
- The whole system should be powered by a 4S 12C LiPo battery of 5870 mAh.
- Hovering flight requires 124 W of mechanical power (0.05 Nm at 5600 RPM) to achieve 1375 gf of total thrust.
- WOT flight requires 590 W of mechanical power (0.14 Nm at 9600 RPM) to achieve 4125 gf of total thrust.
- This configuration should achieve around 26.9 min of hover and around 2.3 min of flight at WOT.

As can be seen, both the propeller and the motor were successfully selected and the estimated flight time has been calculated. The propeller is of lower pitch than in the reference drone, which might be explained by the unavailability of 9x5.5 propellers in APC's range, and 9x6 being too power-consuming. Especially interesting is the choice of E-series (electric airplanes) propeller over MR-series (multirotors), which can be influenced by numerical errors due to interpolation, specifically at low speeds required for hovering. Comparison of power characteristics of propellers considered in this example can be seen in Figure 3.10.

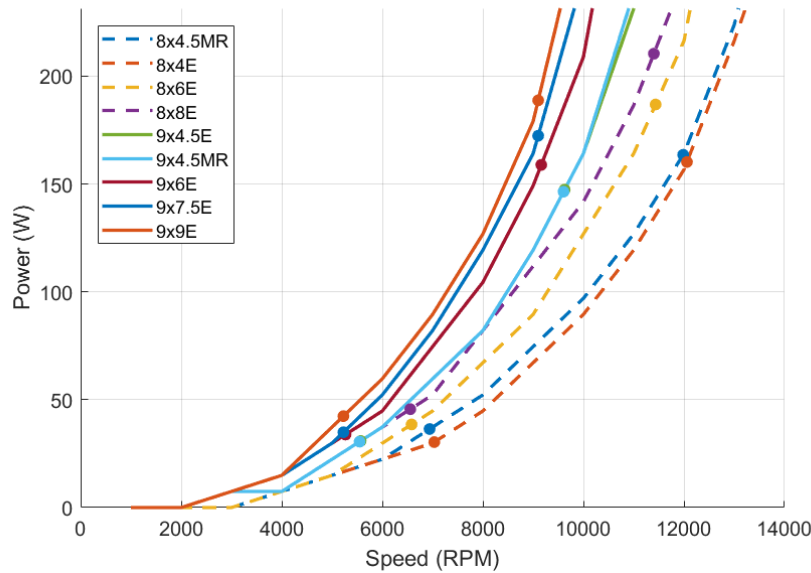


Figure 3.10: Comparison of power-speed characteristics of 8 and 9 inch propellers.

Hacker B20 26L is a surprising choice for the application, as it is an inrunner motor that usually comes with gearing to increase its torque for traction applications. However, in this case it is used in direct drive configuration, which is possible due to the low speed of a large propeller. Its measured KV is 2080 (as opposed to 2020 stated by the manufacturer (Hacker, 2019)), which puts the hover operating point almost at the maximum of the efficiency curve, therefore increasing the flight time, as can be seen in Figure 3.11.

The calculated flight time seems to be in line with the achievements of the reference drone. Maximum flight time stated by the manufacturer is 30 min (DJI, 2019), but it was probably measured in flight at best endurance speed, which uses slightly less power than in

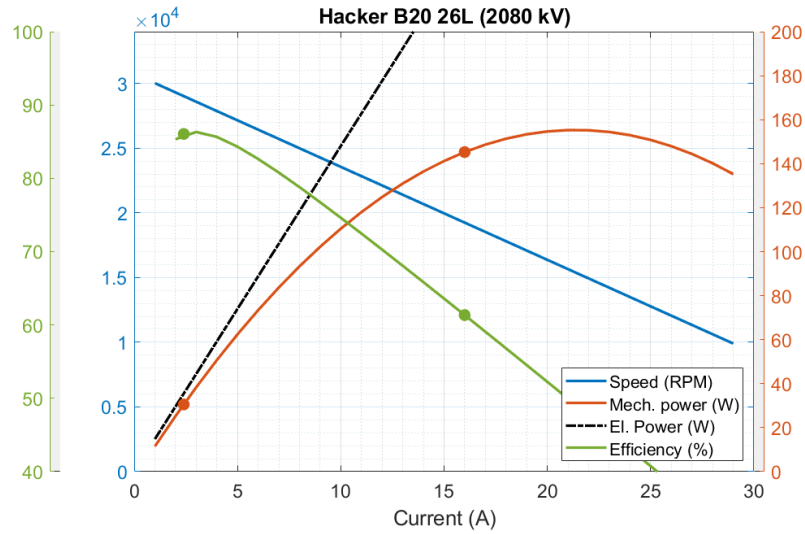


Figure 3.11: Simulated operating characteristics of Hacker B20 26L brushless motor.

hover ((Di Franco & Buttazzo, 2015)) due to the reduction of the induced drag. Therefore, it can be assumed that the maximum hover time will be close to the 27 min calculated, which seems to be confirmed by independent tests achieving 23-26 min of hover (Luna, 2018; Smith, 2018). However, as the calculations do not include dynamic effects of flight, the prediction accuracy for the WOT operating point is considerably lower. Furthermore, that point is set arbitrarily based on thrust-to-weight ratio, and is rarely measured in real operation, so no validation could be performed.

For input parameters matching that of reference commercial multirotor, the sizing methodology returned propeller and motor components, their parameters, and an estimate of flight time for chosen operating point. The results were of similar value to the reference, which may indicate that the chosen configuration has performance close to optimal. The reference drone is a commercially popular product, therefore it can be assumed that its performance is close to optimal for its given weight and application (aerial photography). Considering the accuracy of results, the assumptions and estimations used, and the low computational cost, methodology performance can be considered satisfactory for applications in other research projects and on its own.

3.3.2 Further validation

In similar manner to validation through comparison with DJI Phantom 4 v2.0, more tests of different configurations were conducted. The input parameters are summarised in Table 3.5. 6S batteries were assumed for Fox 4 and PD6-AW2 BASIC platforms, as those are more suited for the heavy lifting application. The weight of IRIS+ is taken with a sample payload. Thrust-to-weight ratio was adjusted so if more payload was added up to maximum allowable mass, the drone would still maintain controllability with thrust-to-weight ratio of two. In three of the test cases, results shown in Figure 3.12 seem to be in satisfactory agreement with the manufacturer's specification considering that the methodology does not include the power usage by the flight controller, sensors, RC communication or payload.

Table 3.5: Drone parameters used in further testing.

Name	GTQ Mini 2016	IRIS+ 2019; 2015	PD6-AW2 BASIC 2019	Fox 4 2019
Take-off mass [kg]	0.5	1.3	10	4
Thrust-to-weight ratio	2	2.6	3.5	2.5
Rotor count	4	4	6	4
Min. propeller diameter ["]	3	8	18	10
Max. propeller diameter ["]	5	10	21	15
Battery cell count	4	3	6	6
Battery capacity [mAh]	850	5100	2×16000	2×5000

The significant difference in the case of GTQ Mini needs to be addressed separately. The methodology has returned similar results to those of the methodology presented by Bershadsky et al. (2016). Our methodology has chosen 5x4.3 propellers as compared to 5x3, 1378 KV motor as compared to 1383 KV and uses 4.54 A in hover (at full battery) as compared to 4.49 A. However, there is a 1.9 min difference in calculated hover times. With the same battery capacity and similar current drawn, the discrepancy might be that in (Bershadsky et al., 2016) the simulation is stopped when battery reaches 3.6 V, while our implementation is set up to stop earlier at 3.7 V. Another difference is probably in the battery model used, as our methodology simulates the decrease of voltage with dis-

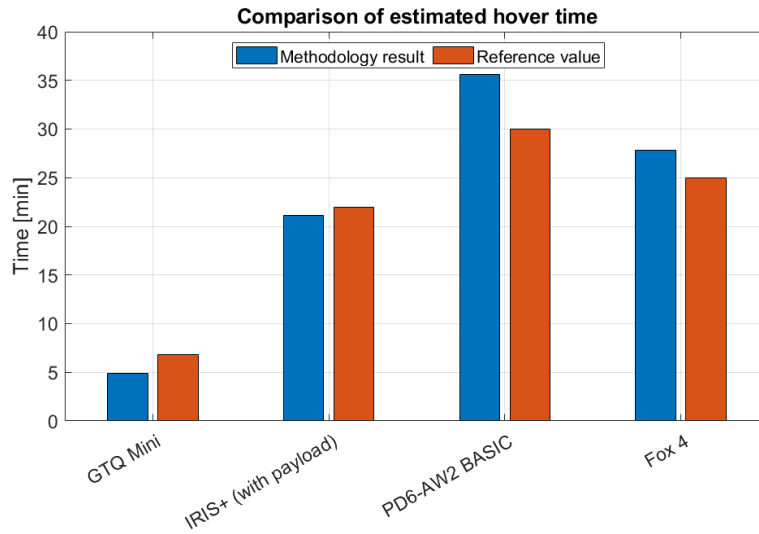


Figure 3.12: Comparison of calculated hovering time with longest expected time.

charge, leading to the increase in current drawn from 4.54 A to 5.15 A throughout battery operation.

3.3.3 Personal Air Vehicles

The current implementation of the methodology as a MATLAB script does not allow for the sizing of heavy platforms, such as PAV, due to the lack of a sufficiently large propeller in database. However, the methodology can be implemented with different databases and even modified to help with the design of components: propeller specification provides enough data for pre-sizing of an electric motor, and thrust requirements along with size and weight constraints can be used as input in propeller design. Additionally, using only scarce data, a flight time estimation can be performed to validate the design of components. This is an especially important feature, as the methodology has been designed with the ability to be used inside another algorithm to further enhance the optimisation process. That way questions, such as rotor number, propeller size or maximum payload, can be answered. This is especially important for PAV, where the mass constraint is very tight because of the payload in the form of a passenger. Table 3.6 outlines example uses of the methodology in scenarios with different data available.

Table 3.6: Uses of sizing methodology based on data available.

Propeller data	Motor data	Example uses
available	available	complete sizing of multirotor propulsion system; flight time estimation; optimisation of flight time
available	not available	propeller sizing; preliminary motor design
not available	available	battery and ESC sizing; flight time estimation
not available	not available	–

Some of the problems of PAV, such as high weight of the platform, can be addressed by alternative multirotor designs. Papa (2018) discusses a multirotor in which a part of the lifting is done by a balloon. The methodology described here is simple and flexible enough to complement the approach in (Papa, 2018). Papa’s method can be used for sizing the balloon while this methodology sizes the multirotor part by subtracting the calculated balloon’s lift from the estimated platform’s weight and using it as an input. Validation of this approach, however, has not been performed.

3.4 Summary

This chapter introduces the actuating chain of a multirotor air vehicle. Based on its structure, simple models and component databases are used to develop the actuating system sizing methodology. In addition, expected flight time for the sized system is obtained. The approach has simple inputs (MTOW) and outputs (flight time), as well as reduced number of iterative loops, therefore can be computed quickly to obtain preliminary actuating system design or as a part of another routine. The result were validated with a number of examples using data from commercial small- and medium-sized vehicles. The approach described here was also used in Section 5.2.1 to generate a reference BLDC motor for each specification set.

Although there are no conceptual constraints preventing the use of the methodology for sizing large passenger multirotors, considerable limitations are introduced by the databases used, which rarely provide data on large propellers in the 50-60 inch range and motors able to support them. However, it is assumed, that certain elements of the method-

ology, such as flight time estimation based on limited data, can be useful in the process of PAV design. The proposed methodology is also flexible enough to accept data of custom designed components or to be used for sizing of certain alternative multirotor topologies.

Similarly, certain elements, like the use of propeller database, and the overall approach can be retained when creating an actuating system methodology that uses a different motor technology (for which a component database is not available). The next chapter evaluates the uses and requirements for such a methodology in regards to SR motor actuating systems and proposes three methodologies of increasing model complexity.

Chapter 4

Actuating System Design Methodology

With multiple components of the actuating system having to be created from scratch, the specifications driving the design need to be planned out with great detail. There is no component database for SR motors, commercially available motors cannot be easily scaled down to the required size (due to weight constraint), and accurate non-linear models are costly to compute. Therefore, the main challenge in developing the design methodology is to combine low computation time (which has been achieved in the pre-study) with high accuracy of results. The work in this chapter provides a tool for achieving the first and second research objectives, which are completed in the next chapter.

The designed system needs to be proven to be able to provide enough thrust for flight. Therefore, there are two objectives that the adopted design methodology needs to achieve:

- generate design requirements for each component in the system (a design specification set) early in the sizing process,
- provide tools for verification of the system feasibility at given vehicle size.

The combination of these goals should result in an approach that can both provide a complete overview at the initial design stages and is flexible enough to accommodate additional data during the process.

4.1 Requirements

Creating a custom design methodology comes with the advantage that it can be tailored to a specific application. Yet, there is a benefit in keeping it as general as possible, so it is flexible enough to accommodate any unforeseen changes throughout the design process. Therefore, it is essential to first lay out requirements for the methodology.

The first aspect to consider is the starting point of the design process. As described previously, power may not be the best choice in this case due to being tied to a component that will be different from standard. Another disadvantage is the poor connection with variables describing the whole vehicle - the calculations required to determine the resulting multicopter's size and performance would be too time consuming, while needing a lot of accurate data. To avoid such issues, the methodology should be able to focus both on the complete system, as well as the individual components. Furthermore, its starting point should be positioned equally between those scopes allowing them to affect each other in the same capacity.

From the requirements set out in the previous paragraph stems another one - that of the input data. It is clear that the main sizing parameter should be related to the weight of the vehicle, as it makes it easy to include the payload requirements. What is more, for testing of various vehicle configurations, the methodology should also allow to manually set the number of rotors.

As the focus of the project is to incorporate SR motors into the actuating chain, it is obvious that the design methodology should be able to accommodate different component types. This incorporates the physical aspects like the number of wires, conceptual like mathematical models, as well as the software uploaded onto the system, specifically motor control algorithms. Therefore, it should be possible to design both: a BLDC motor-based system using off-the-shelf components as well as a novel SR motor-based system using components that are yet to be designed. Furthermore, the methodology should actively facilitate and contribute to the custom component design processes.

The requirements mentioned above can be summarised in the following list:

- Scope - include the ability to design both the entire propulsion system and individual components,
- Starting point - starting from the meeting point of entire system and individual component approaches,
- Input data - vehicle weight is the main parameter of the sizing,
- Scalability - usable for vehicles with different numbers of rotors,
- Generality - allow the use of off-the-shelf and custom designed components,
- Growth - contribute to component design process.

Although these requirements may seem general, they stem from, and are closely tied to, the application - multirotor UAV. Therefore, the resulting design methodology should be specifically tailored to this type of vehicle, and take advantage of its unique aspects, to make the design process quick and effective.

4.2 Assumptions

Being able to design for a specific set of missions is an invaluable asset when working with aerospace applications, as there are different design requirements for each phase of flight. Most of these missions involve the cruise state, which requires precise knowledge of vehicle aerodynamics to estimate lift and drag. In general aviation this is not a problem, as the aerodynamic aspect is the main component driving the whole design process. However, this is not the case for multirotor vehicles, as the lift produced mainly comes from the rotors, which potentially allows separating the actuating system design from the aerodynamics design process. This is remarkably useful, as the multitude of distinct possible configurations of multirotor vehicles makes the lift and drag predictions, especially at early stages of the design process, extremely challenging.

Thanks to this separation, the actuating system can be designed first to achieve a desired level of thrust (and therefore lift), which then could be used as an input or parameter when calculating vehicle's aerodynamics. This approach, however, means that it is impossible to estimate the cruise characteristics and its derivatives such as maximum endurance or range. Therefore, the set of use cases considered at this stage needs to be reduced. The only applicable mission that can be computed without the need for drag value is loitering in hover. This state lends itself nicely for the design purposes, as it links the motor thrust directly with vehicle's weight. Furthermore, it allows for the design of systems for transitioning configurations (tilting rotors), because during hover all rotors are pointing in the same direction - upwards.

A single design specification is of course not enough to create a system that is able to carry out any mission. Therefore, it is required to extend it to other use cases. In this case, it is done following the trend among RC multirotor operators of multiplying the thrust required for hover by a number corresponding to desired performance. Popular values are summarised in Table 3.1. Two is generally considered the minimal value that would guarantee enough controllability for a safe flight and corresponds to the vehicle being able to maintain hover if a rotor/motor fault occurs in an 8+ rotor vehicle.

As the sizing is based mainly on the weight of the vehicle, it needs to be made clear what this parameter relates to exactly. Thanks to the batteries not changing mass during discharge, the vehicle mass does not change during flight. Therefore, the Maximum Takeoff Weight (MTOW) becomes gross weight for the whole duration of the mission (assuming payload is not jettisoned during flight). Thus, three different weights can be considered for design purposes: Operating Empty Weight (OEW - without batteries or payload), OEW with batteries (but without payload) and MTOW. For simplicity and ease of calculations, MTOW will be used for the design process, because it is not affected by any weight changes of sized propellers, motors or batteries, as it is assumed that any unused weight will be devoted to payload.

4.3 Approach

In order to fulfil the requirement of scalability from Section 4.1 and to simplify the process, the symmetry in typical multirotor actuating systems is exploited. Each arm includes the same components, as shown in Figures 3.1 and 4.1, and these are mostly independent from each other, except for the connection to a common power source (battery) and Flight Controller (FC). The main difference is therefore the spinning direction and rotor configuration (as a pusher or puller). However, this has no influence on the actuating system design, as the main objective of providing upwards thrust is still achieved. Therefore, for the purposes of the design process, the individual actuating system arms can be considered fully independent. It must be noted however, that this does not apply to the 3Y configuration, where one rotor needs to be bigger to balance out the yawing moment, but this configuration is relatively unpopular and therefore not considered in this study.

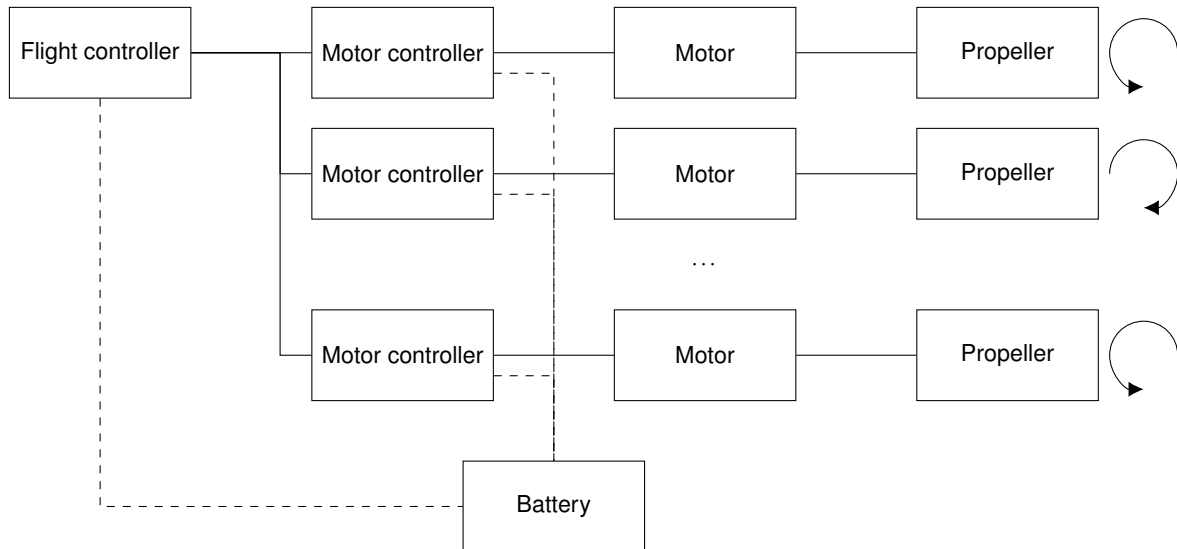


Figure 4.1: Multirotor actuating system schematic.

If the actuating system arms are independent, then the problem can be reduced to the design of one arm that needs to support a fraction of the vehicle weight. To aid with this approach, a new variable, here called the *lifting ratio* (in $\frac{\text{kg}}{\text{rotor}}$), is introduced that correlates vehicle weight with the number of rotors in the analysed configuration.

Therefore, it is expressed as:

$$l_r = \frac{\text{MTOW}}{\text{no. of rotors}}. \quad (4.1)$$

The basis of each design process is a model of the system. In this study it was chosen to use a black-box model represented with a block schematic. There were 2 main arguments in favour of this approach: design parameters can be explicitly stated as inputs and outputs of a block and the block itself can be later amended with a mathematical model of the component, as explained in Section 4.4. Using this approach, the multirotor's propulsion system can be expressed as a closed loop, as shown in Figure 4.2. There, the answer to the requirement of scope is clearly visible - the system can be divided into 2 parts: the actuating chain, and the aerodynamics and motion. The actuating chain, occupying the lower half of the chart, starts from the FC as thrust requirement T_k^* and ends as thrust from the propeller T_k . Then this force is propagated through aerodynamical and inertial properties of the vehicle and ends up as translation and rotation of the vehicle, which can be both measured by the FC or acknowledged by the operator.

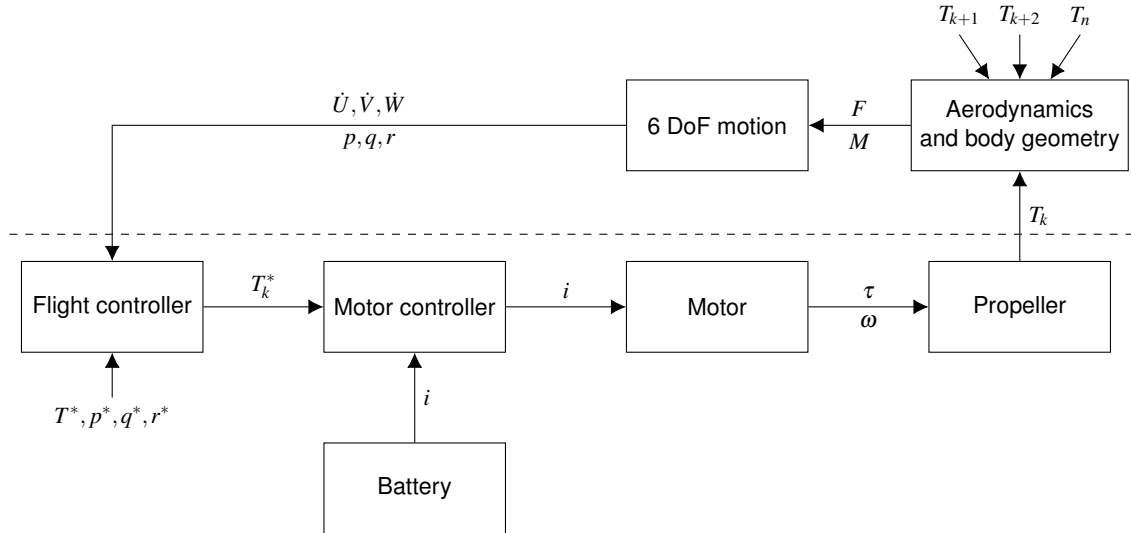


Figure 4.2: Block schematic of a multirotor as a dynamical system.

With the model established, the next step is to transform it to be able to obtain the desired output variables. At this point, an important assumption is made that the model (and

each sub-model) is observable and controllable, therefore the designed systems should also possess these qualities. The combination of these qualities means that knowing the right input we are able to achieve any (physically possible) output, and also that knowing the desired output we are able to find the necessary input. Therefore, this makes it possible to reverse the flow of information in the graph to start from the desired thrust and obtain, torque, speed, current, etc. This is demonstrated in Figure 4.3.

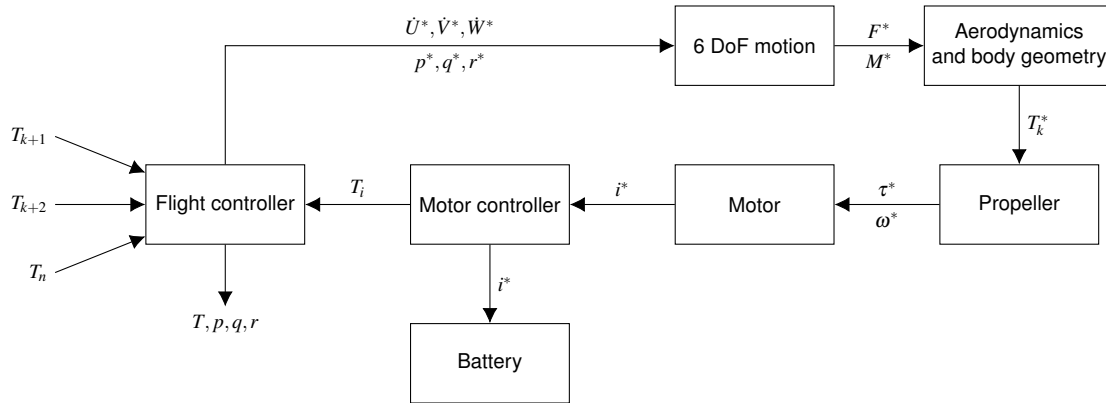


Figure 4.3: Reversed block schematic of a multirotor as a dynamical system.

Finally, the schematic can be reduced to only the actuating system section, as this is what is concerned at the design process stage, as shown in Figure 4.4. This schematic functions as the analogy to the one in Figure 3.3, but generalised for all actuating systems of this structure. At this stage, the block schematic can also be populated with simple mathematical models or look-up tables to allow for the computation of preliminary design variables. These simple models are intended only to assess the possible capabilities of the system and to provide input specifications for the actual design of each component. Therefore, it suggested to use the following models:

- Propeller - speed-thrust look-up table,
- Motor - DC static motor model, preferably with decoupling between torque and speed,
- ESC - direct connection (wire),
- Battery - voltage source.

This set of very simple models will give very rough estimates of system's performance, but they also require very little input data and are quick and easy to compute, making it an excellent choice for sizing procedures, as has already been shown. Therefore, using the fact that the inputs and outputs of each block are already sized, and assuming the system is linear (or able to be linearised), the system's optimisation process may be done through the optimisation of each component. This allows for easy parallelisation of tasks in the optimisation process.

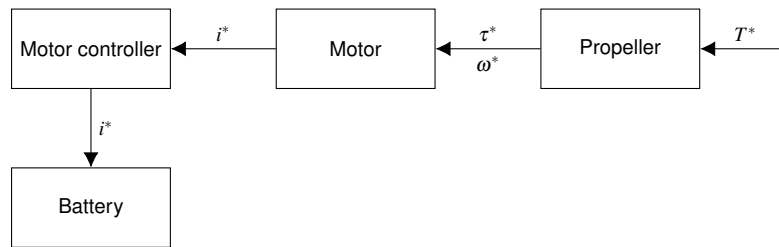


Figure 4.4: Multirotor actuating system design computational approach.

Parallelisation can also be achieved in other aspects of the project. Going away from the mathematical origins of the approach, it can also be used for other things, such as workload scheduling. The parallelisation possibilities there come from the different aspect of component design, for example, for a BLDC motor there is: electromagnetic design, mechanical design, casing design, thermal analysis, vibration analysis, mounting solution selection (with the propeller and to the vehicle body), ground testing, flight testing, and other specialised tasks dependent on the specific design. Figure 4.5 details the main tasks undertaken during this study and their dependence on each other.

4.4 simulation model complexity

Simple static models used for preliminary sizing give only basic understanding of the system's capabilities. The main parameters that can be obtained in this design step are: **propeller diameter; motor power, speed and current; and battery voltage**. Specifically starting, rated and maximum operating points are of interest. However, this data

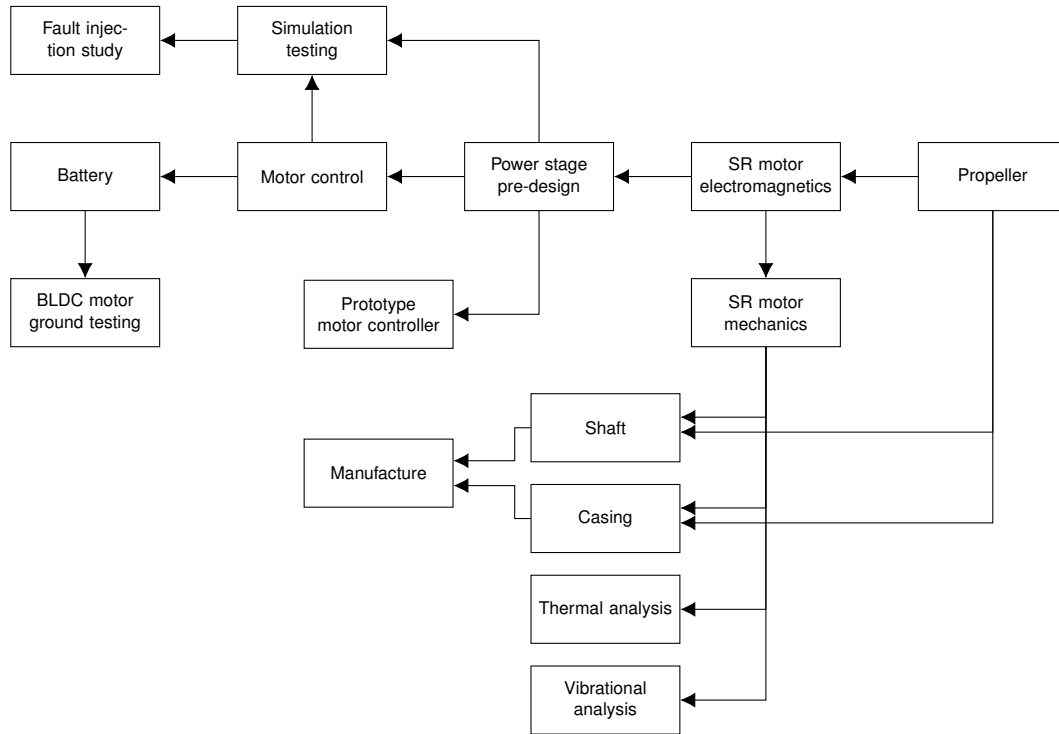


Figure 4.5: Multirotor actuating system design workload parallelisation.

(apart from being highly inaccurate) does not involve any technology-specific peculiarities. Therefore, more accurate and complex models need to be applied to the methodology.

Digital twin (DT) is a relatively new term, so an universal definition has not yet been agreed on. Glaessgen and Stargel (2012) provide a definition in regards to NASA and U.S. Air Force operations:

A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin. (...)

This paints a clear picture of a simulation that is perfectly matched (with the help of data-gathering systems) with the physical system and can both: replicate system's previous performance and predict its future behaviour with a high degree of certainty.

To complete the definition, (Wu, Yang, Cheng, Zuo & Cheng, 2020) cite Gartner on the following four required elements of a DT: *'digital model, linked data, identification*

and real-time monitoring capabilities'. Furthermore, Fuller, Fan, Day and Barlow (2020) clarify a common misconception by explaining the difference between a digital model, digital shadow and digital twin - digital twin requires a two-way **automatic** data-exchange between the object and simulation.

It is possible to modify the methodology's structure to include the communication between the system and its simulation. However, a full implementation of a digital twin is outside the scope of the project. Therefore, it has been decided to stop at the digital model stage, while retaining the possibility of upgrading to a digital twin at a later date. However, effort was made to develop the model in line with the DT definition above, therefore simulating multiple aspects (as shown in Figure 4.5) using as detailed models as it was reasonable, with constantly updated data.

Of course it would be unwise to move straight from a preliminary model to a digital twin-ready system. Therefore, the development has been divided into steps, as shown in Figure 4.6. The first step is the already mentioned preliminary DC motor-based model that was used to size the vehicle and actuating system - select propeller, battery and provide operating points for motor sizing. Therefore, the next step is motor design optimisation - it requires a model that is able to model instantaneous current, inductance and torque at different speeds and voltages. This model is described in more detail in Chapter 5.2. After the motor design has been chosen, to obtain its behaviour in the application, yet another, more complex model needs to be used. This one allows for simulation of the complete actuating system, including power stage, motor controller and propeller load. It can be considered as the 'digital model' for the need of a digital twin. The resulting simulation software is described in more detail in Section 6.1 and is also used for the purpose of system fault and uncertainty simulation in Section 7.2.

This progression of model complexity roughly corresponds to the different problems in mechanics. The first step is a simple static model describing a predetermined equilibrium. Step two is a kinematic model describing rotor motion and the associated electromagnetic circuits. Continuing, step 3 is a dynamic system that reacts to changes in

load torque or thrust demand. However, step 4 - full digital twin - escapes the confines of classical mechanics definitions. Nonetheless, this analogy showcases the ability to freely increase the complexity of the models without breaking the structure imposed by the system architecture. It is a strength of this methodology that comes from using a dynamical system as a base.

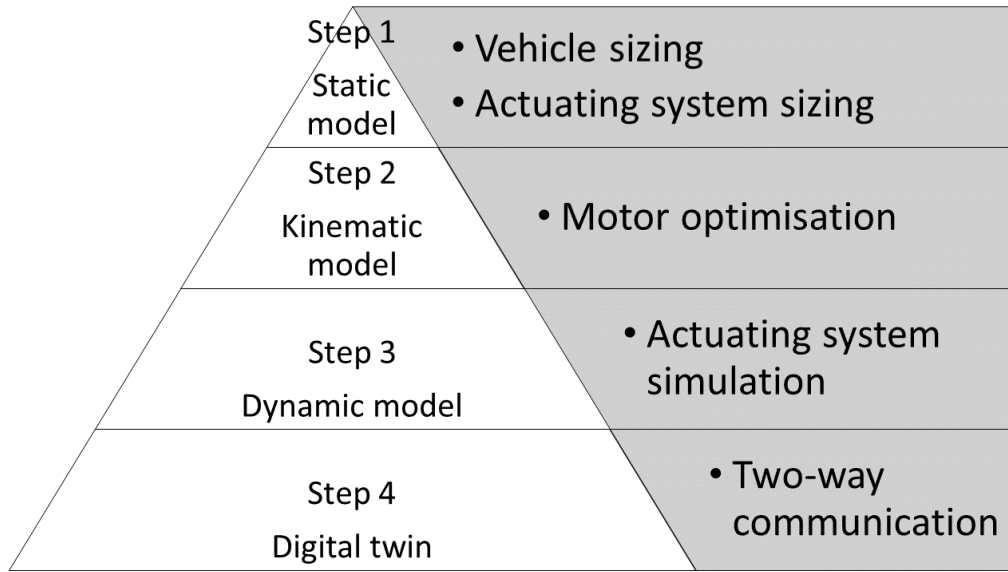


Figure 4.6: From methodology to digital twin - simulation model development.

4.5 Implementation

Having established the design methodology, its assumptions and strengths, it could be used for an actual design exercise. As already established in Section 1.2, the objective is to design a complete SR motor-based actuating system that can be used in a multirotor air vehicle. The previous section has already split this process into 3 steps: preliminary design, motor optimisation, system control and simulation. This section will detail models, data and actions for each of these tasks.

At this point in the project, no data was available on SR motor performance at small sizes and under weight constraint. It was infeasible to select a suitable vehicle to serve as a reference, because the resulting system might have been impossible to realise. Therefore,

alternative approach was chosen of assuming a range of vehicles of different sizes and configuration and going through the first two steps of the design methodology for each of them, thus creating specification set and respective SR motor designs as mentioned in Section 5.2.1. This is where the lifting ratio l_r parameter came in handy, to decouple weight (and therefore thrust demand) from the vehicle configuration.

The first step (preliminary design) is fairly straightforward - using the simple DC motor models presented in Section 4.3, obtain propeller diameter and pitch, motor rated torque, speed and efficiency, and reference current. The procedure starts from the thrust demand T^* per actuating system arm, which is a product of lifting ratio l_r (different for each size of vehicle) and expected thrust-to-weight ratio r_T (constant throughout the design process):

$$T^* = l_r \times r_T. \quad (4.2)$$

Of course, to obtain specific curves ($\omega = f(T^*)$ and $\tau_p = f(\omega)$) for look-up table and motor parameters (K_T , K_V , R), external databases need to be used. In this work Propeller Performance Data by APC Propellers (APC Propellers, 2019) and the database bundled with Drive Calculator software (Persson, 2019) were used. In this case, specific propeller and motor were obtained to maximise specific thrust at the hover operating point. This was done through an exhaustive search after pre-filtering of the datasets. Graphical representation of this procedure is presented in Figure 4.7. Please note, that certain constraints (motor and propeller weight, propeller diameter) and parameters (no. of battery cells, expected thrust-to-weight ratio) were omitted from the graph for clarity. This is a generalisation of the approach presented in Chapter 3.

For the second step, as shown in Figure 4.8, propeller model stays the same, so it is possible to use previous results. Here, however, the motor model changes into an SR motor model with its own geometry, FEM-based flux network, and torque equation. When coupled with simple PWM current control with custom firing angles, performance at spe-

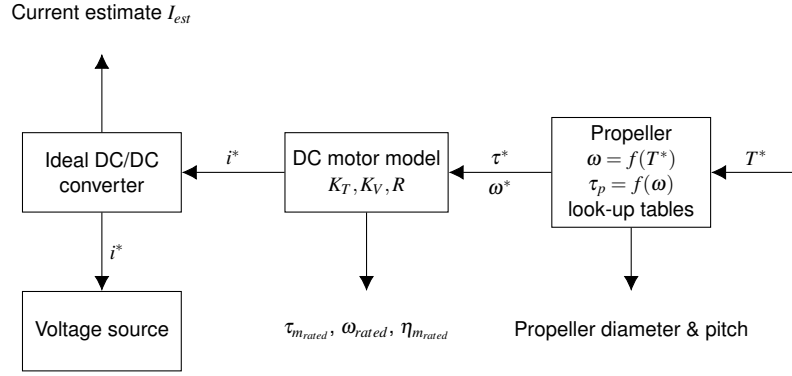


Figure 4.7: Implementation of design methodology with preliminary ‘static’ models.

cific operating point can be obtained with reasonable accuracy. Thanks to the fact that the phases are independent in a conventional SRM, only one phase needs to be simulated and then can be multiplied and shifted to obtain waveforms for a complete system. In addition, this model is used in an optimisation effort with the input of (rated) speed becoming a constant parameter and torque used in the objective function. This procedure is described in more detail in Chapter 5.

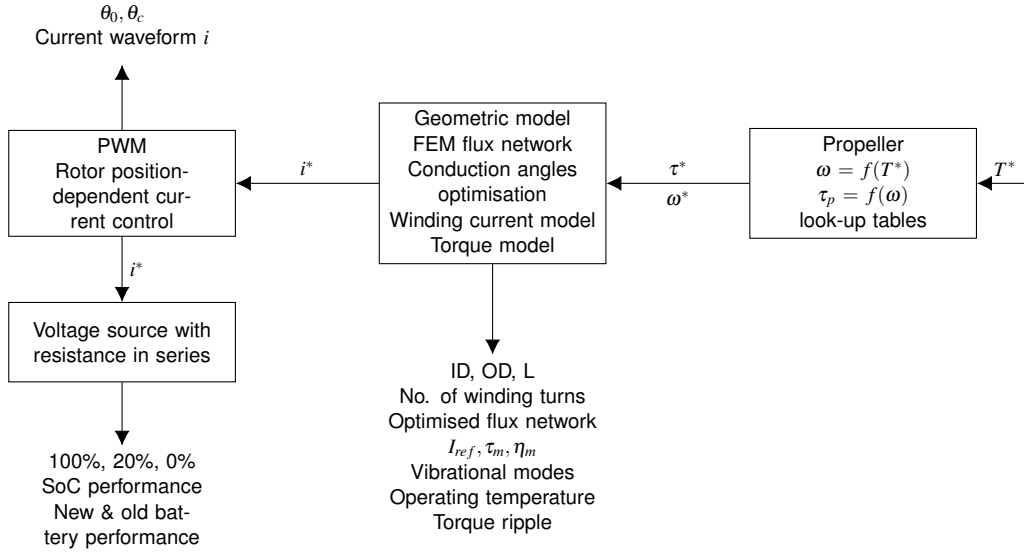


Figure 4.8: Implementation of design methodology with ‘kinematic’ models for SR motor optimisation.

A noticeable change is brought with Step 3 (Figure 4.9) - connections between models become two-way. This is because at this point, improvements in the design of any component affect others. For example, development of the current control solution changes

motor efficiency and torque, different propeller affects speed controller, more accurate measurement of phase resistance enforces different firing angles, and so on. What is more, within this structure, faults can be simulated in specific components that affect the whole system, as detailed in Section 7.2.2.

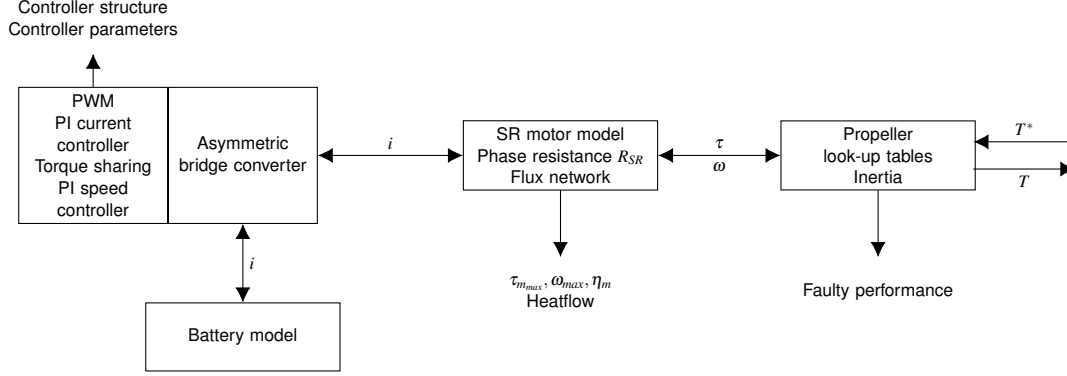


Figure 4.9: Implementation of design methodology with ‘dynamic’ models for system control and simulation.

Finally, additional tasks, not directly related to system performance, like shaft design or testing, can be conducted in parallel to the main three steps. The outline of this approach was already given in Section 4.3. As this technique was mainly used to optimise workload, the results are summarised as a Gantt chart in Figure 4.10. The main design task follows the Three Step formula, while most of the parallel tasks start from the end of Step 2 - kinematic model. The battery task is positioned earlier than it would arise from Figure 4.5, because their preliminary sizing is discussed as a mitigation approach during SR motor design in Section 5.4.1. Motor control is split into two tasks, corresponding to the two control loops (current control and speed control), depending on specific need for simulation data - performance at specific speed, performance during a mission or behaviour after fault injection.

4.6 Summary

The above-mentioned implementation example showcases the strengths of the design methodology, not only as a mathematical tool, but also as a task management system.

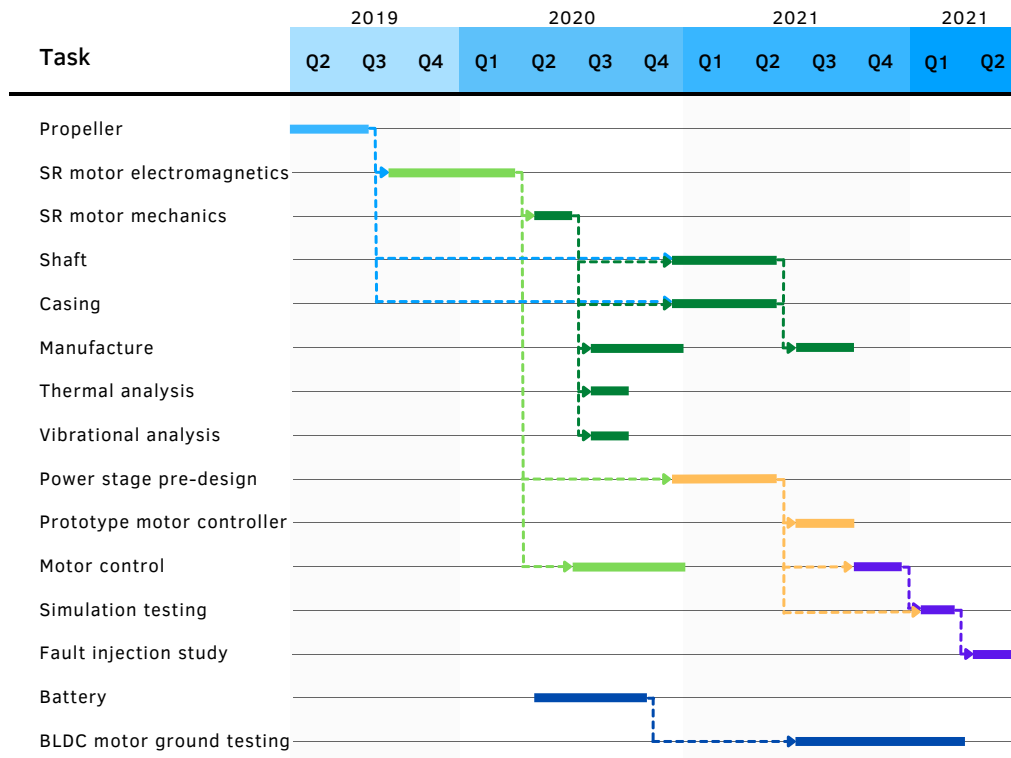


Figure 4.10: Implementation of design methodology to parallelise tasks and manage workload.

Especially valuable is the ability to quickly and easily obtain rough results and then be able to increase their accuracy with more detailed models, while still retaining the same approach structure. The three presented levels of complexity are a way of overcoming the challenge of combining low computation time and high accuracy. That way these parameters can be adapted to a specific use. The static models are used to determine system feasibility in the first research objective, the kinematic models are used in motor geometry optimisation partially realising the second research objective, and the advanced, dynamic models serve as a basis of simulator used in the third and fifth research objectives.

Furthermore, it is not only able to accommodate models of different complexity, but also variable topologies. However, it is unknown if this flexibility would be retained when applied to a physical system with more complex structure. Another drawback is the lack of clearly defined tools aiding with the design. Therefore, this methodology is more suited to research environment, where the trial and error method is encouraged, or to be used in conjunction with other design optimisation approaches, such as the ‘V’ (or ‘Vee’) model

(Walden, Roedler, Forsberg, Hamelin & Shortell, 2015, chap. 3).

Chapter 5

SR Motor Geometry Optimisation

As mentioned in Section 1.3, a ready-made SR motor actuating system is not available, specifically one tailored to the needs of multirotor applications. It is clear that the market currently has no need for SR motors of such a small size and power (<1 kW) and if any units are made, they are usually designed and manufactured for a specific application (such as kitchen appliances (Shenzhen Power Motor Industrial Co., 2022)). Another issue is the need for the motor controller to be designed specific for a given machine to maximise the speed and torque capabilities.

To check the feasibility of such system, the likelihood of finding a suitable SR motor geometry for a range of multirotor sizes (weights) was evaluated. This has allowed to identify a suitable vehicle range for SR motor actuating system, completing the first research objective. Out of the subset of converged designs, an SR motor geometry was chosen, and later adapted for manufactured, with load specification (propeller) in mind and with focus on minimising assembly weight. Together with the propeller, controller and DC converter data generated during the process, a complete actuating system design was created, fulfilling the second research objective.

5.1 Topology

Although SR motors are still not widely popular, over the years of this technology's existence, multiple designs were created with vastly different geometries. Therefore, the first step of the design process was to choose a suitable topology, which will serve as a geometric template for the design.

This study aims to showcase and evaluate the potential of the technology itself when applied to air vehicles. Therefore, the selection of topology becomes a balancing act between performance, safety and representativity. In this work, only the four popular topologies described in Section 2.4.2 are considered.

The segmented rotor of SR-SRM and DSSRM is composed of multiple separated parts, which makes it a complex part in terms of design and manufacture, while SR geometry is generally considered as very simple. In addition, these topologies are not yet much explored, serving as a poor representative of the current state of the technology as a whole. On the other hand, while MCSRM has increased torque density, it introduces additional points of failure (and reduced fault-tolerance) in the form of phase coupling. Therefore, whilst the least powerful, the conventional SRM geometry was chosen to be pursued in this study because of its popularity and highest degree of separation between phases.

SR machines can be designed with as little as one phase, but only from $m = 3$ they gain self-starting capabilities without major changes in the design. As the power density in the chosen topology is much lower than in comparable permanent magnet motors, it was decided to focus on the fault-tolerance aspect in the design process. That way, performance became a secondary concern and had only to be kept at the level ensuring the feasibility for the multicopter application. Therefore, $m = 4$ **phases were selected as the reasonable balance between power, safety, and weight**. According to T. J. E. Miller (2001), for such a machine, only one configuration is recommended, which is 8/6. Therefore, the machine used in the study was a conventional 4-phase SR motor with 8 stator teeth and 6 rotor teeth.

5.2 Optimisation method

With the motor shape roughly defined, the optimisation process could start. The objective is to obtain a machine of required performance (torque and speed) while keeping weight and operating temperature low. For this purpose, three things are required: an optimisation algorithm, desired operating point (specification) and a way to calculate motor performance. Out of those three, the last is the most complicated, as it encompasses multiple different aspects:

- calculation of flux network based on specified geometry,
- optimisation of firing angles,
- calculation of motor current and torque (instantaneous and average),
- calculation of losses,
- estimation of machine temperature.

The main problem in simulation of an SR machine is the non-linearity of its flux-current-position characteristic, which needs to be calculated anew with each modification of the design. The common approach to obtaining this data is to use a Finite Element Method (FEM), with the alternative being to analytically calculate flux paths at different positions. In order to balance the accuracy of FEM and the calculation speed of the analytical method, a low-resolution (4x4) matrix of FEM results was used and interpolated using splines. This approach has proven to be more accurate than the analytical method (RMSE = 0.00060 versus RMSE = 0.00110 when comparing with a high-resolution matrix of FEM results), while still fast enough for use in an optimisation loop. To further enhance the accuracy, the flux characteristic is calculated only up to the currently analysed reference phase current value, so the full domain is always utilised. This is further enhanced by the fact, that after the optimisation process is completed, a high-resolution matrix can be calculated for the final design.

The control solution simulated for the use in motor performance calculations is a simple bipolar PWM current control. In order to save some computational effort, only the firing angle θ_{on} is optimised using the MATLAB *fminbnd* function, using an objective function provided with MRVSIM software. The conduction (or magnetisation) angle θ_m is kept at 180° electrical. This value means that at every moment, two phases are energised, regardless of rotor position or firing angle. This increases average torque at the expense of copper losses, but has been proven to be a reasonable compromise between simple control and high performance at small motor size. Due to the interaction between phases, some mutual inductance would be observed (not modelled at this stage), but its value does not affect motor operation. In addition, electrical and mechanical independence of phases is retained, thus preserving reliability and fault-tolerance capabilities.

Operating parameters at given speed are calculated with MRVSIM software (Kolli, Krebs, Mininger & Marchand, 2012). The exact formulas used for calculation are obscured within the software, but instantaneous current and torque are presumed to be based on electromagnetic energy conversion equations:

$$v = Ri + \omega_m \frac{d\psi}{d\theta} \quad (5.1)$$

$$T_e = \frac{1}{2} i^2 \frac{dL}{d\theta} \quad (5.2)$$

Any additional parameters are probably derived from those (and input parameters) and calculated using common physics equations. In particular, wire diameter d_{wire} (in mm) is calculated using the equation:

$$d_{wire} = 2 \sqrt{\frac{FF A_{slot}}{2N\pi}} \times 10^{-3}, \quad (5.3)$$

where FF is the slot fill factor, A_{slot} is the available slot area and N is the number of

winding turns. In a similar manner, the current density J (in $\frac{A}{mm^2}$) is calculated:

$$J = \frac{2Ni}{FFA_{slot}\sqrt{2}} \times 10^{-6}. \quad (5.4)$$

The thermal simulation is done using the Heat Flow Problem solver in Finite Element Method Magnetics (FEMM) software. The geometry is taken directly from MRVSIM and the heat generated by the coils is calculated from copper losses divided by the volume of the simulated block (including the end winding). To imitate the standard temperature test for BLDC motors used for small UAVs (external bell temperature after 3 and 10 minutes), the simulation is run iteratively in 1 min increments. To obtain the thermal conductivity of the winding, treated here as a uniform block, an additional small-scale simulation of wires inside the coil is performed, as seen in (Dong, 2019).

With all calculations regarding motor performance implemented as a set of MATLAB scripts, an external optimisation algorithm could be used. DIRECT (Finkel, 2003) was selected for its easy implementation in MATLAB, no need for knowledge of the objective function's gradient and the low number of parameters required to run it. As it was designed to find the global minimum of the objective function, the risk of converging on a local minimum is minimised.

All these elements connect together to allow for an optimisation loop, as shown in Figure 5.1. The base design uses default parameters and is required to initialise the software. DIRECT manages the optimisation process, calculates the objective function and computes new optimisation variables. The loop itself functions as described above - after a new set of variables is entered, a low-resolution FEM is run to obtain the flux network, which is then used to obtain firing angles and performance data. The number of maximum iterations was set to 250, which has been proven to allow for convergence (assuming permissible) while not running into the problem of overoptimisation. After the optimisation result has been obtained, a high-resolution FEM is ran (and performance computed) to ensure the accuracy of the solution. Finally, thermal simulation is performed to ensure

the motor does not overheat (to ensure high degree of reliability).

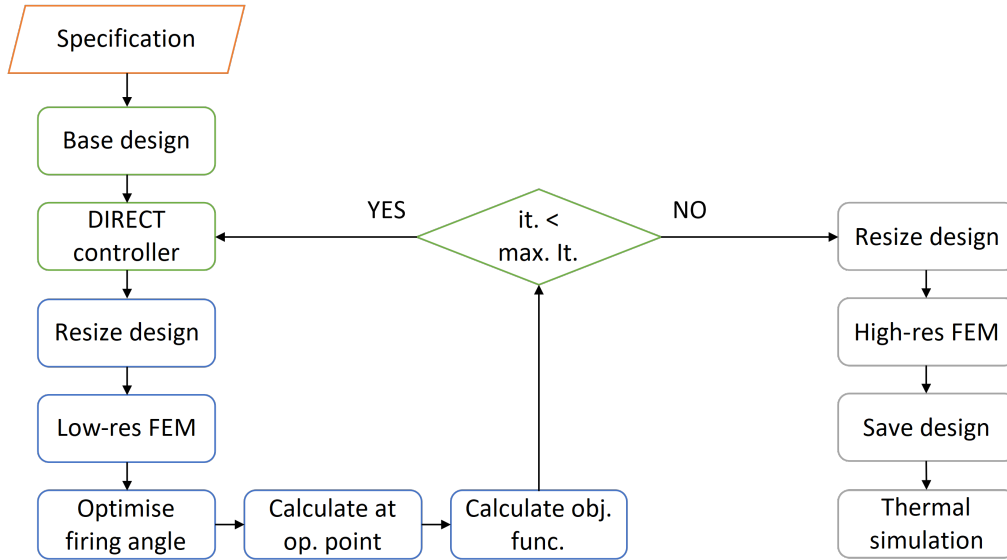


Figure 5.1: SR motor geometry optimisation flowchart.

5.2.1 Specification set

To properly formulate the specification set (serving as the input to optimisation process), a number of assumptions needs to be made first. These are summarised in Table 5.1 and were made in order to reduce the number of variables during the optimisation.

Table 5.1: Summary of main assumptions for a specification set.

Airgap thickness	0.2 mm
Fill factor	0.6
Stator inner/outer diameter ratio	0.55
Stator & rotor material	NO20 electrical steel (thyssenkrupp, 2017)
Coil material	copper
Stator teeth polar angle	15°
Rotor teeth polar angle	16.5°
Yoke thickness	0.5 teeth thickness

Airgap thickness was chosen after consultation with experts as the lowest value still allowing for easy manufacture. Similarly, the fill factor was chosen arbitrarily at a value that would allow easy winding manufacture. The ratio of inner to outer stator diameter

was chosen based on machines used for electric vehicles, as no previous reference point was found for application considered.

The specification set itself consists of three parts: objectives, primary constraints and secondary constraints, summary of which can be seen in Table 5.2. The objectives deal with the expected power of the machine at the rated operating point. However, in order to ensure proper operation with a propeller as load, a decoupling between torque and speed needs to be included. Primary constraints are created with respect to the application - weight, or the motor winding - temperature and current density. Finally, secondary constraints are put in place as limits for the optimised variables.

Table 5.2: Summary of a specification set.

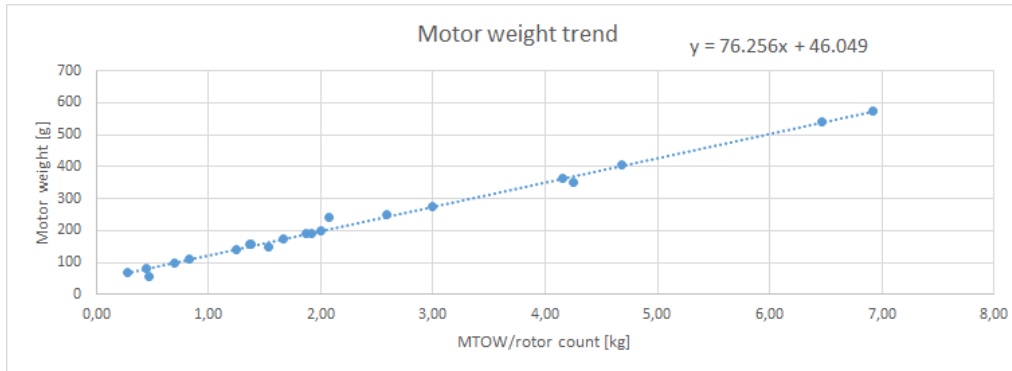
Objectives	torque τ_{spec} speed ω_{spec} lifting ratio l_r
Primary constraints	active mass current density J_{spec} battery voltage U_{batt} reference BLDC motor
Secondary constraints	min./max. outer diameter OD min./max. stack length L min./max. phase current I_{ref} min./max. number of winding turns N

Two batches of specification sets were prepared: the first focusing on finding the range of l_r for which SR motors were feasible solutions, and the second analysing the influence of propeller size. Table 5.3 specifies the batches' configuration in more detail and the full dataset can be found in Appendix A. The specification sets themselves were found using a database-based method described in Chapter 3. The torque values in specification sets were increased by a safety factor $SF = 5\%$ over calculated values to account for any uncertainties in input data or software models. A database of APC propellers made from plastic and ranging in sizes between 4 and 27 inch diameter. The method was set up to find a specification with the lowest power at hover and the thrust-to-weight ratio was set to $r_T = 2$. The limit for motor weight and the propeller diameter were calculated from regression of data from different sized multirotors available commercially. The exact

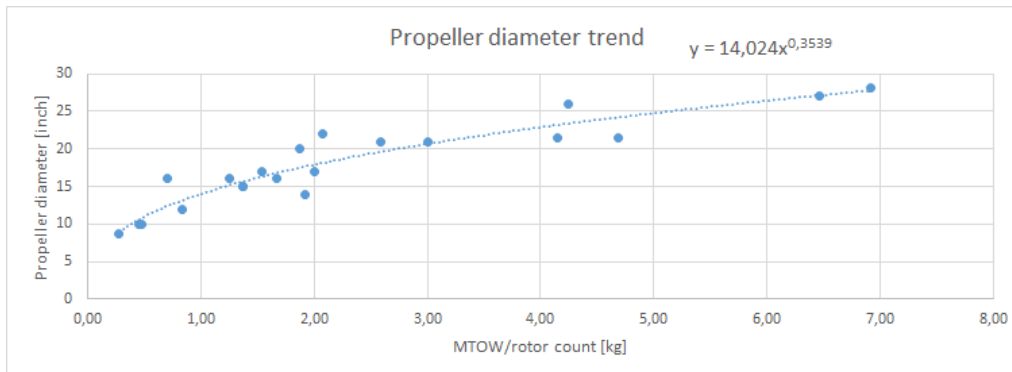
expressions used can be found in Figure 5.2 and the full data table is available in Appendix C.

Table 5.3: Overview of analysed specification sets.

Batch 1	l_r from 0.5 to 1.5 every 0.1 and from 2 to 4 every 0.5 propeller size - based on Figure 5.2b
Batch 2	l_r from 1 to 2.2 every 0.2 propeller size - based on Figure 5.2b $\pm 10\%$



(a) Motor weight regression.



(b) Propeller diameter regression.

Figure 5.2: Regression of motor weight and propeller diameter.

5.2.2 Objective function

With the assumptions in place, the variables to undergo simulation could be selected. Assuming a cylindrical coordinate system, the main parameters defining the geometry are diameter and length. In this case the stator outside diameter was used for easier interpretation of the results. Two more variables are added due to the lack of a reliable

and fast method of calculating them - reference phase current and the number of turns per phase. As the reference current value is required for calculation of the flux characteristic, the only alternative would be to use analytical methods, which might yield non-optimal results for this unusual application (small size and high current). As the number of turns is an integer, it can be found in finite time by simulating motor performance with the increasing number of turns until a peak of average torque is reached. However, doing this for every tested geometry set will result in a much longer computation time considering that control angles need to be recalculated for every configuration.

As SR motors do not use magnets, the thermal requirements are significantly reduced, yet they still apply to prevent wire insulation from melting and causing short circuits. However, doing a full thermal simulation for every iteration is too time consuming, so taking advantage from the fact that the motor will be operated in short periods (up to 30 min), the operating temperatures are approximated with current density, which incorporates 2 important qualities of the coil - r.m.s. current and volume. The limit have been set to 20 A/mm^2 for rated operating point, which should roughly correspond to 10 A/mm^2 for the nominal operating point, which is the standard for forced air-cooled machines in the industrial setting.

As used electromagnetic simulation software allowed to calculate performance at given speed, average torque error became the focus of the objective function with current density and motor mass serving as constraints. The objective function and the optimal design problem can be expressed as:

$$\begin{aligned}
 f_{obj}(\tau, m, J) &= (a_1(\tau - \tau_{spec}))^2 \\
 &+ a_2 \max \{e^{m - m_{spec}} - 1, 0\} \\
 &+ a_3 \max \{e^{J - J_{spec}} - 1, 0\},
 \end{aligned} \tag{5.5}$$

$$\begin{aligned}
 \mathcal{P}_{opt} &= \{D_{out_{opt}}, L_{opt}, N_{ph_{opt}}, i_{ref_{opt}}\} \\
 &= \underset{D_{out}, L, N, i_{ref}}{\operatorname{argmin}} f_{obj}(\tau_k, m_{Fe_k} + m_{Cu_k}, J_k),
 \end{aligned} \tag{5.6}$$

where a_1, a_2, a_3 are penalty coefficients, τ_{spec} is the target average torque, m_{spec} is the mass constraint, D_{out} is outer diameter, L is stack length, N is the number of winding turns per pole and i_{ref} is reference phase current. The specific form of the function is so the value of the constraint penalties is zero when the design values are under specification and quickly rises when they are above. The penalty coefficients are used to balance out the units' orders of magnitude.

5.3 2D model results

Out of 39 specification sets analysed (Appendix A), 12 had converged within constraints (Appendix B). During the optimisation process 6946 unique configurations were tested. This creates a suitable dataset for both qualitative (Section 5.3.1) and quantitative (Section 5.3.2) analysis.

5.3.1 Valid designs

A summary of the valid designs is presented in Table 5.4. It is easy to see that these cover the range of lifting ratios from 1 to 2.2 kg/rotor . Assuming quadrotor configuration, these would suit 4 to 8.8 kg vehicles, which is around the middle of weight range for commercial units (Appendix C). Typical applications include photography, surveillance and small package delivery.

What is worth noting is that **there is no particular trend in regards to motor size as lifting ratio** (and therefore torque) **increases**. What is more, even the same performance specifications, such as designs 10 and 11, end up with machines of different dimensions (although with similar weight) and performance. The same lifting ratio with different propellers (thus different torque and speed), as is the case with designs 1, 2 and 3, also does not follow a clear progression in terms of motor size. This may be due to different reference current limits, with higher currents allowing for larger OD (and lower length).

Therefore, it is hard to make any meaningful comparisons between the total of SR mo-

Table 5.4: Overview of valid optimised SR motor designs.

#	Batch	l_r	OD [mm]	L [mm]	N [turns]	Mass [g]	Propeller	τ_{spec} [Nm]	ω_{spec} [RPM]
1	2	1	50	13	26	166	13x4E	0.32	8210
2	1	1	71	6	84	217	14x6E	0.41	6475
3	2	1	43	29	26	242	15x4E	0.34	6580
4	1	1.1	65	8	54	210	15x4E	0.38	6905
5	1	1.2	64	8	54	203	15x4E	0.41	7194
6	1	1.3	70	6	64	210	15x4E	0.45	7468
7	2	1.4	81	6	48	299	14x5.5MR	0.65	7110
8	2	1.8	83	8	58	375	17x6E	0.84	6270
9	2	2	83	6	54	318	16x4E	0.71	8270
10	1	2	71	15	42	405	18x5.5MR	0.96	5508
11	2	2	83	9	48	403	18x5.5MR	0.96	5508
12	2	2.2	90	8	48	455	17x6E	1.05	6910

tors and BLDC motors (or any other motors). A different approach is needed - application based. For a specific application a suitable BLDC motor can be compared with a suitable SR motor in terms of how well they achieve application's objectives. This method lacks generality, but allows very simple, direct, and most of all, accurate comparison. Thus results can be taken at face value. Of course, use in any other application (at different vehicle size), would require certain extrapolation, but the accuracy of this process can be controlled. In addition, the usability of this approach increases the more comparisons are made for different applications.

It is still possible to infer some relationships (or the lack thereof) from secondary motor parameters. Data for WOT (rated) operating point is summarised in Table 5.5, while hover (nominal) operating point table is given in Appendix B. The value of current density J_{WOT} for design 9 exceeds the constraint of $20 \frac{A}{mm^2}$ because it was taken from an equivalent model, but using a higher resolution matrix of FEM results computed at the end of the optimisation process, as shown in Figure 5.1. However, a decision was made to keep this result due a relatively low value of error.

The most important observation to be made here is the fact that relative torque ripple $\Delta\tau$ is inversely proportional to the firing angle θ_0 . This is even more interesting when considering the fact that pushing the firing angle towards negative values is used in high-

current machines to develop more torque (by allowing current to raise before rotor and stator teeth overlap). Therefore, this becomes an exercise of balancing high torque with low torque ripple.

Table 5.5: Performance data of valid optimised SR motor designs at WOT (rated) operating point.

#	Size	I_{ref} [A]	θ_0 [° el.]	τ_{WOT} [Nm]	ω_{WOT} [RPM]	η_{WOT} [%]	J_{WOT} [A/mm ²]	$\Delta\tau$ [%]	$I_{DC-link}$ (peak) [A]	$\Delta I_{DC-link}$ [%]	F_{radial} [N]
1	50x13-26	28	-2.7	0.30	8210	70%	19.0	23%	38	222%	67
2	71x6-84	23	-63.4	0.39	6475	55%	17.9	74%	36	135%	38
3	43x29-26	18	-8.1	0.32	6580	72%	16.8	10%	29	218%	106
4	65x8-54	19	-19.1	0.36	6905	68%	15.1	29%	33	175%	59
5	64x8-54	20	-23.8	0.39	7194	67%	16.7	29%	34	161%	60
6	70x6-64	26	-24.2	0.43	7468	60%	18.6	20%	42	141%	55
7	81x6-48	36	-23.8	0.62	7110	63%	16.5	23%	53	151%	65
8	83x8-58	51	-57.7	0.80	6270	66%	15.9	62%	64	156%	68
9	83x6-54	49	-75.1	0.68	8270	58%	20.1	82%	82	156%	53
10	71x15-42	35	-61.2	0.91	5508	72%	16.8	81%	68	234%	93
11	83x9-48	45	-15.2	0.91	5510	64%	16.3	19%	69	163%	108
12	90x8-48	61	-51.3	1.00	6910	70%	15.0	52%	89	169%	83

On the other hand, relative DC-link current ripple $\Delta I_{DC-link}$ values are high (in the range of 100-300%), but not affected by the firing angle, as the magnetisation angle and the offset angle between phases are constant. However, peak DC-link current $I_{DC-link}$ values are mostly around 1.45 times larger than the reference current I_{ref} value, which might be useful information when selecting vehicle's battery.

Achieved efficiency η_{WOT} values are far from desirable (around 80% in an comparable BLDC motor, as shown in Figure 5.3), however the achieved range of 55-73% is satisfactory for prototyping purposes, especially considering challenging application and immaturity of the technology. However, efficiency is not visibly related to torque ripple, DC-link current ripple, nor reference current, so it can be assumed that these parameters can be safely reduced with control, without impacting performance.

In an SR motor there are two types of forces: motional and radial, with the latter being the main contributor to vibration. Motional forces $F_{motional}$ (per pole, in N) can be

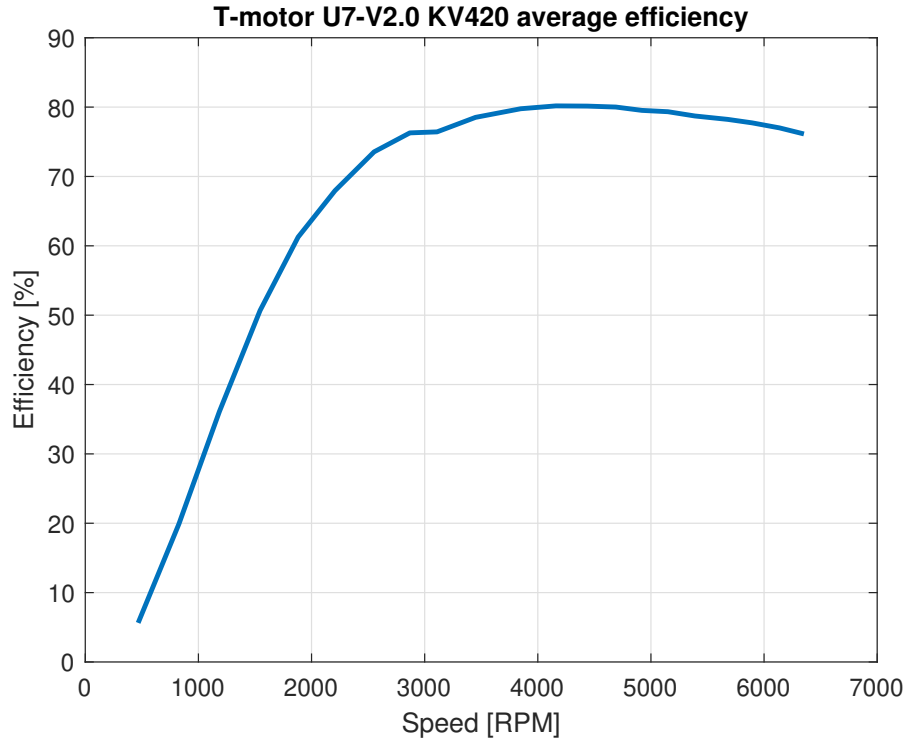


Figure 5.3: T-motor U7-V2.0 KV420 BLDC motor efficiency variation with speed.

estimated with the following formulas:

$$F_{motional} = \frac{\tau}{k_{ID/OD} OD - l_{airgap}} \times 10^3, \quad (5.7)$$

where $k_{ID/OD}$ is the ratio between inner and outer stator diameter from Table 5.1 and l_{airgap} is the airgap thickness (in mm). Comparing with the radial force values F_{radial} from Table 5.4, a big disparity can be seen. Using the Energy Conversion Efficiency (ECE) metric from (Abbasian et al., 2010) and given by:

$$ECE = \frac{F_{motional}}{F_{motional} + F_{radial}} \times 100\%, \quad (5.8)$$

the average value of 17.4% is obtained for the set of optimised designs, with the range being [11.4%;22.0%]. These values are higher than those obtained by Abbasian et al. (2010), but still confirm the conclusion that in SR motors the majority of produced force does not contribute to the motion.

MRVSIM software allows for a quick and easy calculation of vibration modes. Comparison of the fundamental 1st and 3rd harmonics with frequencies (for two operating points) calculated using the equation (T. J. E. Miller, 2001):

$$f = m \frac{\text{rpm}}{60} \times N_r \quad (5.9)$$

is shown in Figure 5.4. There is no visible trend relating motors' operational frequencies with their outer diameter, as is clear from the equation above. The averages of motor operating frequencies for the two states is close to constant, while the frequency of the harmonics decreases with the OD, while. This creates a situation, where throughout their operation, motors would get close to or even cross harmonic frequency, thus leading to resonance. Therefore, preference is towards either very small machines with operating frequencies falling below the 1st harmonic, or larger machines (OD > 65 mm) with operational frequencies between the 1st and 3rd harmonic. However, the specific magnitude and its influence on motor operation and noise generation could not be calculated at that time. That being said, methods exist, such as 'the 39 steps', commutation control (T. J. E. Miller, 2001, chap. 4), or radial force shaping (Bilgin et al., 2020), that reduce the magnitude of this phenomenon.

5.3.2 Intermittent designs

During geometry optimisation a total of 10209 designs were tested. The DIRECT algorithm script was set up to terminate after 250 iterations for batch 1 and 300 iterations for batch 2. Unfortunately, some of the results got corrupted, lowering the total number slightly. Due to the same parameter domain limits within each batch, initial probed points were always the same (as the algorithm was establishing the domain). Therefore, only 6946 unique configurations were analysed. However, some designs differ only in the number of winding turns (current density is not affected, due to wire size being calculated based on set fill factor), thus by selecting only the version with highest torque at operating

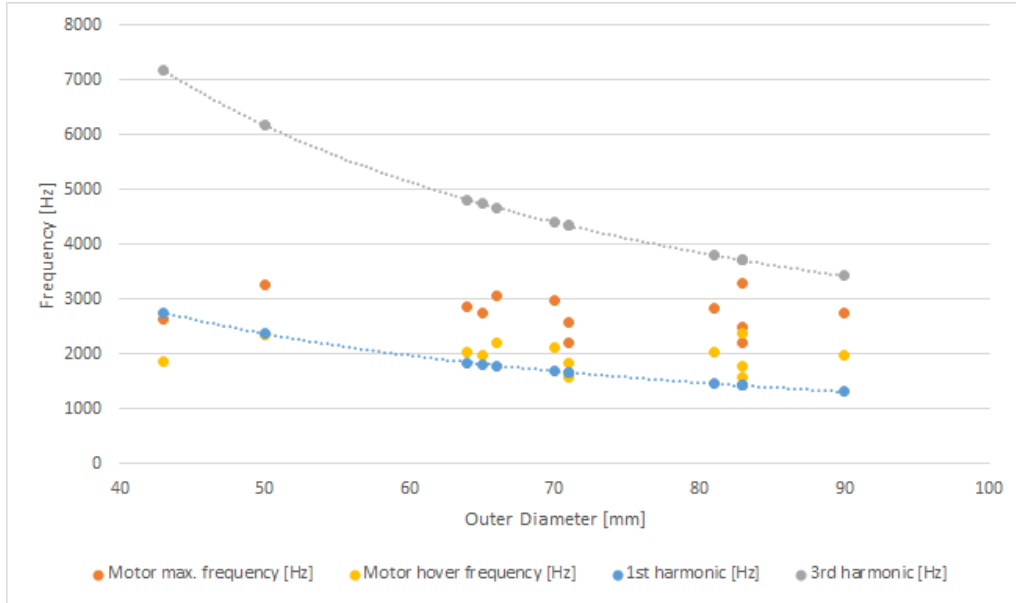


Figure 5.4: Motor operational frequency with 1st and 3rd harmonics for given geometry.

point in question, the number of configurations for analysis is brought down to 3260. This has increased clarity and readability of graphs presented.

Figures 5.5 and 5.6 present an overview of the analysed domain in terms of the four optimisation parameters. This shows basic relationships easily, such as a clear, singular maximum of torque. Worth investigating is the fact that it is situated not at extreme parameter values (except for winding turns), as intuition would suggest. This might be connected with the existence of a layer (‘ceiling’) of mid-range torque at high current levels. This might hint at magnetic field saturation or inability to reach desired current due to back-e.m.f. effects.

Another information inferred from this graphs is that the SR motor model at sizes considered in this work is highly nonlinear. Therefore, the approach of using FEM data was correct, as analytical models would provide inaccurate. In addition, Figure 5.6 validates the method of reduction of analysed results by showcasing that current density depends only on motor size (thus slot size, thus copper volume) and not on reference current or number of windings.

Focusing the scope of analysis on the elements of the objective function - torque, current density and weight - interaction between these three can be seen. This is shown in

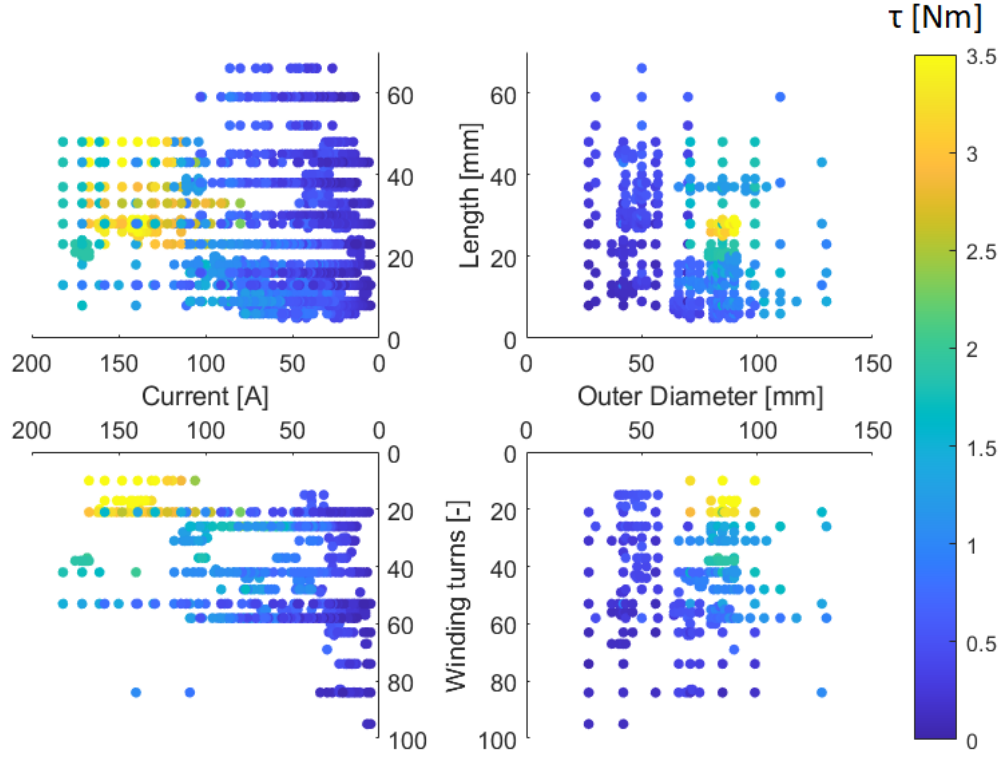


Figure 5.5: Set of 2D projections of torque results on optimisation parameters.

Figure 5.7. Of course, apart from the trivial conclusion that more relaxed constraints yield higher torque, another finding is important - the relationship closely (RMSE = 0.2093, $R^2 = 0.9217$) follows a polynomial surface. Using MATLAB's *fit* command with the *poly24* argument, it was described with a function (expressed as torque τ in Nm):

$$\begin{aligned}
 \tau = f(m, J) = & -0.246 + 8.08 \times 10^{-6}m + 0.00530J + 1.19 \times 10^{-8}m^2 + 0.000170mJ \\
 & + 9.83 \times 10^{-5}J^2 - 3.18 \times 10^{-8}m^2J - 4.89 \times 10^{-6}mJ^2 + 5.68 \times 10^{-7}J^3 \\
 & + 6.73 \times 10^{-9}m^2J^2 + 1.79 \times 10^{-8}mJ^3 - 5.86 \times 10^{-9}J^4
 \end{aligned}
 \tag{5.10}$$

thus providing a quick and easy estimate of torque in regards to constraints. It can be used for feasibility studies due to reasonably high accuracy (based on a large number of simulation results).

As the DIRECT algorithm converges on a solution, the density of points becomes

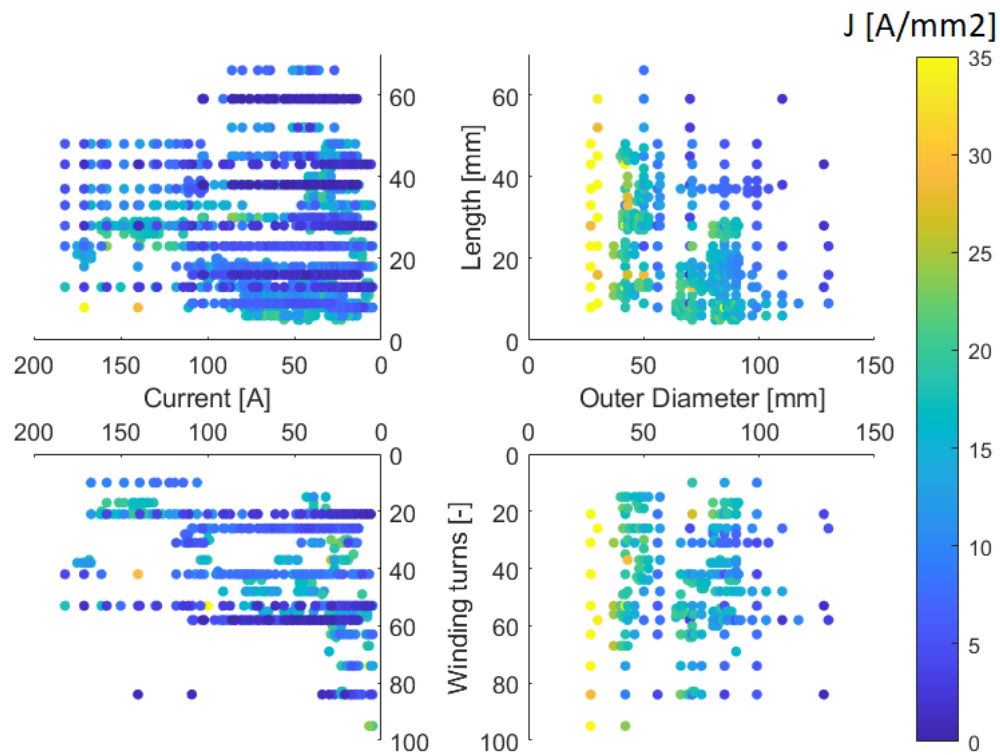


Figure 5.6: Set of 2D projections of current density results on optimisation parameters.

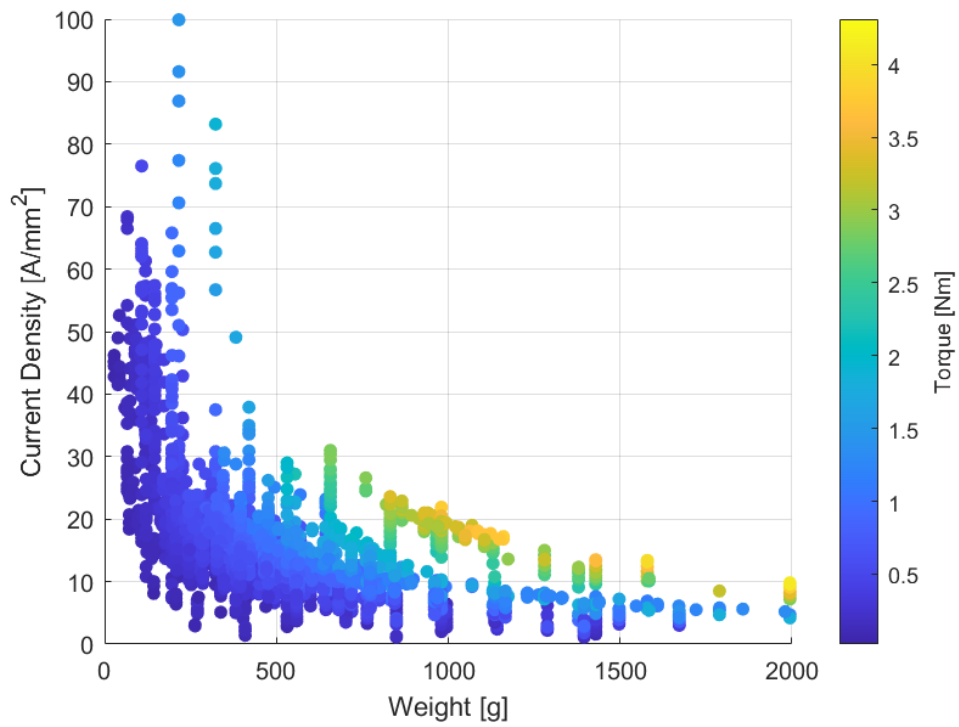


Figure 5.7: Pareto front of objective function.

higher, forming a cluster. Analysing the layout of these clusters from different specification sets, gives a good idea of the domain and how constraints affect the process. As can be seen in Figure 5.8, the clusters are positioned in an U-shape. From low diameter, low current and large length; through medium diameter, medium current and low length; to large diameter, high current and large length. It is easy to infer that this shape is due to combination of two constraints. Preference of length over diameter is due to the weight constraint: length has linear influence on weight, while diameter - parabolic ($A = \pi \left(\frac{d}{2}\right)^2$). Lean towards larger diameter is because of current density constraint that, as has been previously established, is closely related to stator slot size (thus motor diameter and to a lesser degree length). The imposed limit of 20 A/mm^2 is closely followed throughout the U-shape, as is shown in Figure 5.9.

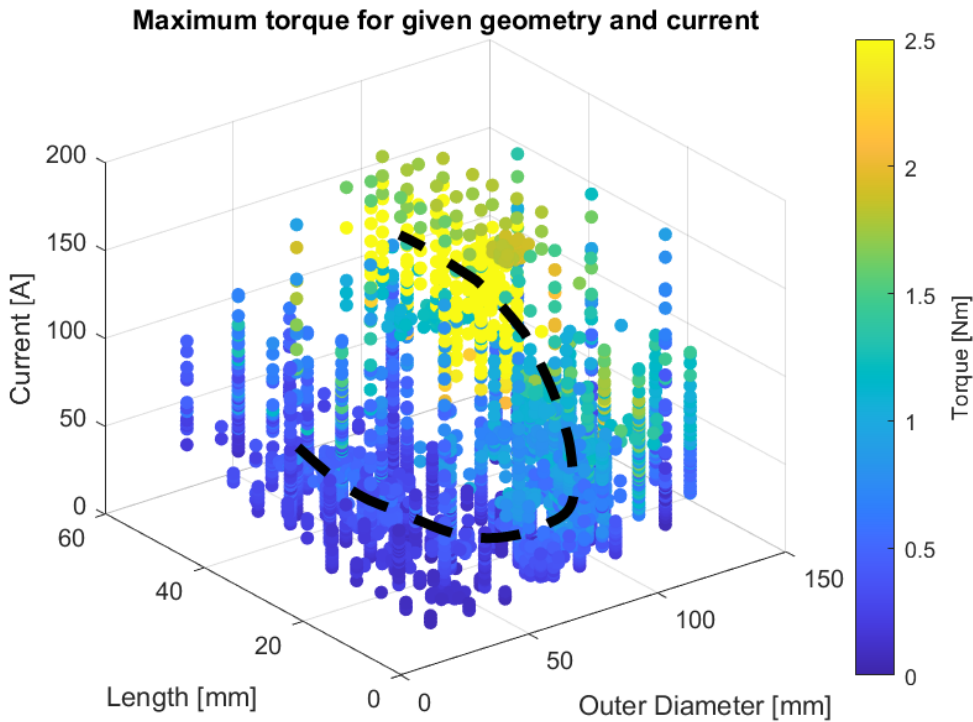


Figure 5.8: Torque against motor size and reference current.

As mentioned previously, at certain reference current level, torque stops increasing. This was attributed to the inability of achieving desired current shape due to other factors. This seems to be confirmed with constant r.m.s. current value in these saturated regions,

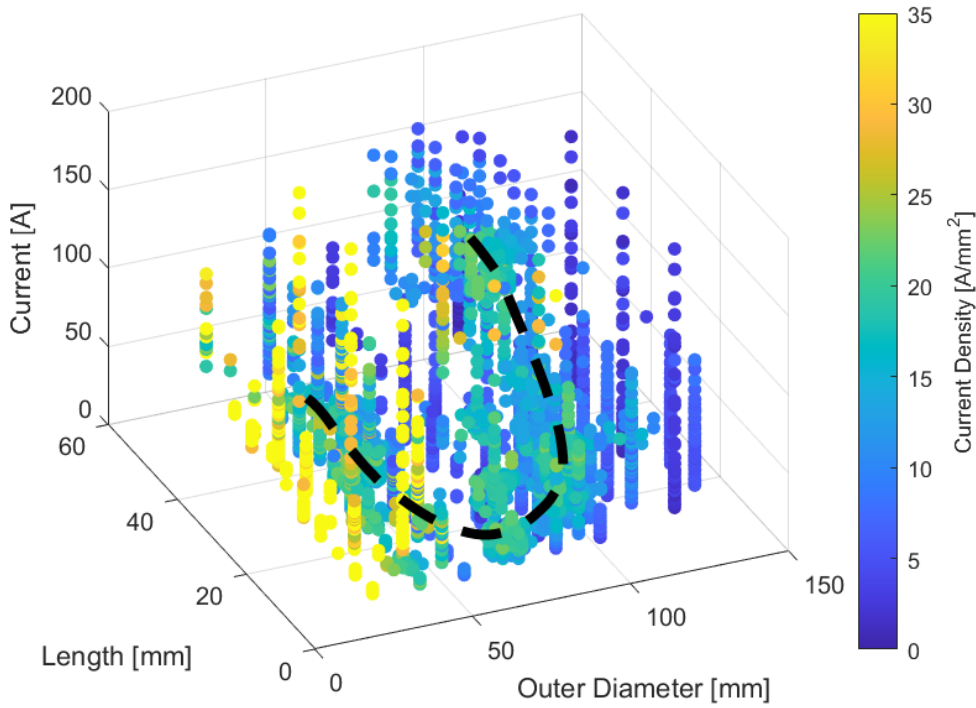


Figure 5.9: Current density against motor size and reference current.

as shown in Figure 5.10. Not only torque gets saturated at different levels depending on the number of winding turns, but also the slope of the linear region (torque constant K_T) is not consistent.

5.4 3D model results

Out of the 12 valid designs, the configuration of 71x15-42 (71 mm outer diameter, 15 mm length and 42 winding turns) was chosen for manufacture. The main reasons were high efficiency and suitable size for easy manufacture. The design was sent to a manufacturing company in Germany¹. 2D simulations conducted there confirmed expected results in terms of torque and current.

In addition, the company was able to estimate the effects of end windings and flux leakage in 3rd dimension. These predicted a $\Delta L_{au} = 0.0498$ mH increase of aligned unsaturated and $\Delta L_u = 0.1507$ mH of unaligned flux linkage curve, as shown in Figure 5.11.

¹MACCON GmbH & Co. KG (Maccon, 2015)

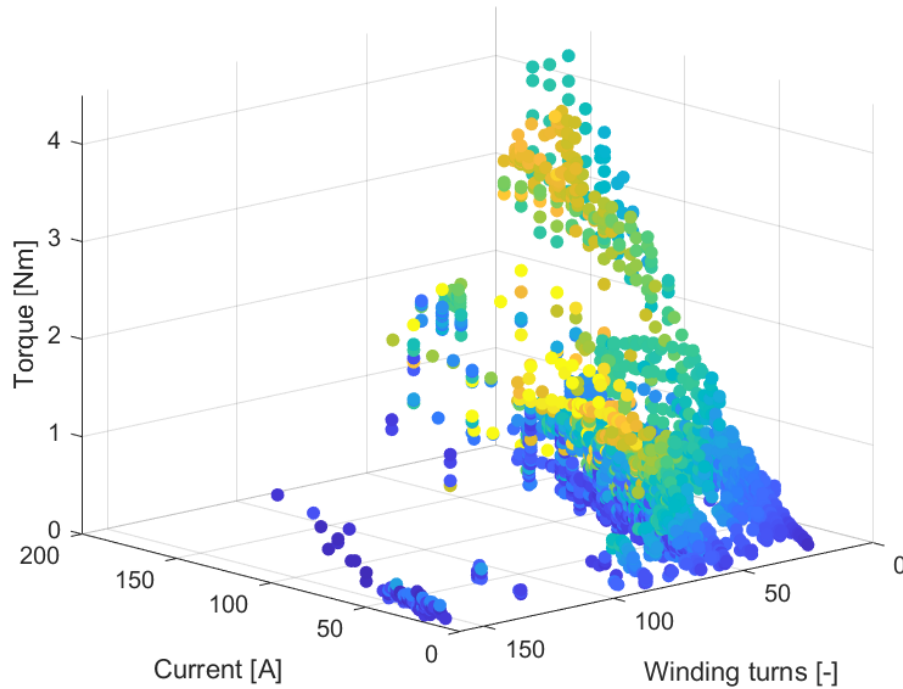


Figure 5.10: Saturation of torque with estimated r.m.s. current (denoted by the colour).

While the former change is overall positive, as it means larger energy exchange area (at the cost of quicker saturation), the latter significantly decreases it. This results in lower energy stored in the magnetic field, thus lower m.m.f., thus lower torque.

Models used up until now were unable to include these effects, as they relied on 2D FEM analysis of a single layer and multiplied the results by length. Literature (Kocan, Rafajdus, Bastovansky, Lenhard & Stano, 2021) (Castellini et al., 2016) shows it as a viable solution for industrial and transport applications, although Potgieter and Kamper (2014) investigated these effects with respect to Permanent Magnet machines. However, T. J. E. Miller (2002) notes the importance of these effects and estimates their contribution to be around 20-30% increase in L_u , which is much lower than observed in this case. With the small machine size in this case, the end winding length is close to the active winding length, thus cannot be ignored. These additional sections of coil contribute to increased self-inductance, thus affecting the torque directly, as per (2.17).

The influence of 3D effects was confirmed with a set of 3D simulations conducted by

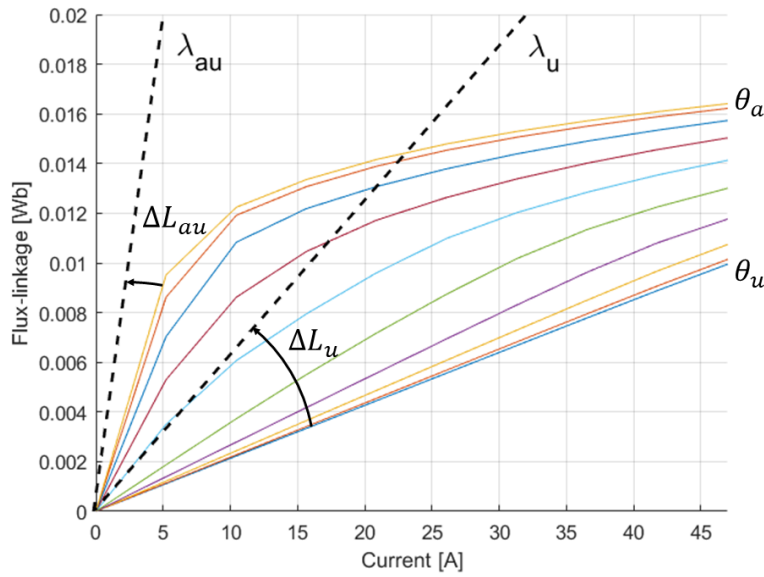


Figure 5.11: Flux network of 71x15-42 SR motor (based on 2D model) with 3D effects predictions.

the manufacturing company. Comparison of the 2D and 3D model results is shown in Figure 5.12. The immediately noticeable difference is the nonlinearity of the unaligned curve in the 3D model. This proves that most of the available analytical sizing methods are unfit for this application, as they assume the unaligned position to be represented by a line. Compared to the predictions, there is little change in the aligned unsaturated slope, but the saturation level was significantly increased. All in all, the available energy (area between curves) has decreased from $S_{pre}=0.40$ J to $S_{post}=0.32$ J for the range 0-47 A, which corresponds to 25.2% decrease.

This decrease is also clearly visible in operational performance. Figure 5.13 shows performance at two operating points when using 2D and 3D model-based flux networks. Even if required power at hover can be maintained, the efficiency has dropped significantly due to the requirement of higher current, thus higher copper losses. For the other (WOT) operating point, efficiency drop is lower, but the motor cannot achieve required power, making it unsuitable for the use in application. Worth noting is the fact, that not only the available area is smaller, but also the winding is de-energised before it reaches aligned position, further lowering energy conversion.

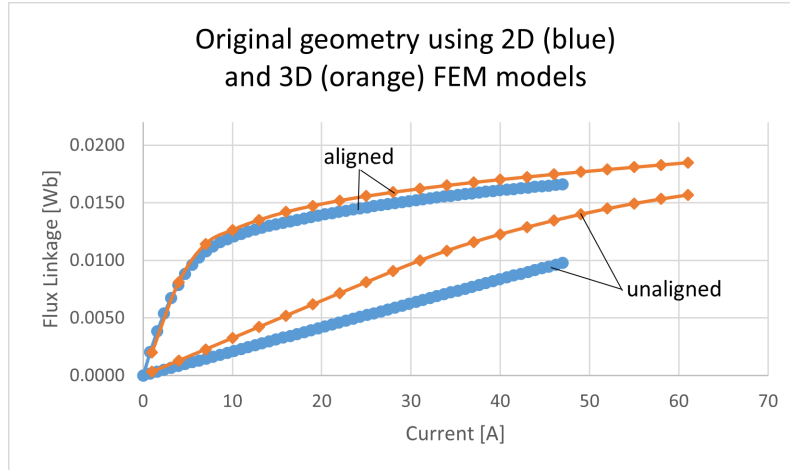


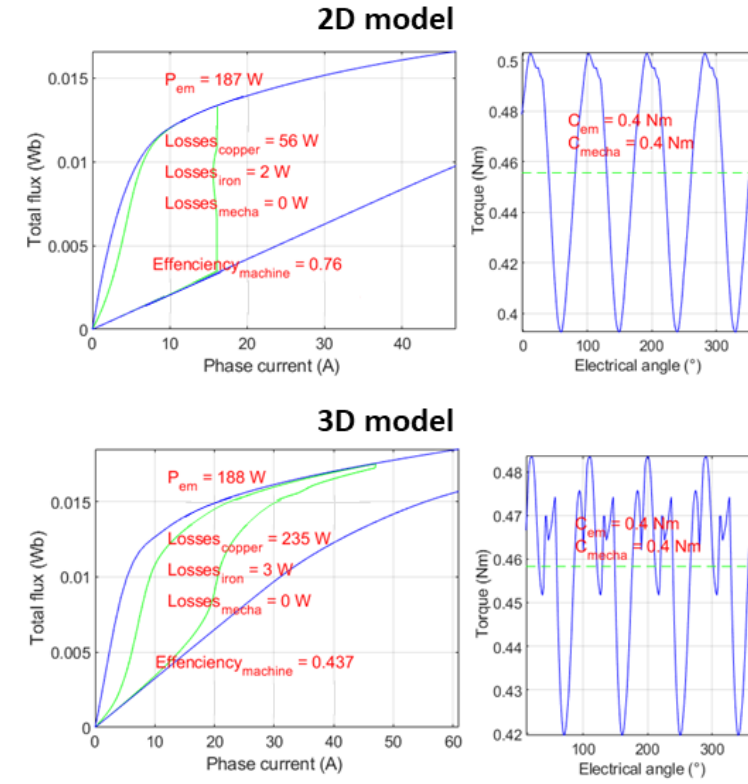
Figure 5.12: Comparison of 71x15-42 SR motor flux network based on 2D and 3D models.

5.4.1 Mitigation approaches

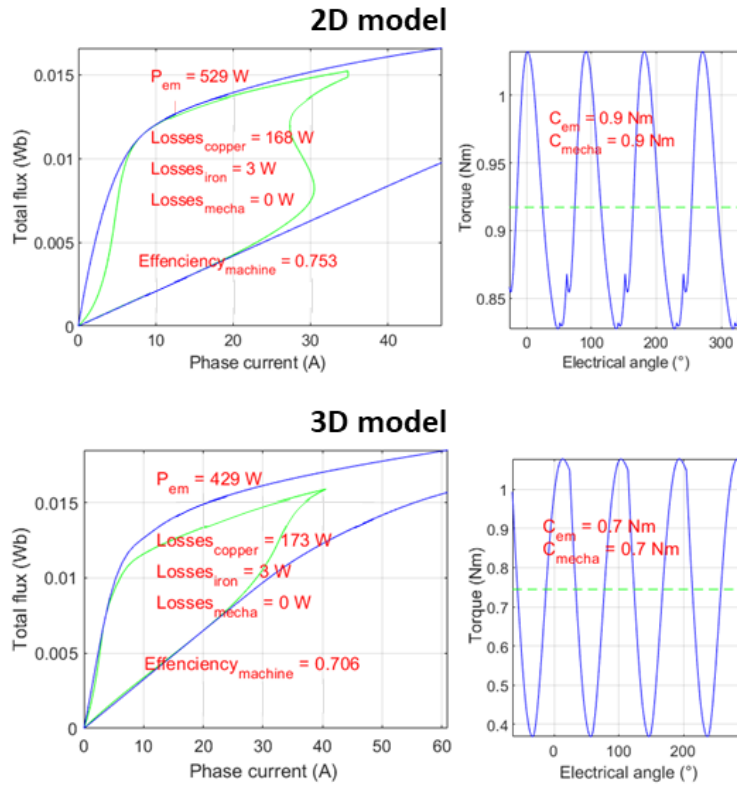
To resolve the decrease in performance coming from 3D effects unaccounted for, a number of methods were investigated, as described in (Biczyski et al., 2021). Two general approaches of flux curve-shaping and voltage-based, with two methods each, were applied, with varying results.

Flux curve-shaping focuses on bringing the flux network to the designed shape, by addressing problems related to 3D effects. This being mainly increase of self-inductance due to end windings and saturation of magnetic flux. The former can be addressed by manually adjusting the design (Figure 5.17), as the current approach using 2D models would run into the same issues. The adjustment process was handled by the manufacturing company. The latter is easily solved by changing material to that with higher saturation level, with the best being cobalt-iron alloy reaching up to 2.3 T. Comparison of flux networks between original geometry, modified geometry and using cobalt-iron is shown in Figure 5.14. Event though Figure 5.14b uses only a 2D model, the increase in available energy conversion area is clear in both cases.

Voltage-based methods, as name indicates, focus on increasing voltage to decrease the effect of back-e.m.f. on the current waveform. This can be done in two ways: by changing the supply (battery) or by increasing it through electronics in the form of a step-

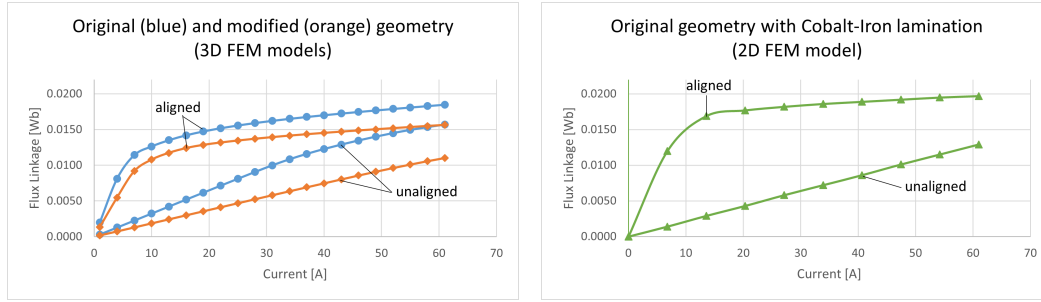


(a) Hover operating point.



(b) WOT operating point.

Figure 5.13: Comparison of 71x15-42 SR motor performance based on 2D and 3D models.



(a) Flux network of original and modified geometries. (b) Flux network of cobalt-iron alloy material.

Figure 5.14: Comparison of flux curve-shaping methods.

up converter. LiPo batteries come as cells of set voltage, therefore every increase can only be done in steps of 3.7 V (nominal). With 6S battery originally, addition of only one more cell (to 7S) allows to reach the target performance. The same increase of 3.7 V can be also achieved through a step-up converter added either at the motor or phase level, shown in Figure 5.15. Performance with increased voltage is shown in Figure 5.16. These two methods, both show a substantial increase in the average torque, making the full-load operation possible again. The fluctuations in voltage introduced by the step-up converter appear in two ways:

- high-frequency, low-amplitude noise due to motor current draw and low-frequency,
- low-frequency, high-amplitude oscillations due to step-up converter operation.

However, the average voltage is close to the designed 25.2 V, therefore motor performance, even at the WOT operating point, is at the expected level. The difference in the torque level and torque ripple between Figures 5.16a and 5.16b comes from the difference in simulated model, therefore is not commented further.

Each of these four methods have its own advantages and disadvantages. In regards to the application, these can be judged by deviation of performance from original design, increase in weight and price. General comparison of methods in these categories is shown in Table 5.6.

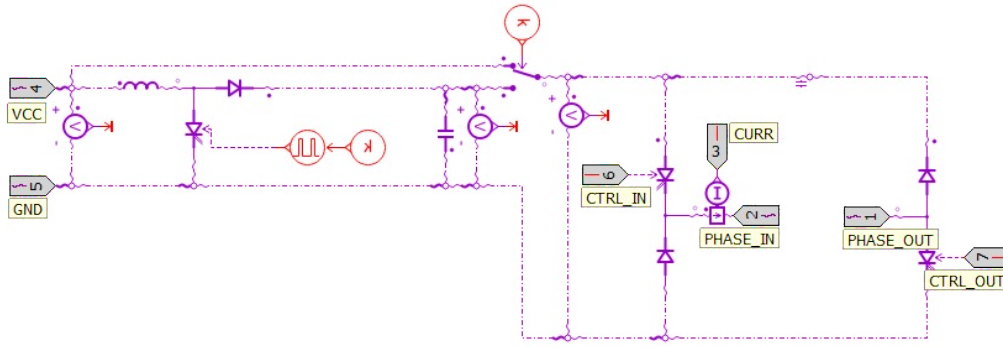


Figure 5.15: Simulation model of the in-phase step-up converter.

Table 5.6: Comparison of 3D effects mitigation methods.

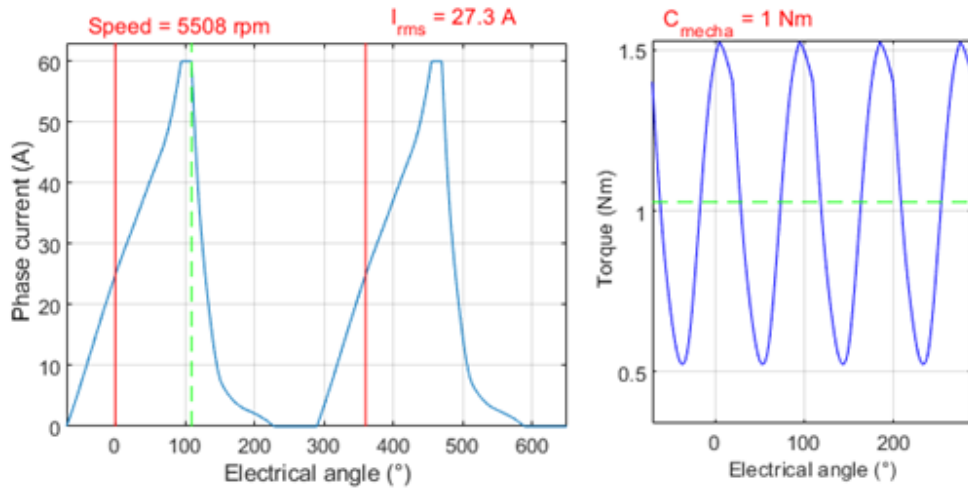
Method	Performance (compared to 2D model results)	Weight	Price
Material change	Minor increase	Minor increase	Major increase
Design modification	Negligible change	Minor increase	Medium increase
Battery change	Minor decrease	Minor decrease	Medium increase
Step-up converter	Minor decrease	Minor increase	Major increase

5.5 Final design overview

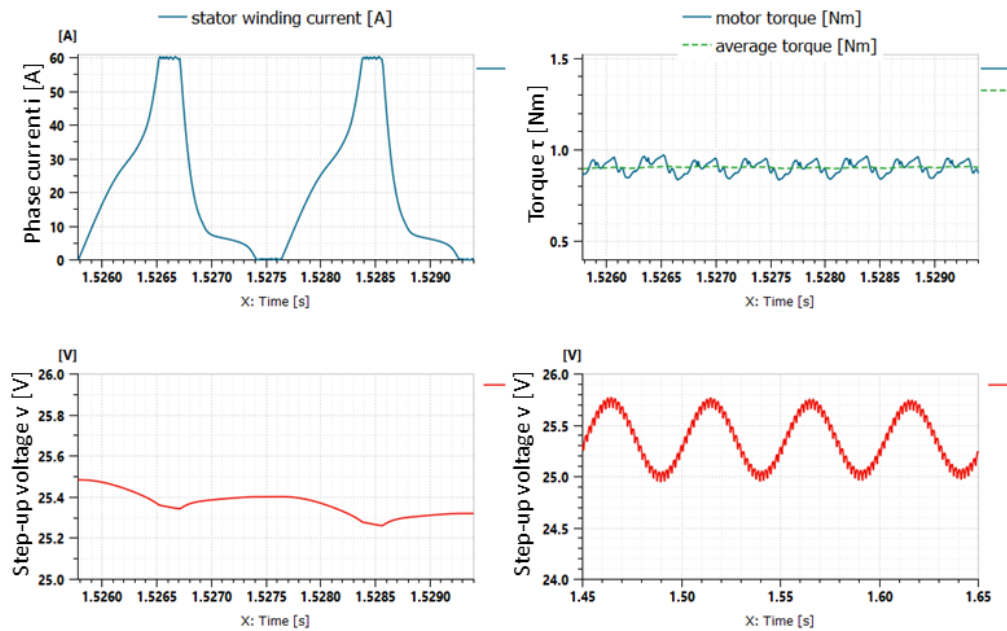
Out of the four methods presented above, any one is feasible, but the final selection depends both on the specific application and the state of the project. Therefore, modification of geometry was selected as the solution because of a better performance at similar price point to battery exchange method. Due to the decrease of winding turns, the new design is referred to as **SRM 71x15-30**. Comparison of new and old design parameters are presented in Table 5.7 and Figure 5.17. The manufactured motor and shaft assembly is shown in Figure 5.18.

With the final design established, additional data could be gathered to estimate behaviour during operation. Of particular interest is influence of voltage (due to battery discharge), series resistance (due to battery age), and speed (due to propeller model uncertainties). These types of simulations are possible with this model, as the 3D effects were already taken into account in the flux network, supplied from the 3D simulations.

Battery used in the demonstrator vehicle is a 6-cell LiPo battery, with voltage ranging



(a) Performance of SR motor with 7S battery.



(b) Performance of SR motor with step-up converter.

Figure 5.16: Comparison of voltage-based methods.

Table 5.7: Comparison of original 71x15-42 and modified 71x15-30 design parameters.

Parameter	Original design	Modified design
Stator teeth	8	8
Rotor teeth	6	6
Stator outer diameter	71.00 mm	71.00 mm
Stator inner diameter	39.00 mm	40.40 mm
Stator yoke thickness	3.23 mm	5.50 mm
Stator pole arc	15.00°	20.00°
Stator taper angle	6.75°	3.00°
Airgap thickness	0.20 mm	0.20 mm
Rotor outer diameter	38.60 mm	40.00 mm
Rotor inner diameter	17.85 mm	17.85 mm
Rotor yoke thickness	3.06 mm	5.00 mm
Rotor pole arc	16.50°	21.50°
Rotor taper angle	−3.38°	−3.00°
Stack length	15.00 mm	15.00 mm

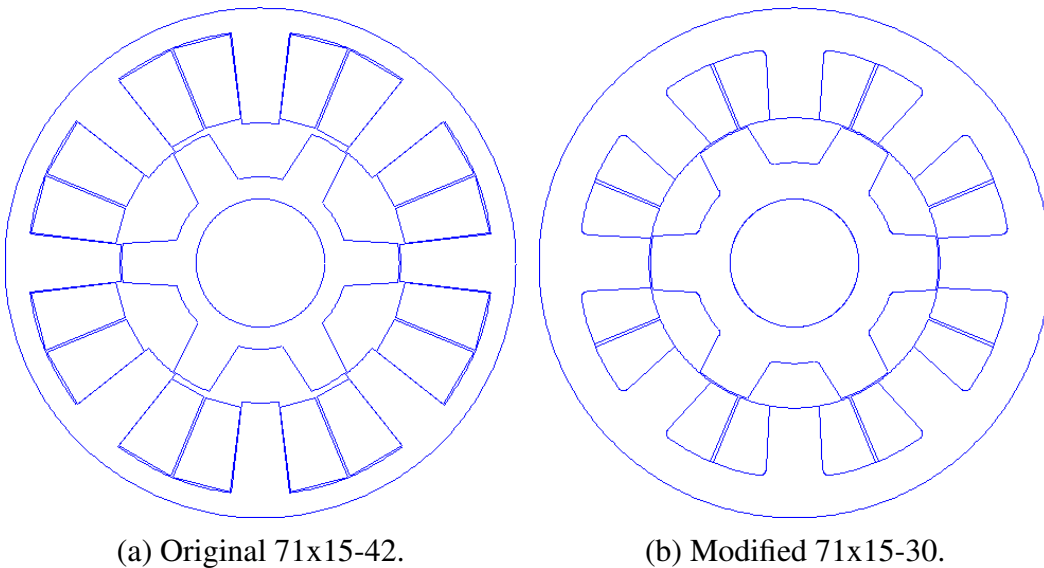


Figure 5.17: Comparison of original and modified SR motor geometry.

from 3 V (empty, 0% charge), through 3.7 V (nominal, 20% charge) to 4.2 V (full, 100% charge) per cell. This gives 18 V, 22.2 V and 25.2 V respectively. This type of battery can be safely discharged only to about 20% charge before damaging the unit, therefore the design process was performed at this voltage level. Figure 5.19 shows SR motor performance for these voltages. As expected, higher voltage results in better performance (higher torque output), which may be useful during takeoff. However, even with an empty battery the minimum torque level of 0.45 Nm required for hover was maintained (but



Figure 5.18: Manufactured 71x15-30 SR motor with shaft.

in the actual application this would be at much lower speed due to load characteristic). Therefore, even if the battery discharge has influence on motor performance, designing the motor for nominal voltage gives high confidence in being able to deliver expected performance with a necessary safety margin for emergency situations.

LiPo battery, as every electric component, has some internal resistance. As the battery ages and is being used, this resistance increases. New batteries have typically 1 to 3 m Ω per cell, which can progress up to 20 m Ω per cell after years of extensive use (Gatti, 2017; Jeong et al., 2020). Batteries acquired for the project (Tattu 6S 12000 mAh) were tested and measured 1 m Ω per cell and 6 m Ω in total. Figure 5.20 shows results for 6 and 72 m Ω battery internal resistance, but also for 24 and 288 m Ω which are supposed to emulate the voltage drop in a quadrotor (4 motors) vehicle. Even at 6 m Ω the drop in average torque is noticeable and at 72 m Ω (simulated 4 motors) the desired performance becomes

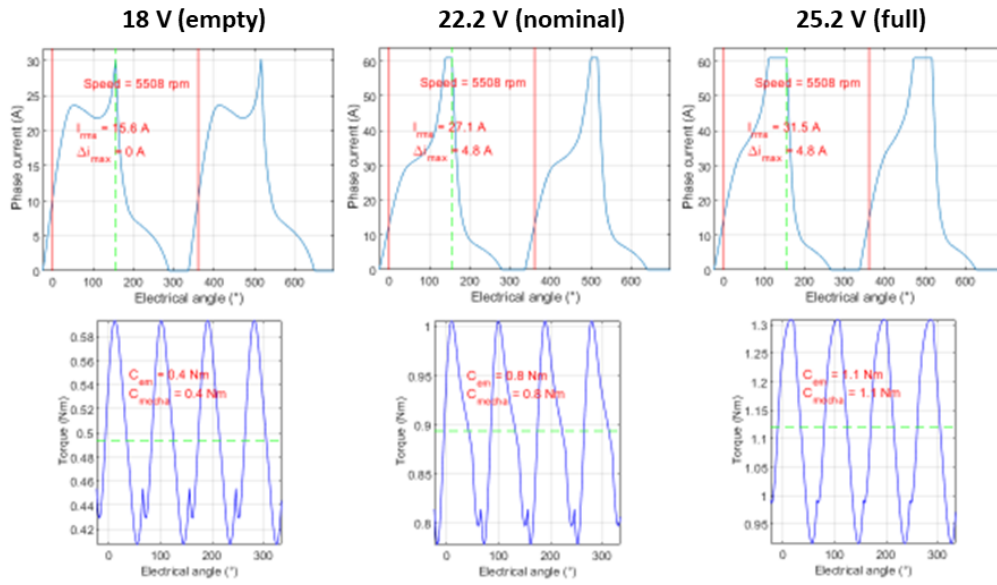


Figure 5.19: Influence of battery voltage on 71x15-30 SR motor.

unachievable. However, in application, 4 motors working at WOT operating point would happen only during climb and result in slightly slower climb speed. In addition, during operation with non-empty battery (SoC >20%) the added benefit from higher voltage most likely would balance the battery internal resistance influence.

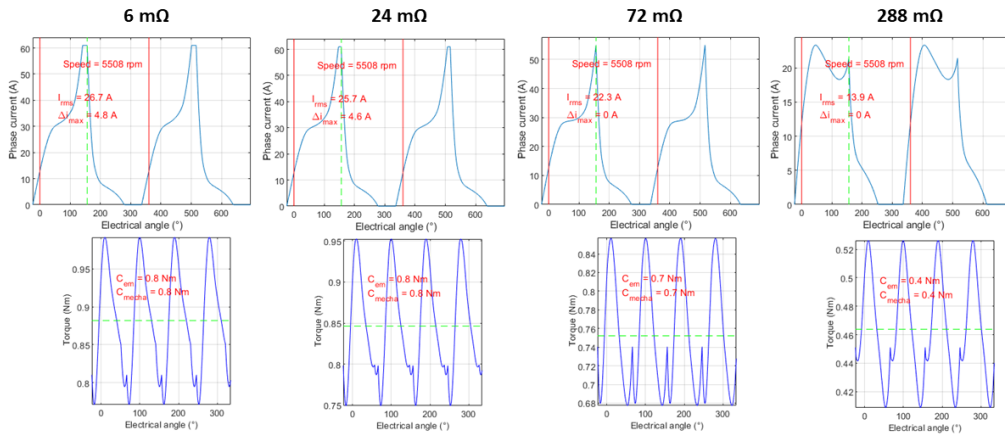


Figure 5.20: Influence of battery internal resistance on 71x15-30 SR motor.

At this stage of the project, the propeller model was based on simulation data from the manufacturer (APC 18x5.5MR (APC Propellers, 2014)). However, the demonstrator vehicle used as a reference for the study, uses a different kind of propeller, so it is important to analyse whether the motor would be able to provide required thrust with a different

propeller. This is done by checking maximum torque at different speeds throughout a wide speed range, as shown in Figure 5.21, which presents the torque-speed characteristic of the motor. What may be surprising is a very small constant power region. Therefore, due to load characteristic, propellers operating under the rated speed are preferred. In addition, a visible change in the slope of firing angle decrease at around 6500 RPM is visible, most likely signifying the base speed and the transition from PWM control to single pulse control. This value, however, does not correspond to the peak power.

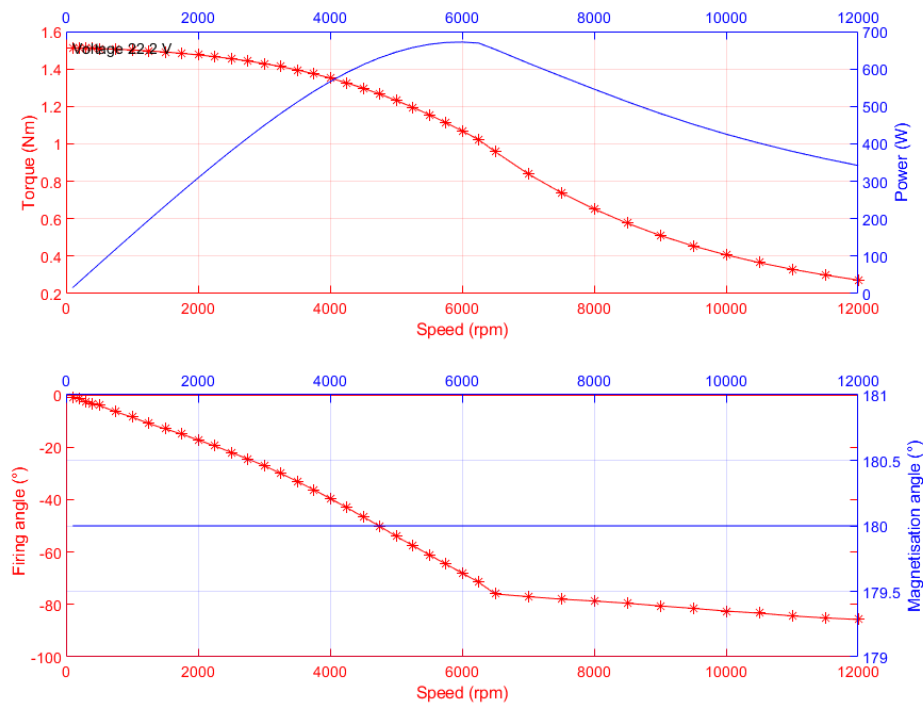


Figure 5.21: Torque-speed characteristic of 71x15-30 SR motor.

The last stage of the SR motor geometry optimisation flowchart, as shown in Figure 5.1 is the thermal simulation. It was done using the Heat Flow module in FEMM (Meeker (2018a)) software. Thanks to a well-documented MATLAB API (Meeker, 2018b), geometry could be generated from parameters by a script. The testing methodology was adopted from multirotor-specific BLDC motor datasheets, which list stator temperature after 10 min of full speed (under propeller load) operation. Of course, SR motors have different structure, so in addition, temperature inside of coils was also measured.

The simulated environment condition is a slow flight at $15 \frac{\text{km}}{\text{h}}$. Airflow generated by the propeller is omitted due to being relatively small (low radius). Based on this assumption, it is possible to roughly estimate the convection coefficient h (in $\frac{\text{W}}{\text{m}^2\text{K}}$) with the equation (The Engineering ToolBox, 2001):

$$h = 12.12 - 1.16v + 11.6\sqrt{v}, \quad (5.11)$$

where v is airspeed in $\frac{\text{m}}{\text{s}}$. The copper losses from end windings were added to copper losses of coil elements actually modelled in the 2D simulation, so that the total heat generation would match that of a 3D model. Iron losses were taken from MRVSIM directly.

Results of simulations are shown in Figures 5.22 and 5.23, which present heat progression in a cold stator during WOT operation. This is not a real scenario (although possible to emulate in a wind tunnel), as thrust generated at WOT would accelerate the vehicle to a much higher speed, but it combines the maximum heat generation with typical heat dissipation conditions.

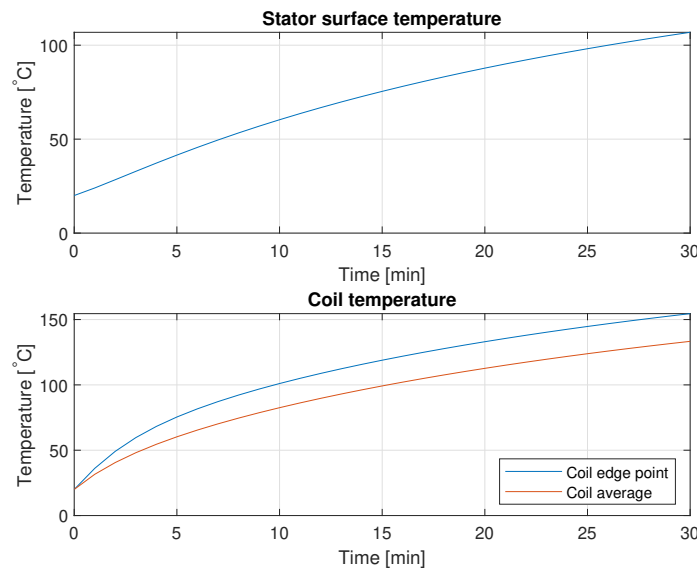


Figure 5.22: Temperature change at stator surface and within a coil in the 71x15-30 SR motor at rated operating point.

The main conclusion is that the coil temperature is kept under 150°C for most of the simulated time. During typical missions (mainly nominal operating point, up to 25 min

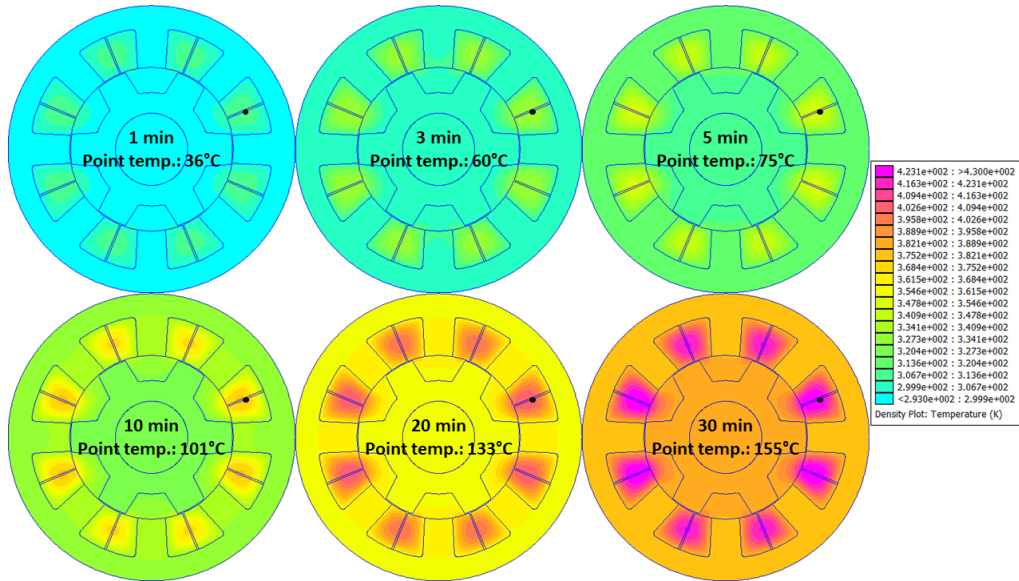


Figure 5.23: Heat flow in the 71x15-30 SR motor at rated operating point (temperature measured at a point on the coil edge, denoted by a black dot).

operation), the temperature would be well within specification for typical enamelled coil wires (ELEKTRISOLA, 2022). In addition, minimal impact of rotor on heat exchange can be seen. This is due to the absence of rotor copper losses, low iron losses and separation by airgap between coils and rotor. Therefore, in this type of analysis it can be omitted for increased computation speed.

Finally, due to the modification of geometry, vibration modes have also changed. Operational frequencies still depend only on speed, thus were kept at 1574 Hz (nominal) and 2203 Hz (rated). However, as shown in Figure 5.24, resonant frequencies have moved upwards, such as being well above values attained during normal operation, thus eliminating the risk of resonance.

5.6 Summary

The SR motor, being the central component of the actuating system, was designed as a custom component. Different topologies were investigated, eventually settling on a conventional 4-phase 8/6 machine because of its inherently higher fault-tolerance. The electromagnetic performance was optimised for a range of potential vehicle sizes. The

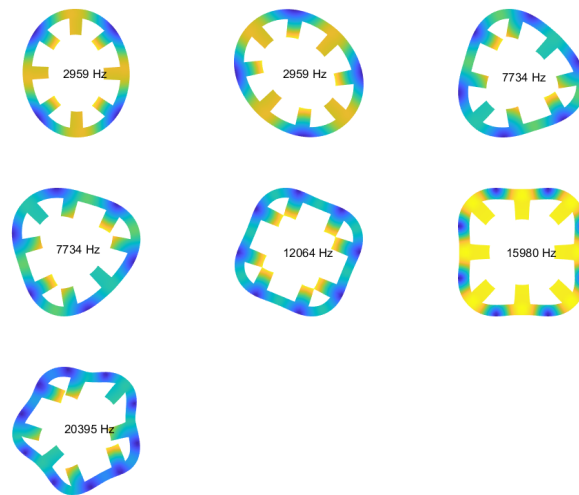


Figure 5.24: Vibration modes of 71x15-30 SR motor.

resulting designs were analysed in terms of performance at operating points and trends arising from the technology and the optimisation process, completing the first research objective. One design (corresponding to a 8 kg quadrotor vehicle) was selected for manufacture, but the 3D effects not included in the model used for optimisation resulted in a significant performance drop. Therefore, four mitigation methods were investigated. After implementing the approach of manual geometry modification, the final design of 71x15-30 was manufactured. This concluded research objectives two and four. With the SR motor design established, a simulator of the whole actuating system can be built to aid in the development of a control solution and to conduct fault injection studies.

Chapter 6

SR Motor Control and Simulation

This chapter serves as a bridge between SR motor design and simulation results. It details simulator set-up, its parameters and control scheme used. The software developed here then is used in pursuit of the third and fifth research objectives. It also talks about the power stage design and its implications. Therefore, it compliments Chapter 5 in achieving the fourth research objective.

6.1 Actuating system simulator

The SR motor actuating system simulator was developed using Simcenter Amesim 17¹. It was chosen for its native support of 4-phase SR motors, user-friendly interface and tools for parametric analysis and optimisation. Simulations are run with a fixed step size of 1×10^{-7} s to ensure numerical stability. The simulator is to be used for the following purposes:

- verification of motor design,
- motor control solution development,
- fault and uncertainties simulation.

¹formerly known as LMS Imagine.Lab Amesim <https://www.plm.automation.siemens.com/global/en/products/simcenter/simcenter-amesim.html>

The simulator was built based on the structure discussed in Section 4.5 and shown in Figure 4.9. Therefore, it follows a modular structure with each module corresponding to a specific component of the vehicle, as shown in Figure 6.1. The naming convention used in the figure is as follows:

- MICRO - micro-controller (including PWM generation),
- POWER - power stage with asymmetric bridge converters and current sensors,
- WIRE - connection between the power stage and the motor, used strictly for fault injection,
- MOTOR - SR motor with inertia and friction,
- ENC - incremental encoder (position sensor),
- PROP - propeller,
- BATT - battery and DC-link capacitor,
- TESTER - test and simulation control unit.

The TESTER module has no physical counterpart, as it exists only to facilitate simulation and data gathering. In addition, there is also a colour convention used to help differentiate between the type and function of elements:

- red - control logic,
- purple - electrical,
- green - mechanical rotational,
- blue - fault and uncertainty injection,
- brown - simulation control and post-processing.

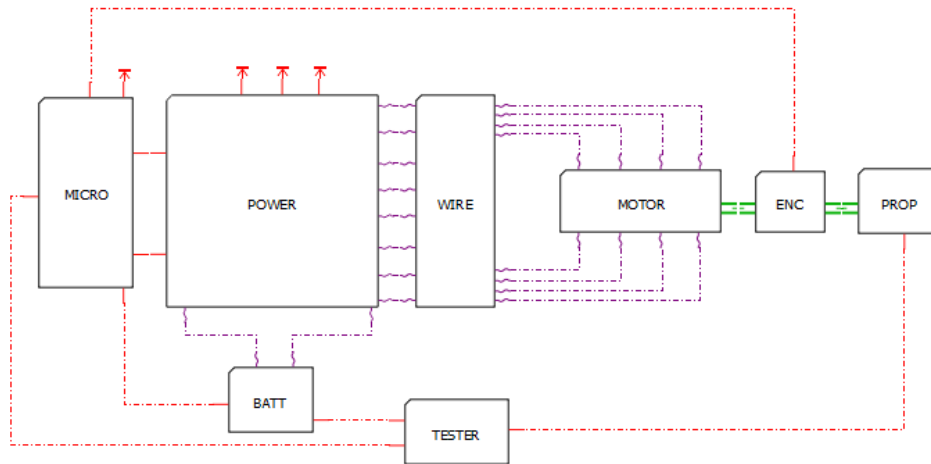


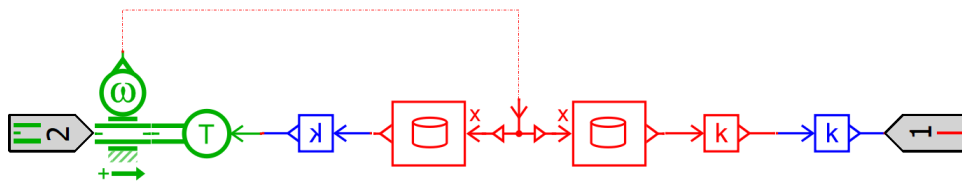
Figure 6.1: Overview of simulator structure.

The following paragraphs will briefly explain the structure of each module, leaving out the blue fault injection elements, that are explained in Chapter 7.2. The methods and the results of real parts measurement are described in Section 6.3.

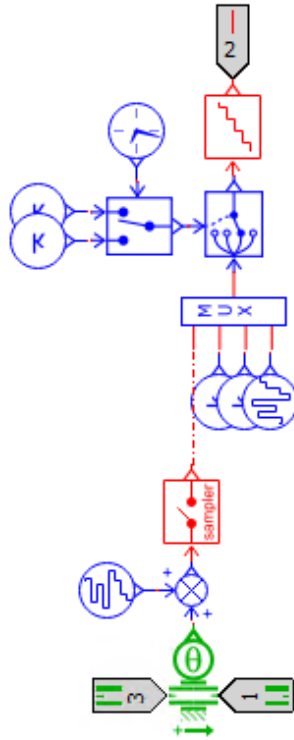
The propeller module shown in Figure 6.2a is basically just two look-up tables, one for thrust and one for torque. Thrust is re-calculated from N to kg.f and used as an output, while torque is fed into the mechanical rotational part of the system. The rotation speed sensor is used only to feed the tables and does not represent a physical part. Initially, simulation data from APC 18x5.5MR (APC Propellers, 2019) plastic propeller was used, as chosen during the sizing process. However, later the data was changed to that of T-motor P18x6.1 (T-motor, 2022) carbon fibre propeller, as used on the demonstrator air vehicle.

The encoder module (Figure 6.2b) uses a simple position sensor with sampling and quantisation. It is modelled after Heidenhain ERN 1020 rotary incremental encoder (Heidenhain, 2019) with 2048 line counts per rotation. The 2-wire signal of the encoder is not modelled, as it would add unnecessary complexity (and therefore increase computation time), while all types of faults can be modelled using a simplified setup.

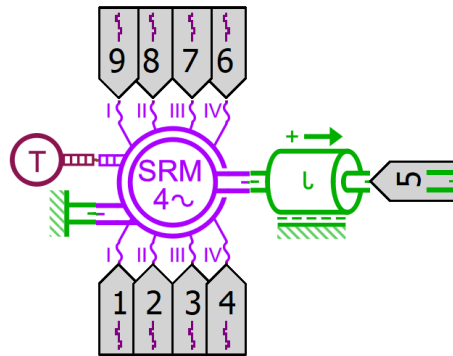
The SR motor module (Figure 6.2c) includes the pre-made 4-phase switched reluctance model with the number of rotor poles set to 6. The rotary inertia element includes



(a) Propeller module.



(b) Encoder module.



(c) SR motor module.

Figure 6.2: Structure of propeller, SR motor and encoder simulator modules.

both the rotor and propeller inertia, as well as Coulomb (as constant torque in Nm) and viscous friction (as torque coefficient in Nm/RPM). Thermal properties are not modelled at this stage, therefore a constant temperature of 20°C is set.

The power module shown in Figure 6.3 houses 4 asymmetric bridge sub-modules, as well as the current sensors. In addition, the control signal has three states of $\{-1;0;1\}$ (with -1 being de-energising and 1 energising of the winding), so included are sub-modules to de-couple the signals to feed into to MOSFETs. An example asymmetric bridge converter sub-module is shown in Figure 6.4. It represents one converter ‘leg’

(one phase) and is built of two transistor-diode elements, a current sensor and a voltage sensor (mainly set-up for possible sensorless control solution). Switching both transistors ‘on’ produces energising current, switching both ‘off’ produces de-energising current and switching one ‘on’ and one ‘off’ allows for ‘freewheeling’, which would reduce the strain on components of a real unit.

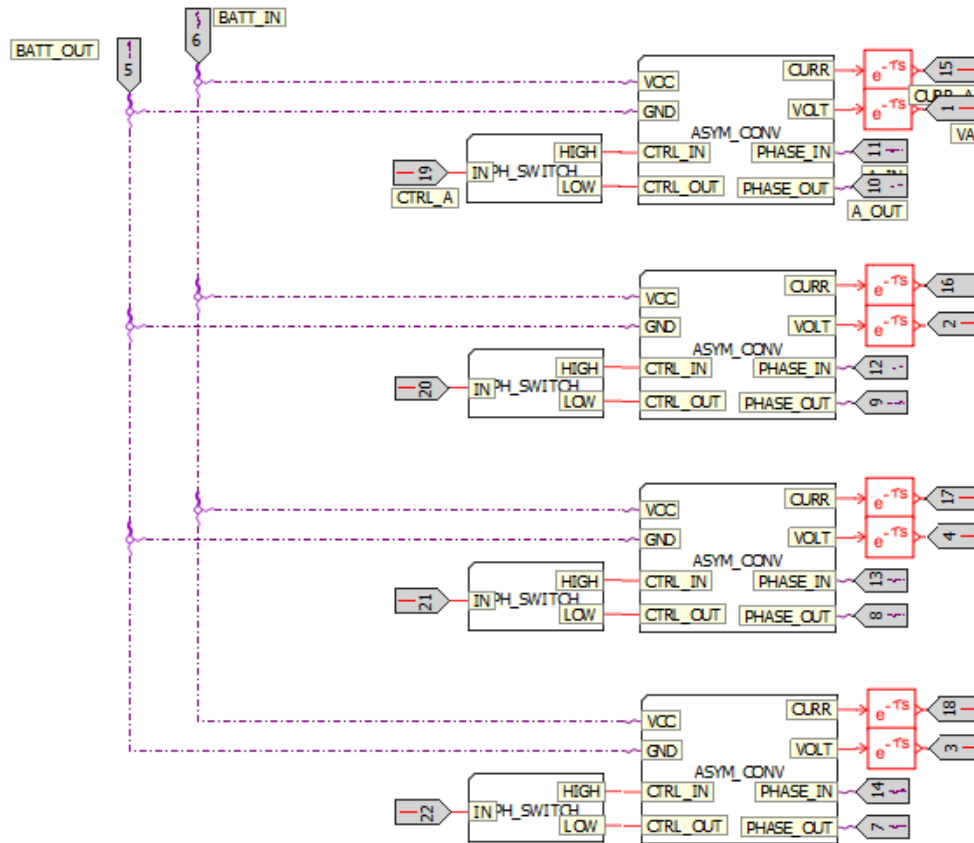


Figure 6.3: Structure of the power module.

Figure 6.5 shows the battery module being a very simple one. Battery is emulated by a voltage source, connected in parallel with a low-ESR capacitor. The current sensor used here is the same as the phase current sensors in the asymmetric bridge converter sub-modules. Also included is a low ESR capacitor, in real life systems used as a current ripple filter. Additional block of SIM_CONTROL is used to catch the situation where battery current rises to a level that would damage (or destroy) the system and stop the simulation, saving computational effort. The test and simulation control unit (Figure 6.6)

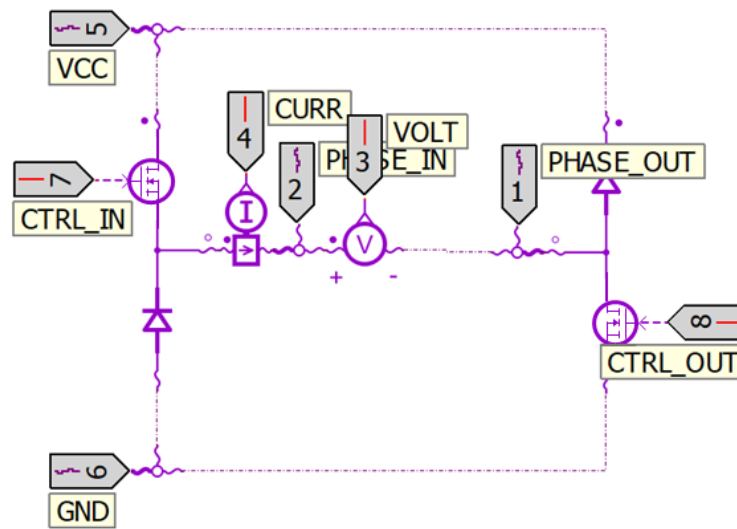


Figure 6.4: Structure of the asymmetric bridge converter sub-module.

provides input signal and voltage level, while comparing the output thrust with reference. It supports both specially constructed scenarios and real test data.

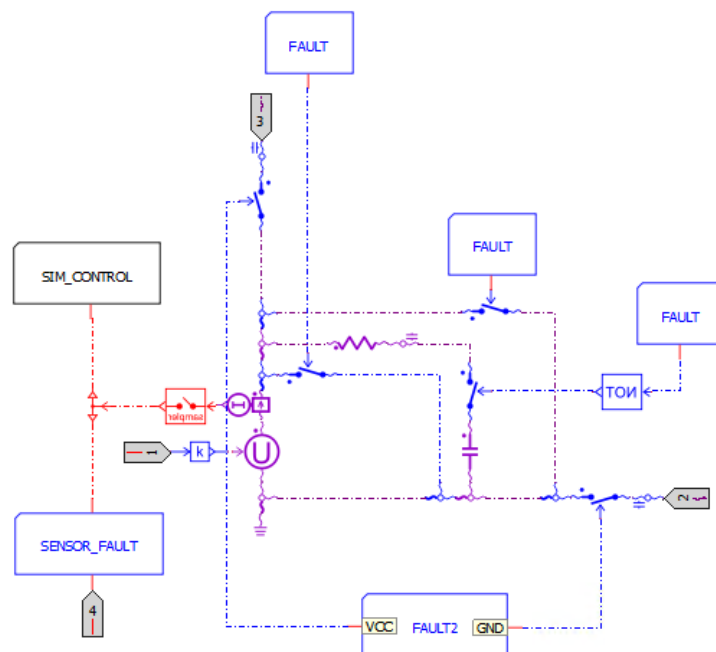


Figure 6.5: Structure of the battery module.

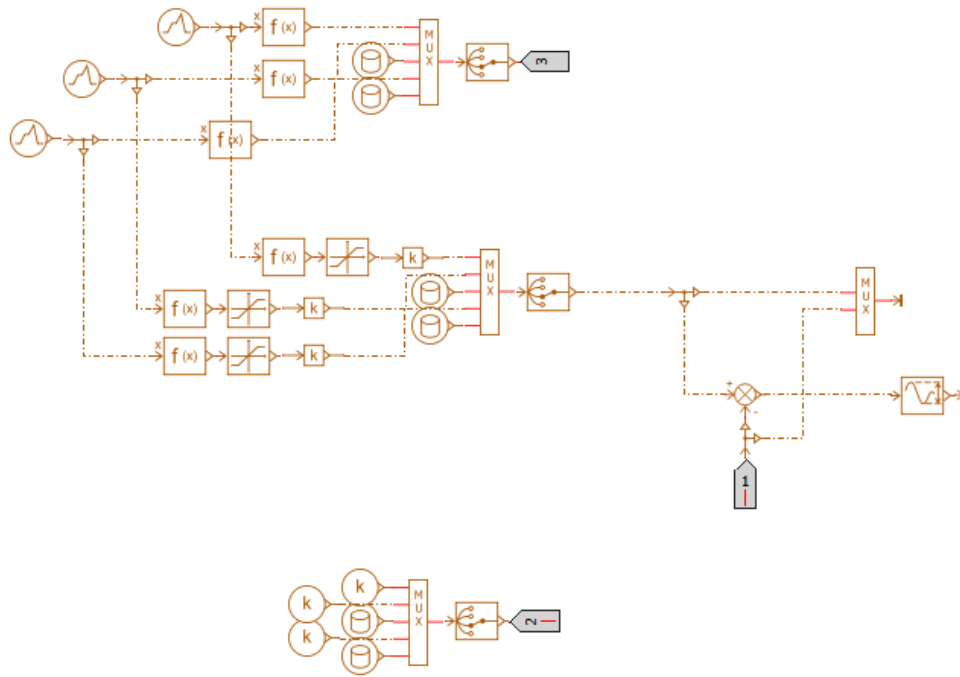


Figure 6.6: Structure of the testing module.

6.2 SR motor control

The motor control scheme is rather a conventional one, previously found in (Saadi, Sehab, Chaibet, Boukhnifer & Diallo, 2017b) (Abdel-Fadil & Szamel, 2018). It is shown in a block diagram form in Figure 6.7. It uses a cascade control approach, with a single PI controller for speed and an array of four PI current controllers, one for each phase. The microcontroller module (Figure 6.8) has multiple sub-modules that correspond to different functions. The BLDC motor actuating system includes an ESC that, among other things, conditions the signal from FC by removing the deadzone and adjusting the response rates. This is mimicked for the SR motor actuating system by using the PRE-SHAPE sub-module, based on the input/output characteristics of the BLDC system. It is defined by the function:

$$u_{conditioned} = (1000 - b_o) \left(\frac{u - (1000 - b_o)}{1000 - b_o} \right)^2 + (1000 - b_o), \quad (6.1)$$

where $u_{conditioned}$ is the conditioned input signal in the range $u_{conditioned} \in [1000; 2000] \mu s$, u is the raw input signal and b_o is the offset value, here empirically selected as 100 ms. The influence of the input signal conditioning is shown in Figure 7.1.

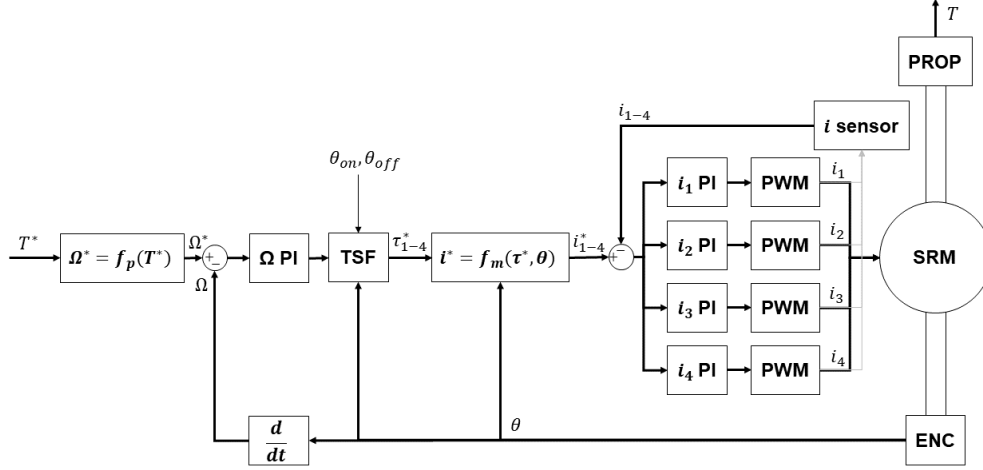


Figure 6.7: Block diagram of the motor controller.

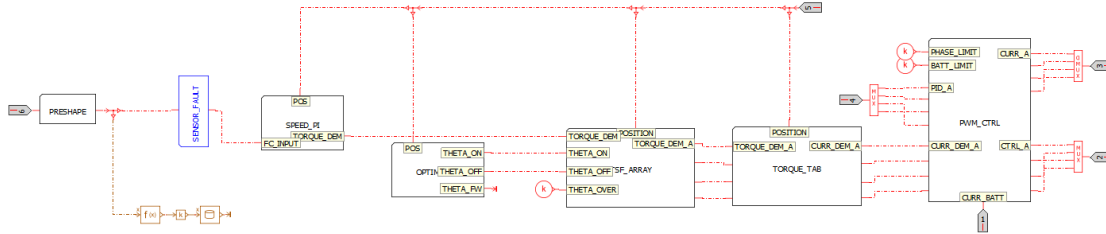


Figure 6.8: Structure of microcontroller module.

The Speed PI sub-module converts the conditioned input signal into thrust demand (as a percentage of maximum value), then into speed demand using a speed-thrust look-up table, compare with speed estimate (from differentiating the position signal) and compute appropriate torque demand value. The controller used is a discrete PI controller with $[0; 1.35]$ Nm output limit and anti-windup. The controller's parameters were roughly found using a manual trial-and-error method, because of the high non-linearity of the system. The aim was to quickly find a set of parameters that worked reasonably well in most situations, rather than delay the project by computing optimal parameters. Out of the

parameter sets tested, the set that resulted in the lowest 5% response time is as follows:

$$K_{P_{speed}} = 0.01, \quad (6.2)$$

$$K_{I_{speed}} = 1. \quad (6.3)$$

The OPTIM_ANG sub-module simply provides optimal firing angles based on speed (calculated by differentiating position) using look-up tables. The angles are optimised using MRVSIM software and stored as files.

The TSF_ARRAY sub-module implements a Torque-Sharing Function (TSF) for each of the phases. No torque feedback is available, therefore an open-loop method based on firing angles has to be used. In this work modified sinusoidal TSF is used, shown in Figure 6.9, as proposed by Gouda, Hamouda and Amin (2017). The overlap angle was found using genetic algorithm optimisation tool in Simcenter Amesim software. The objective of the TSF is to reduce torque ripple by spreading the load between phases, however, during single-pulse control (high-speed) operation, the waveform becomes effectively trapezoidal.

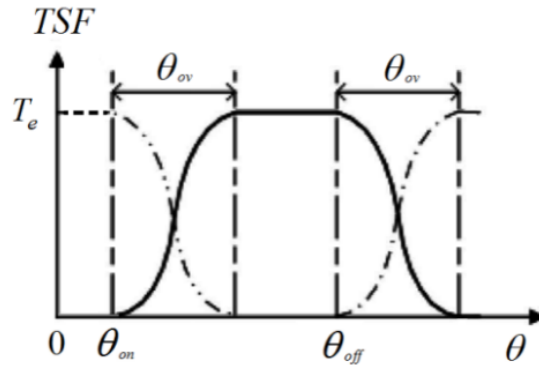


Figure 6.9: Modified sinusoidal TSF (Gouda et al., 2017).

The TORQUE_TAB sub-module implements the $i^* = f(T^*, \theta)$ function, effectively calculating current demand based on torque demand using the current-torque look-up table shown in Figure 6.10a. In industrial settings this works to maximise torque and efficiency. But as this machine usually operates at high current, the current demand simply dips as the back-e.m.f. rises to avoid overcurrent and damage to the system, as shown in

Figure 6.10b.

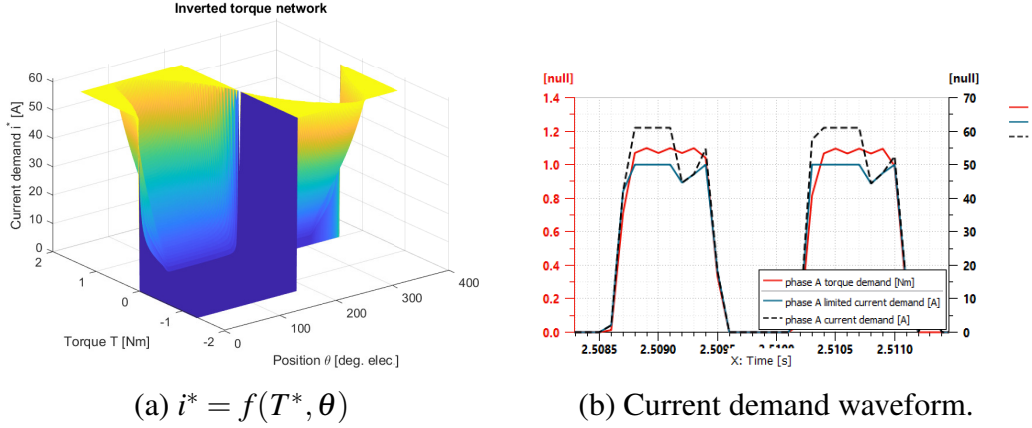


Figure 6.10: Current demand function and its effect on the waveform.

Figure 6.11 shows one phase of the current PI sub-module (PWM_CTRL). The current demand is limited to ensure numerical stability of the simulation. The main element is a discrete PI controller with output limited to $[-U; U]$ or $[0; U]$ (where U is system's estimated voltage, usually 22.2 V) depending on chosen PWM polarity. Similar to the speed PI controller, anti-windup is used and parameters were chosen manually to minimise 5% response time:

$$K_{P_{current}} = 2, \quad (6.4)$$

$$K_{I_{current}} = 1000. \quad (6.5)$$

To keep the control signal bi-polar and in sync (as shown in Figure 2.23), both its positive and negative components go through a separate PWM generator and get combined into signal in the range $\{-1; 0; 1\}$. In addition, phase and DC-link current are continuously tested against pre-set limits and control is adjusted.

Cascade speed and current PI controllers were chosen due to their robustness and suitability for systems with unknown dynamics. However, other control solutions were also investigated. Particularly, traditional voltage-PWM and current-hysteresis, as described by (T. J. E. Miller, 2001, chap. 5.3.3) were found to be underperforming at high speeds (which was expected). However, techniques that use inductance data, like Gain Schedul-

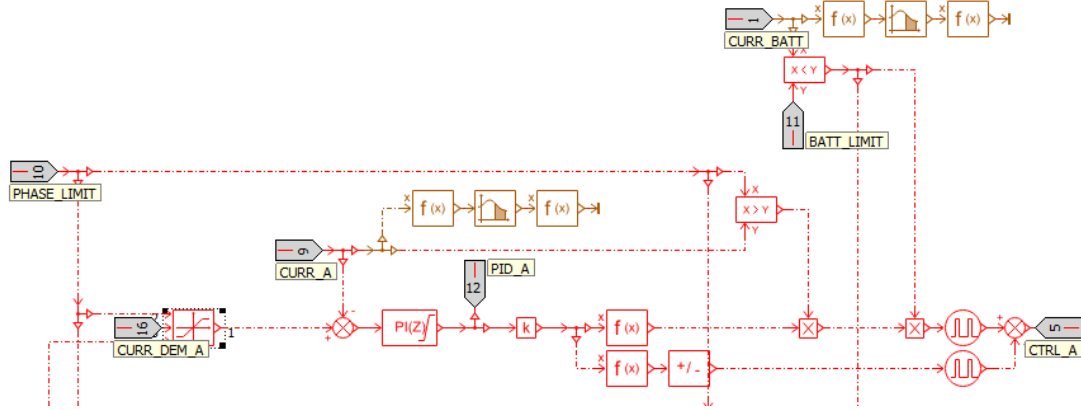


Figure 6.11: One phase of Current PI sub-module.

ing PI controller by Hannoun, Hilaiet and Marchand (2011) or optimal angles calculation by Hamouda and Számel (2017); Hamouda and Szamel (2018), are not well suited to be used for this application. Due to the small size of the motor, self-inductance is small, while saliency is high, therefore control variables computed (specifically current demand) are very high, according to (2.17). Coupled with relatively low voltage and limited current capacity, this makes the control solution unachievable, resulting in sub-par performance. More success was found with adaptive control, such as state-switching control (Lukic & Emadi, 2010), but no parameters that would grant sufficiently high performance could be found.

6.3 Parametrisation

The above sections describe the overall structure of the simulator and the models used. However, to ensure high accuracy of the results, multiple parameters were measured based on the real parts. As will be shown, in some cases the differences were sizeable.

6.3.1 Flux and torque networks

Although flux data was obtained during the design optimisation of the SR motor, as described in Chapter 5, it was based on a 2D model, which was proven to be of low accu-

acy. Therefore, data from a 3D model was used, provided by the company that manufactured the motor. It includes a flux-linkage network $\lambda = f(i, \theta)$ (Figure 6.12a) and torque network $T = f(i, \theta)$ (Figure 6.12b). The raw data was additionally interpolated using splines to increase accuracy (as compared to linear interpolation) and mirrored for along the aligned position to allow it to be used in the Simcenter Amesim software. In addition, the torque network was inverted to obtain $i^* = f(T^*, \theta)$ look-up table (Figure 6.10a) used in the TORQUE_TAB sub-module.

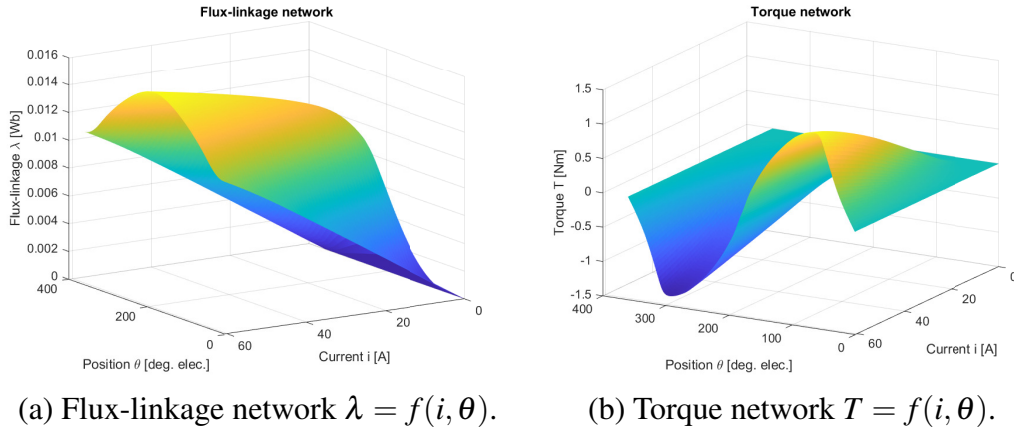


Figure 6.12: Flux-linkage and torque data based on 3D model simulations.

6.3.2 Inertia

In the application, an 18-inch propeller is used, which although lightweight, has considerable inertia due to its size. However, the inertia of the motor's rotor and shaft also needs to be considered due to their high relative weight. Initially, the APC 18x5.5MR propeller was to be used and its inertia (about the shaft axis) was estimated based on the diameter as the average between rod and disc model (Hepperle, 2018; Szafranski, Czyba & Blachuta, 2014):

$$I_{rod} = \frac{2}{3} m_{propeller} R^2 = 0.0021 \text{ kg.m}^2, \quad (6.6)$$

$$I_{disc} = \frac{1}{2} m_{propeller} R^2 = 0.0016 \text{ kg.m}^2, \quad (6.7)$$

$$I_{propeller} = \frac{I_{rod} + I_{disc}}{2} = 0.0019 \text{ kg.m}^2, \quad (6.8)$$

where I is inertia, $m_{propeller}$ is the propeller mass of 60.95 g and R is the propeller radius of $18 \text{ inch}/2 = 0.2286 \text{ m}$. The inertia of motor's rotor was read from MRVSIM software output during optimisation process as $1.5125 \times 10^{-5} \text{ kg.m}^2$, while the inertia of an aluminium disc fitting the rotor's opening ($4.0361 \times 10^{-7} \text{ kg.m}^2$) was assumed as the inertia of the shaft. This data confirms that the propeller is the main contributor to inertia.

As described in Section 6.1, the propeller used for testing is T-motor P18x6.1. Its inertia was measured using a trifilar pendulum (Cooper & Titchener, 2013) constructed using 3D-printed elements and braided fishing line, as shown in Figure 6.13. By ensuring high ratio of line length to the platform radius, the motion can be simplified to that of two dimensions, thus object's inertia is given by the equation:

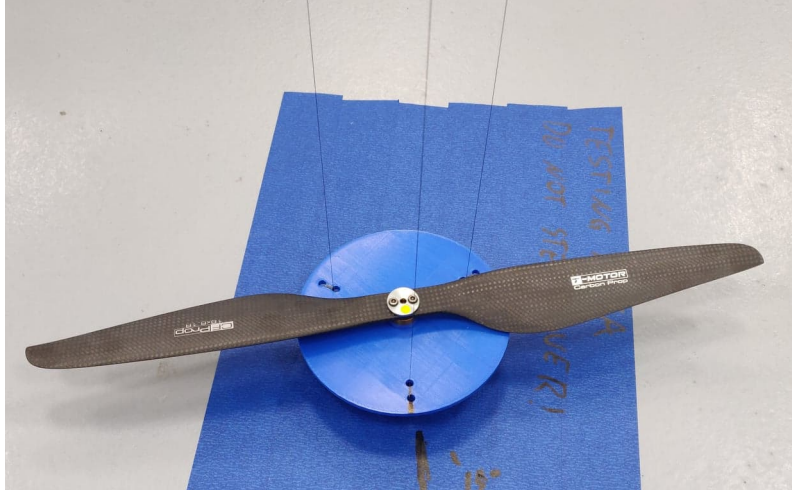
$$I_{object} = \frac{r^2 g \tau}{4\pi^2 L} (m_{platform} + m_{object}) - I_{platform}, \quad (6.9)$$

where r is the distance from the centre of the platform, g is the gravitational acceleration, τ is the period of oscillation, L is the length of the strings. First the measurements were done for an empty platform to obtain $I_{platform}$ and then they were repeated with propeller attached. The same procedure was used for the motor's rotor and shaft assembly. The data of the experiments is summarised in Table 6.1. Due to manual measurement of oscillation period, multiple measurements were taken, thus in the table the average is given.

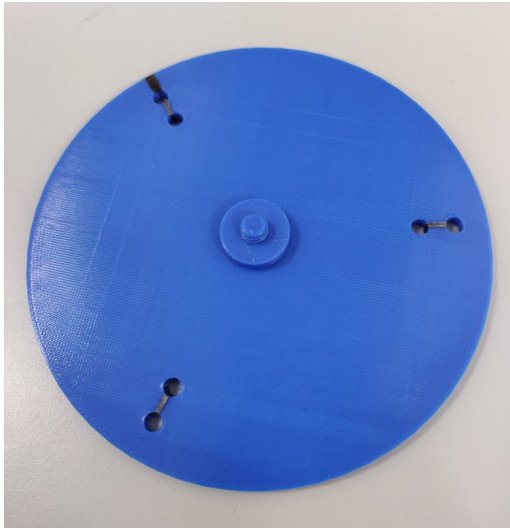
Table 6.1: Summary of parameters and results of the trifilar pendulum experiments.

Experiment	Propeller	Rotor
L [cm]	301	293
r [cm]	5	5
g [m/s^2]	9.81	9.81
$m_{platform}$ [g]	39.5	52.1
$\tau_{platform}$ [s]	3.36	3.39
$I_{platform}$ [kg.m^2]	9.226×10^{-5}	1.272×10^{-4}
m_{object} [g]	38.7	160.5
τ_{object} [s]	5.50	1.83
I_{object} [kg.m^2]	3.956×10^{-4}	2.337×10^{-5}

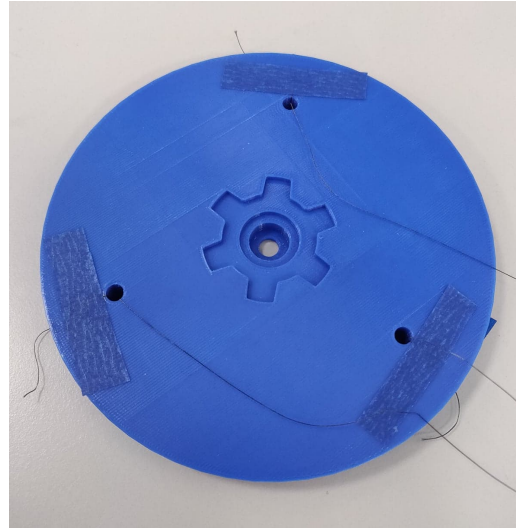
As is shown, the real propeller's inertia is almost 5 times lower, what can be attributed



(a) Experiment setup.



(b) Propeller spinning platform.



(c) Rotor spinning platform.

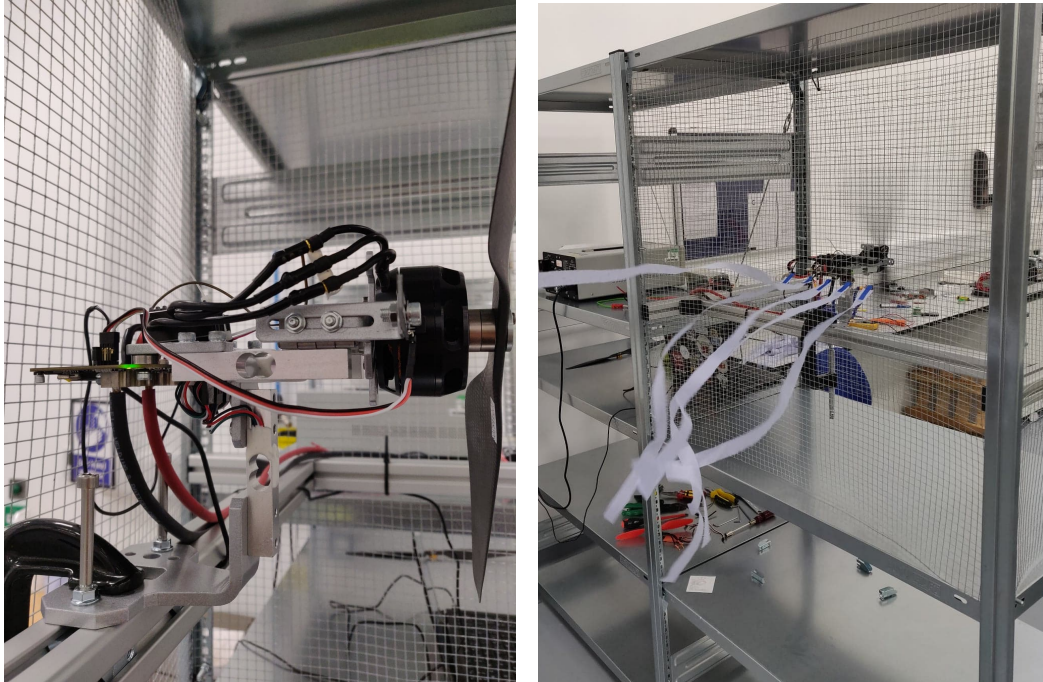
Figure 6.13: Trifilar pendulum experiment setup and spinning platforms.

to greatly reduced weight and different profiling of the blade. While the rotor inertia is about 1.5 times higher, the inertia of the whole assembly is still much lower than initially estimated, which will contribute to better dynamic response of the actuator.

6.3.3 Propeller data

The test-bench used in this study is the RCbenchmark Series 1585 Test Stand (Tyto Robotics, 2022), shown in Figure 6.14a. It features a vertical load cell for measuring thrust and two horizontal ones for differential measurement of thrust. The test-bench is housed

in a safety enclosure, shown in Figure 6.14b, to protect against shrapnel in case of propeller breaking during high-speed operation. The test-bench is controlled from a PC using attached software that also allows for data acquisition and programming of automated test scenarios. The motor is powered with 6S 12000 mAh battery of the demonstrator drone.



(a) Test-bench with mounted BLDC actuator system. (b) Test-bench in safety enclosure during operation.

Figure 6.14: RCbenchmark Series 1585 test-bench.

Propeller data was gathered by running it with the reference motor in a series of steps, as shown in Figure 6.15. At each step the motor waits 3 s for the speed to settle and each measurement is averaged from 20 samples. Data of the 6 passes is then averaged at each input value and split into individual curves for use in the simulator.

6.3.4 Friction

By far, most of the load torque comes from the propeller, but the friction component cannot be ignored. There are three types of friction modelled:

- stiction - effective only at zero speed,

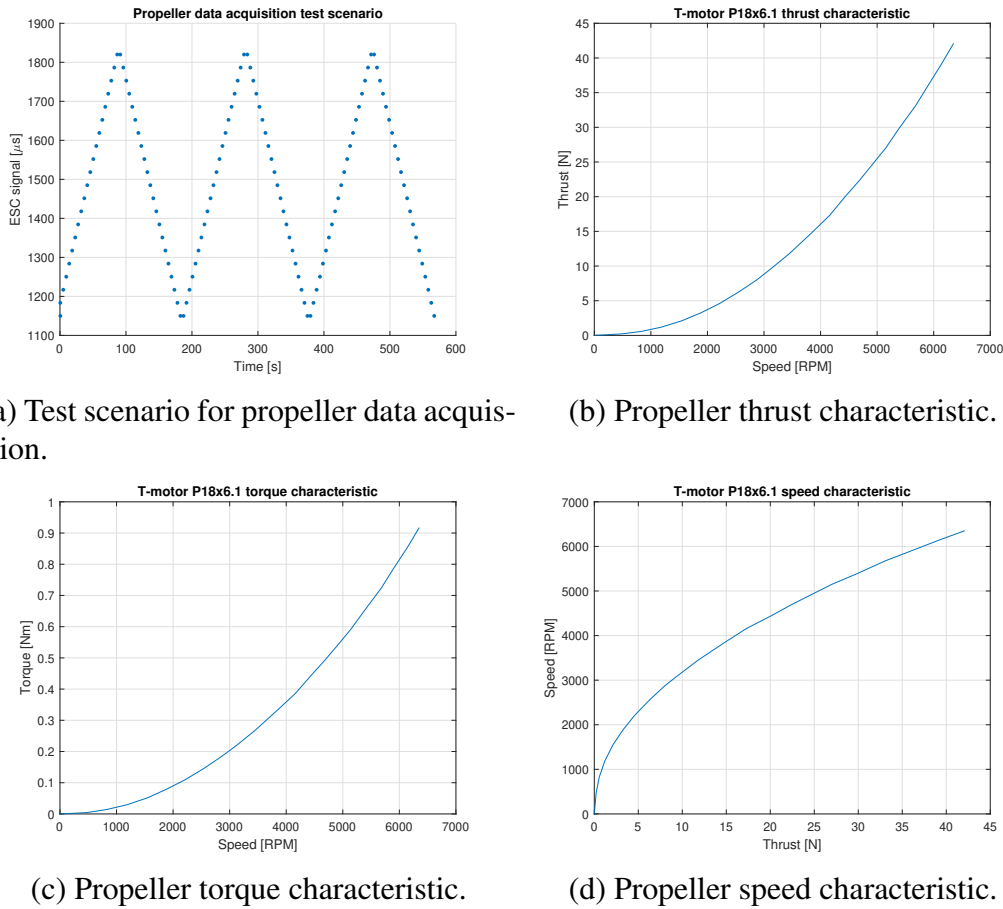


Figure 6.15: Propeller measurement scenario and data.

- Coulomb friction - constant, from bearings,
- viscous friction - dependent on speed, mainly due to windage.

Due to low influence on the results, stiction is given the value of Coulomb friction and largely ignored in the discussion. The other two types can be measured, but time constraints did not make it possible to measure it in the SR motor. Therefore, values from the reference BLDC are used. Coulomb friction is thought to be similar between the motors (due to coming from bearings), but viscous friction most likely would be higher in the SR motor due to rotor shape.

Friction is measured by running the motor without the propeller (as the main source of load torque) and measuring torque. In the test, a similar scenario to that of Figure 6.15a was used. The results are shown in Figure 6.16. The data points form two parallel lines

indicating clear distinction between the Coulomb and viscous friction. Linear regression was used to compute the equations for these lines:

$$T_{positive} = 0.004296 + 2.837 \times 10^{-7} \omega, \quad (6.10)$$

$$T_{negative} = -0.005541 + 3.809 \times 10^{-7} \omega. \quad (6.11)$$

Thus, the friction values were calculated averaging the parameters:

$$F_{Coulomb} = \frac{0.004296 + |-0.005541|}{2} = 0.004919 \text{ Nm} \approx 0.005 \text{ Nm}, \quad (6.12)$$

$$\eta = \frac{2.837 + 3.809}{2} \times 10^{-7} = 3.323 \times 10^{-7} \text{ Nm/RPM}, \quad (6.13)$$

where, $F_{Coulomb}$ is Coulomb friction torque and η is viscous friction torque coefficient.

Therefore, the viscous friction, although visibly present, does not contribute much within the analysed speed range.

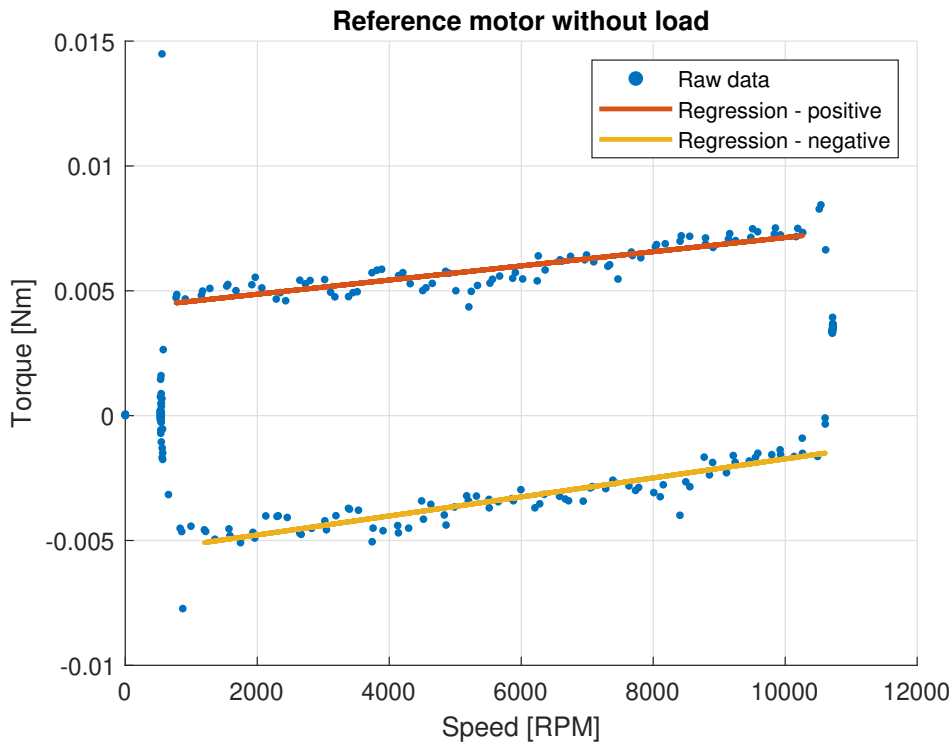


Figure 6.16: Results of a reference motor without propeller.

6.3.5 Winding resistance

An advantage of RCbenchmark Series 1585 over Series 1585 is the ability to measure winding resistance. Three different coils were measured giving the results of $0.1941\ \Omega$, $0.1972\ \Omega$ and $0.1980\ \Omega$, which was then averaged to the final value of $0.1964\ \Omega$.

During the SR motor design process winding resistance was estimated based on coil volume, copper resistance and fill factor. The value was calculated as $0.0579\ \Omega$. This shows a considerable error, which might be assigned to the length of cable used for connection to the power stage, partially visible in Figure 5.18. However, it was decided against removing the cable, as this situation would be possible with certain air vehicle designs. Moreover, this arrangement serves as a pessimistic scenario, making the performance results applicable to a wider selection of situations.

6.3.6 Conduction angles

Conduction angles for the whole speed range were computed alongside the SR motor optimisation process. These can be seen, alongside the expected torque, in Figure 5.21. Conduction angles provided by the manufacturing company were also tested, but because of the low number of data points, the loss of accuracy due to linear interpolation resulted in worse performance.

6.4 SR power stage and controller

To emulate the convenience of the ESC unit of conventional BLDC-based actuating chains, a similar integrated unit has been envisioned for the SR motor system. There are two possible approaches to the controller:

1. FPGA unit - more expensive, but powerful enough to control 2 or 4 motors simultaneously,
2. microcontroller - cheap, but a separate one is required for each motor.

The second approach was chosen due to price consideration and the ease of programming. C2000 Piccolo TMS320F28004C (Texas Instruments, 2021) microcontroller was chosen as the target hardware because of 100 MHz processor speed, 16-channel enhanced PWM system, native encoder support and the availability of a development board. With it in mind, a preliminary system schematic was drafted, as shown in the Appendix D. It features four independent asymmetric bridge converter legs, connected to the controller. Additional connectors for the power source, converter, encode and programmer/debugger module are also included. There were two main challenges identified with manufacture of such unit:

1. providing sufficient heat dissipation for the components when subjected to high current ($\approx 35 \text{ A}_{\text{r.m.s.}}$),
2. finding MOSFET transistors with sufficient rating for handling 60 A peak current.

For the ground testing, however, it is possible to build a prototype power stage and controller unit from off-the-shelf components and without the regard for weight. Apart from the previously mentioned microcontroller, it uses two 2-channel Sabertooth 2x60 H-bridge units (Dimension Engineering, 2011) and four ACS756 current sensor modules (Allegro MicroSystems Inc., 2011).

As a Digital Model, it is imperative that the actuating system simulator represented the tested configuration exactly. That is why it possesses some limitations (most notably in terms of MOSFET switching frequency being limited to 24 kHz) that come from the prototype power stage. However, these limitations are considered to be overcome in case of a fit-to-fly device.

6.5 Summary

This chapter covers three distinct areas: SR motor actuating system simulator, SR motor control solution and obtaining parameters for simulation, as well as a short part on the

design of a physical motor controller component and its considerations. It was shown that the simulator has been constructed as true-to-life as reasonably possible and great care was put into gathering data from manufactured components. Therefore, the simulation results presented in the next chapter can be treated with a high degree of confidence.

Chapter 7

Actuating System Validation

Although Chapter 4 already included some simulation results, these were only to analyse the motor design. Although quite complex, the models included only kinematics of the motor, so simulations of vehicle acceleration were not possible. Similarly, Chapter 2 mentioned possible fault-tolerance benefits, but these were never quantified in regards to the application. Therefore, this chapter will focus on simulating the whole actuating system using dynamic models, to provide an in-depth look at healthy and faulty behaviour. This will complete the third research objective. In addition, the simulation results will be compared with those of a reference actuating system using conventional technology (measured on a test-bench), to achieve the fifth research objective.

7.1 Performance

In a multirotor actuating system, during operation, there is one main desired output variable - thrust. Although torque difference is also used for yaw control. The propeller links thrust to speed to torque with a set of simple characteristics. In this context, the analysis of performance is simple - how well the actuating system tracks the input thrust demand. However, multiple other aspects of the actuating chain will also be looked at to better understand them. Still, thrust is the main focus.

As a testing scenario, three thrust demand levels are considered with ramp change

between them. In terms of raw signal sent from ESC this is done in eight steps:

1. 20% $\rightarrow$ 50% over 0.5 s,
2. 50% for 1 s,
3. 50% $\rightarrow$ 80% over 0.5 s,
4. 80% for 1 s,
5. 80% $\rightarrow$ 50% over 0.5 s,
6. 50% for 1 s,
7. 50% $\rightarrow$ 20% over 0.5 s,
8. 20% for 1 s.

The use of 20% and 80% inputs instead of 0% and 100% is due to the used pre-scaling of input signal, which results in 20% being close to 0% in the conditioned signal and 80% is around the limit of measured thrust characteristic used in the control system. Both raw and conditioned input signals are shown in Figure 7.1 along with resultant thrust profile. Thrust reference is a value directly calculated based on input profile, while thrust output comes from the simulated actuating system.

Figure 7.1 shows the input profile being followed relatively closely. There is a visible overshoot at $t = 0.5$ s when reaching the 50% level, but it is not present at $t = 2$ s when reaching 80% level. This shows that **the damping ratio of the system changes depending on speed**. Changing the type of response from underdamped to overdamped is caused by **high nonlinearity of the system** (due to magnetic saturation) **and variable torque constant**. This is confirmed by Figure 7.2a, which shows that during the second acceleration torque gradually drops (which does not happen during start-up acceleration). In addition, this figure also shows considerable torque ripple, which does not seem to be prominent in the thrust response thanks to the inertia of the propeller. Relatively high inertia is also the cause of a delay in slowing down to zero (4.5 - 6 s) - there is no negative

torque that could assist in the speed braking of the rotor. This, however, is not a problem in the actual application, as the rotors do not slow down that much during operation.

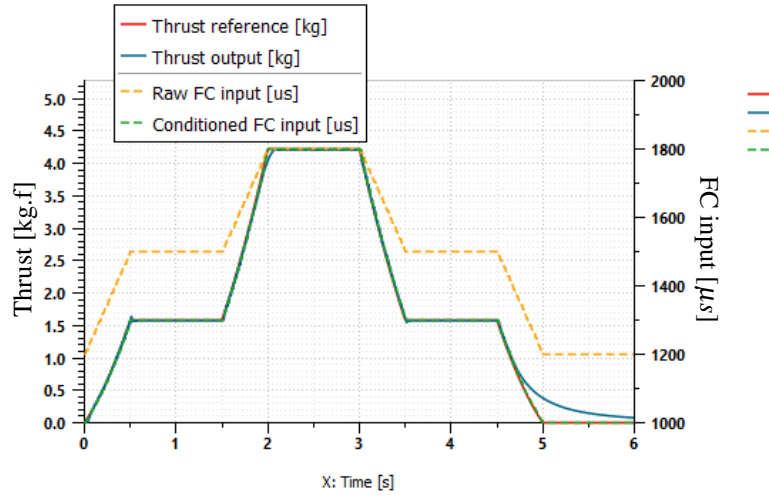


Figure 7.1: Thrust profile of scenario 1.

The torque ripple was analysed with a Fast Fourier Transform (FFT) to investigate the possibility of resonance, as shown in Figure 7.2. Three peaks are visible when operating at constant speeds (50% and 80% levels) and the start-up. They are reasonably close to those calculated in Section 5.3.1 and shown in Figure 5.4. The difference in value comes mainly from different speeds used in calculations and simulation. Still, these are well below harmonic frequencies shown in Figure 5.24.

The speed profile roughly follows the thrust demand, as shown in Figure 7.3. But during acceleration and deceleration periods the waveform becomes non-linear to compensate for the parabolic characteristic of propeller thrust.

The controller used in this study is composed of cascade control loops with speed PI and current PI controllers. As shown in Figure 7.4, the torque demand from speed PI is split between phases using a torque sharing function described in Section 6.2. These signals are then converted into current demand and fed into current PI that produces control solution in terms of voltage. This is shown in Figure 7.5. At low speeds during startup current is almost exactly following the demand profile, but as speed increases the rise time of current in the winding becomes more and more pronounced, and not all of it is being

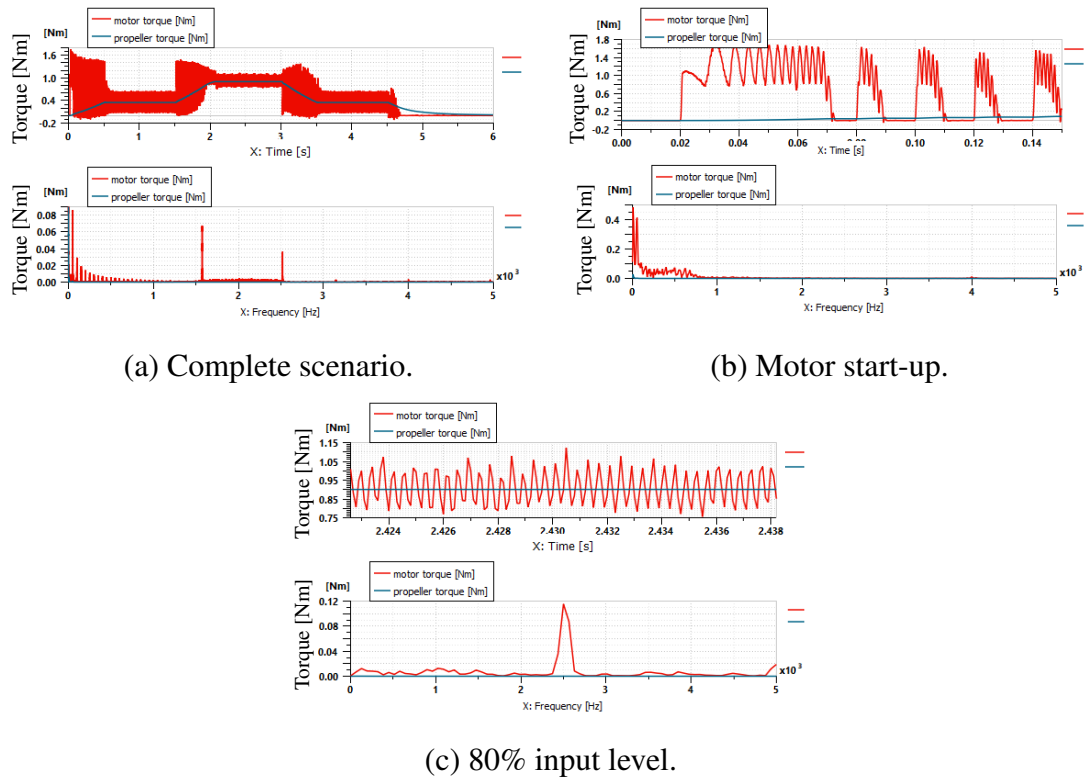


Figure 7.2: Torque profiles of scenario 1.

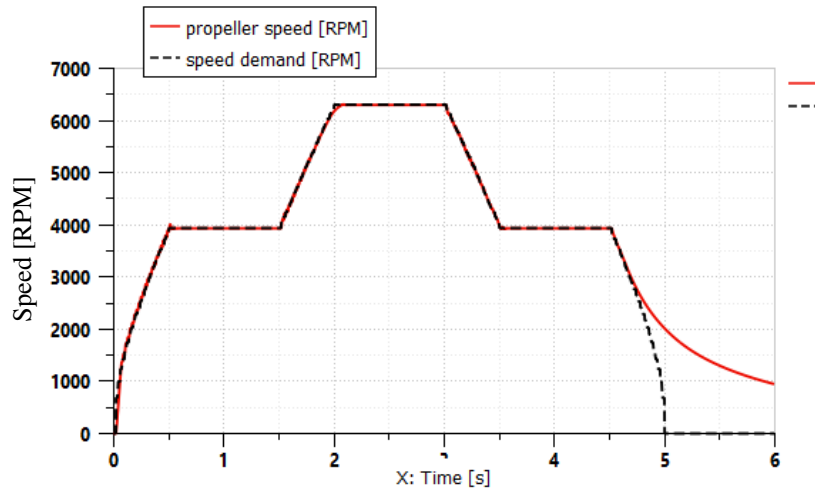


Figure 7.3: Speed profile of scenario 1.

used for energy conversion (increasing losses). Because of it, at maximum speed (Figure 7.5c) the current cannot be brought down to zero resulting in continuous conduction and even higher losses. This is due to the increased resistance of real motor winding and cable. Therefore, it might be possible to reduce it with optimised conduction angles (in

this work the angles were not changed when updating resistance value).

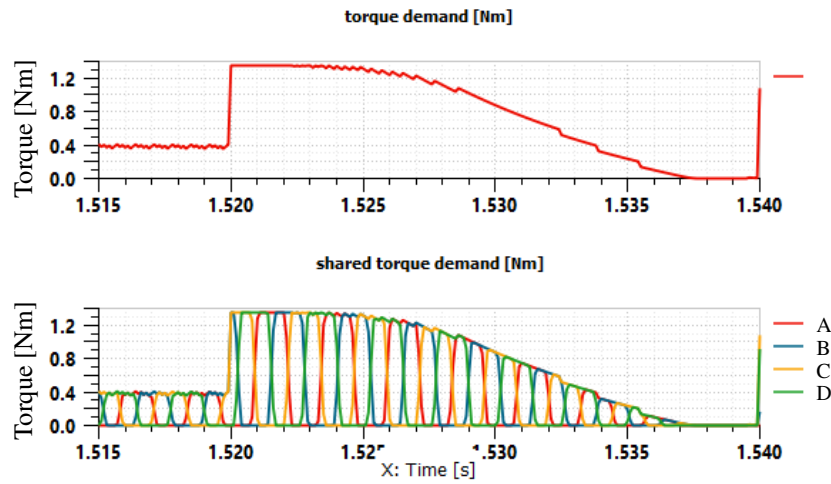
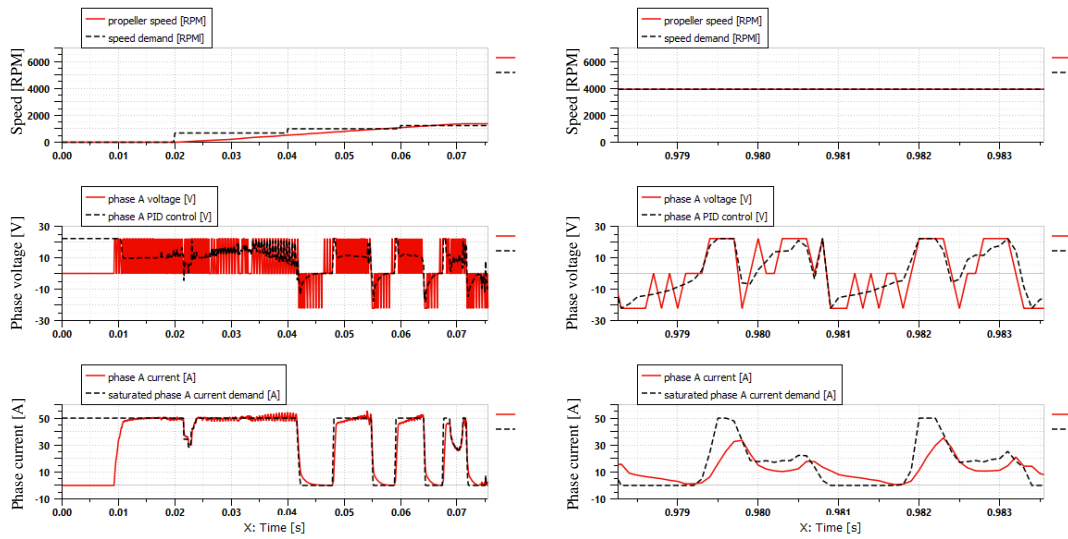


Figure 7.4: Torque sharing in scenario 1.

The continuous conduction region is especially visible in the current graph shown in Figure 7.6. It also shows that the r.m.s. current of one phase does not exceed $35 A_{r.m.s.}$ for one phase and $60 A_{r.m.s.}$. The high battery current at the beginning is a computational artefact due to the charging of the DC-link capacitor - it is due to the way the simulation is initialised. These values are crucial when designing a power stage for the actuating system.

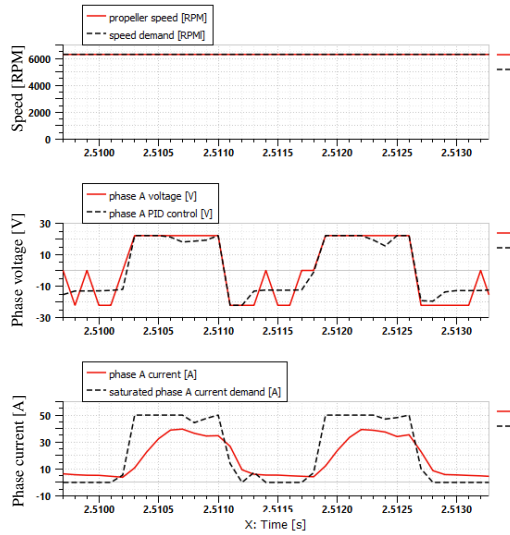
Two other scenarios were simulated to better showcase the capabilities of the system. The one shown in Figure 7.7a is a set of 3 pulses of 80% thrust value and the other is a manual control input gathered during test-bench testing. Although the thrust never drops to zero, the actuating system follows the input in Figure 7.7a consistently. More interesting are the results of scenario 3, which are directly compared to BLDC motor measured data. Both systems follow the input signal reasonably well, with slightly higher accuracy of SR motor system. However, at a very high output level, SR motor actuator gets saturated because of insufficient range of the speed-thrust characteristic used in the controller. This is shown in Figure 7.7c and can easily be remedied by measuring the characteristic anew on a test bench that supports higher output.

Finally, each component was weighted to compare it with a redundant BLDC system.



(a) Motor start-up.

(b) 50% input level.



(c) 80% input level.

Figure 7.5: Control strategy of scenario 1.

Such setup used two T-motor P18x6.1 propellers at 39 g each, two U7-V2.0 KV420 motors at 296 g each (including cables) and two FLAME 80A 12S V2.0 ESCs at 109 g each. This results in 888 g or 670 g excluding ESC. A single SR motor system weighs:

- motor rotor with shaft and adaptor: 161 g
- stator with cable: 611 g
- stator without cable (estimated): 275 g

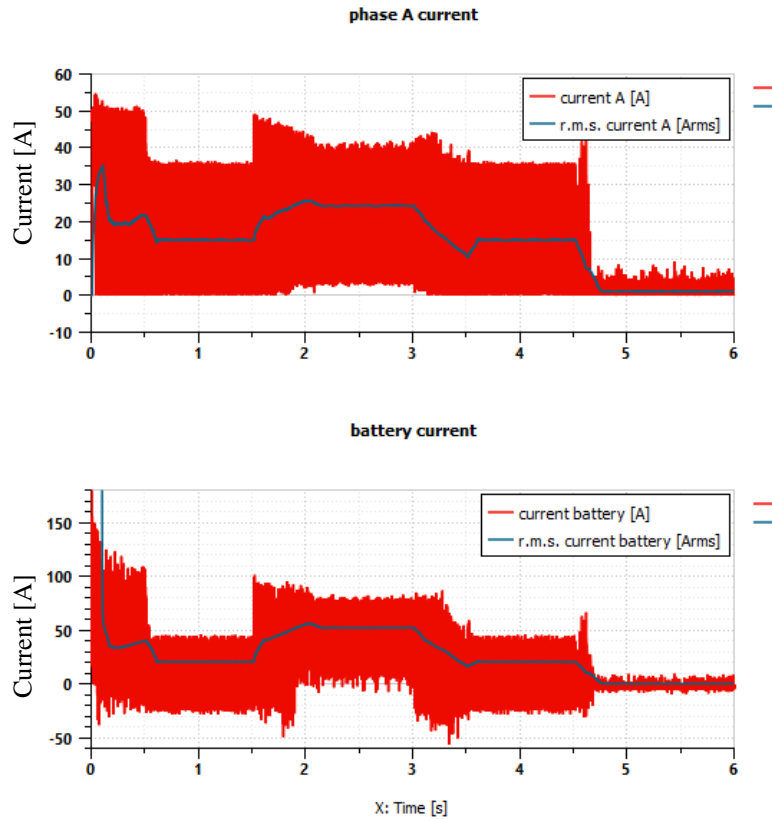


Figure 7.6: Current profile of scenario 1.

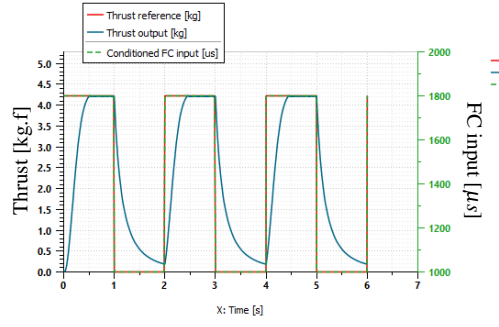
- casing and mounting elements: 126 g

Which gives the total mass (using stator without cable estimate) of 601g, which is just under that of reference BLDC system. In this case the controller and power stage unit would need to weigh at most 287 g to make such a vehicle feasible.

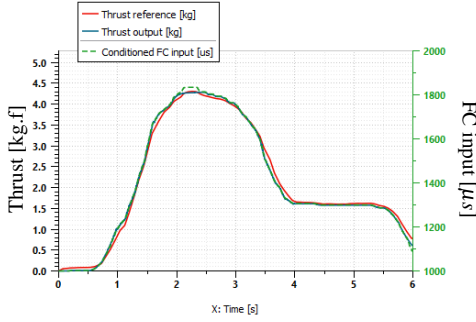
7.2 Fault-tolerance

In Section 2.2.1 it was mentioned that loss of effectiveness (LOE) is a common approximation of an actuating system fault. Even complete loss of the actuating system can be modelled as a 100% loss of effectiveness. Previously mentioned publications show multiple control schemes that deal with faults of this kind.

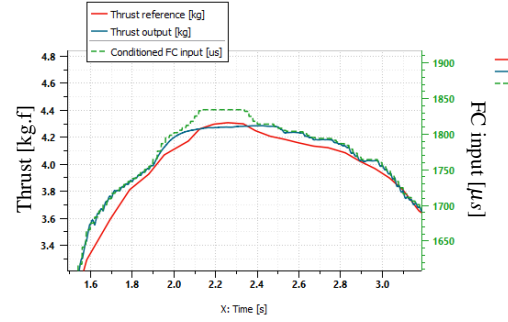
This section investigates different faults and uncertainties in regards to the loss of effectiveness, to allow the integration of the (presumably fault-tolerant) SR motor actu-



(a) Scenario 2.



(b) Scenario 3.



(c) Scenario 3.

Figure 7.7: Torque profiles of scenarios 2 and 3.

ating system with fault-tolerant control schemes to improve overall safety. However, as percentage-based effectiveness score is a metric static in its nature (difference of output at steady state), additional ways to assess the dynamic performance are also provided.

7.2.1 Uncertainties

Uncertainty is a pretty broad term encompassing any unknowns in the system, whether internal or external. In this study, uncertainties specifically relate to unknowns or disturbances present in the system at startup ($t = 0^-$). Thus closely related with the state of the system.

Most uncertainties are modelled simply as percentage-based error of specific variable in the system:

$$x_i = x_{i0} \times \left(1 + \frac{d_i\%}{100\%} \right), \quad (7.1)$$

where x_i and x_{i_0} are real and base values of i^{th} variable (or parameter) and d_i is the error value for this variable. Delays and offsets are simply added to the variable. However, to better emulate real application, signal noise is of normal distribution with variance given as:

$$\sigma^2 = \left(\frac{d_i\%}{100\%} \times \frac{x_{i_{\max}}}{3} \right)^2, \quad (7.2)$$

where $i_{\max}$ is the highest value of the signal. Thus, d_i denotes what percentage of signal range corresponds to 3σ .

The convention used in this study is that the error value of $d_i = 0$ always means that no specific uncertainty is present (perfect knowledge). The parameter d_i can have only positive (e.g. intensiveness of noise) or both positive and negative values. Table 7.1 summarises outcomes of the study as the highest uncertainty magnitudes granting no change or maximum 5% loss of effectiveness. The term ‘n/a’ is used to denote that the negative error values were not investigated while ‘-’ means that no loss of effectiveness was observed in the analysed domain.

Uncertainty study was carried out in a set of 1-second simulations where the system started from still ($\omega = 0$) and at $t = 0$ step input corresponding to $T^* = 4.224$ kg.f is introduced. Effectiveness is denoted as the ratio between thrust T and thrust demand at $t = 0.99$ s, expressed in percent:

$$\text{Effectiveness} = \frac{T}{T^*} \times 100\%.$$

Response time is defined as the time in seconds required for the thrust T to converge within 5% of its value at $t = 1$ s.

Although the FC signal is the input to the system (and the system should try and follow whatever this input is) the LOE due to noise is not as drastic as might be expected. That is most likely to relatively high inertia of the propeller damping the noise. However, as shown in Figure 7.8, at values above 60% the data becomes more scattered and less

Table 7.1: Summary of uncertainty analysis study.

Component	type	negative error value		positive error value	
		5% bound	0% bound	0% bound	5% bound
FC	noise	n/a	n/a	1%	11%
Phase A curr. sensor	delay	n/a	n/a	8×10^{-5} s	8×10^{-5} s
All phases curr. sensors	delay	n/a	n/a	8×10^{-5} s	8×10^{-5} s
	offset	-10 A	-6 A	2 A	5 A
	noise	n/a	n/a	20%	36%
SR motor	initial pos. offset	-18°	-10°	10°	16°
	friction coeff.	n/a	n/a	2000%	5000%
	wind. resistance	-	-	11%	29%
Propeller	inertia	-	-	-	-
	torque	-	-	5%	13%
	thrust	-4%	0%	-	-
	torque & thrust	-4%	0%	-	-
Encoder	gain	-0.010	-0.004	0.004	0.010
	noise	n/a	n/a	3%	5%
	initial pos. offset	-2°	-1°	1°	3°
	sampling period	n/a	n/a	$10^{0.8}$ s	$10^{1.1}$ s
	resolution	-	-	-	-
Battery curr. sensor	noise	n/a	n/a	-	-
Battery	voltage	-6%	-2%	-	-

reliable.

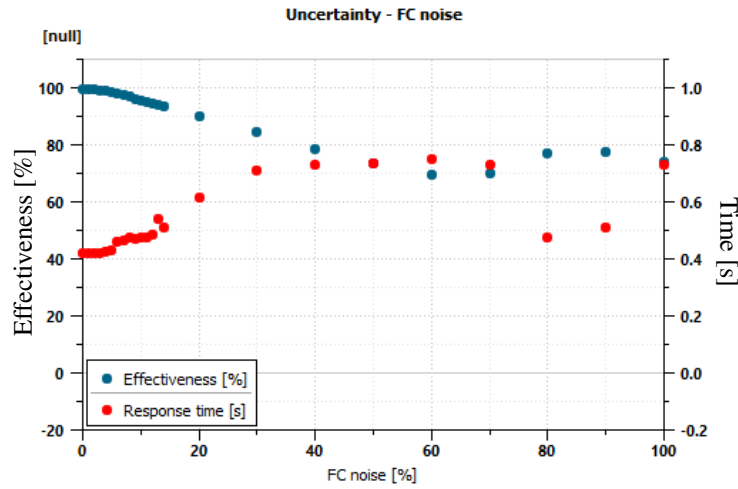


Figure 7.8: Analysis of uncertainties in FC - noise.

The base signal delay of phase current sensor is 5×10^{-6} s. As shown in Figures 7.9 and 7.10a, this can be increased by a further 8×10^{-5} s (equal to about 3° mech. at 6300 RPM) without any change in output parameters. However, signal delay above this value results in simulation not finishing, most likely due to phase current exceeding the flux network range and the system not being fast enough to limit it - the software is not able to calculate results for points outside the flux network look-up table.

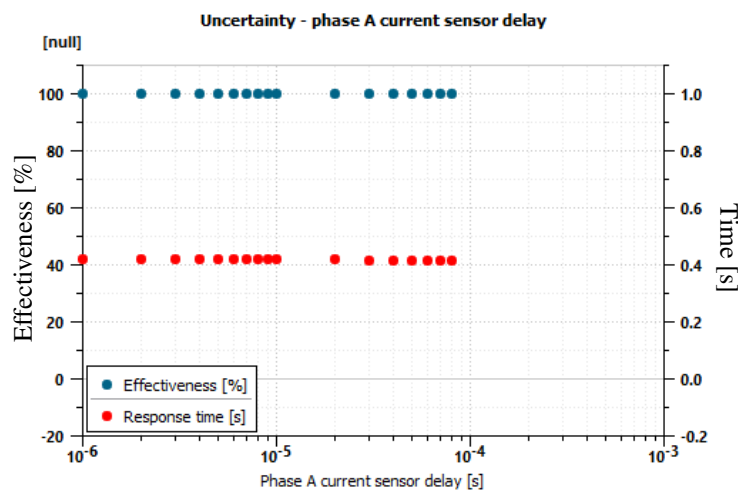
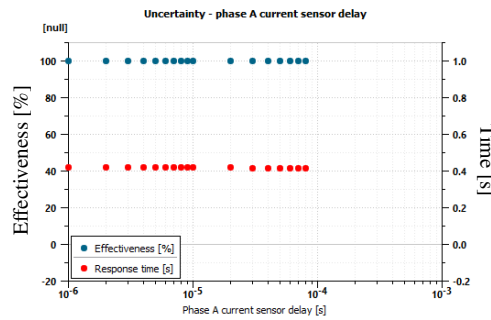


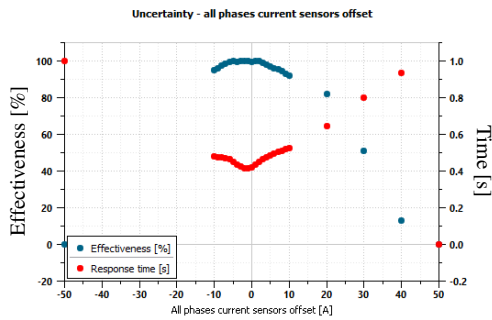
Figure 7.9: Analysis of uncertainties in phase A current sensor - delay.

For positive offset values Figure 7.10b is predictable - due to the sensor offset (or

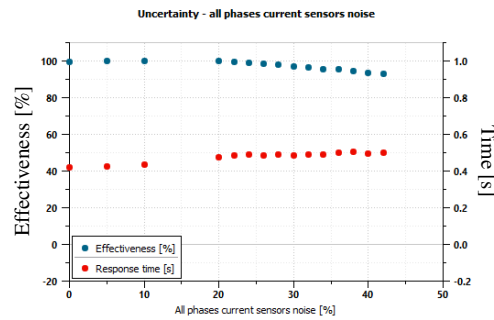
constant bias), the demand value is reached for lower real current, therefore storing less energy in the field and resulting in close-to-linear drop in effectiveness and system response time. Although mathematically it would make sense for the left side to be the mirror of the right side (current never reaching zero, reducing energy conversion area), it is more non-linear, especially in the efficiency case. This is most likely due to the small energy conversion area increase due to current higher than demanded, but limited by non-linear saturation. In addition, for high magnitude negative error values the simulation does not complete, for the same reasons as in high delay. The edge cases of 50 A and -50 A represent the edge cases of always conducting or not conducting at all and can be ignored, as these are also modelled as faults.



(a) Delay.



(b) Offset.



(c) Noise.

Figure 7.10: Analysis of uncertainties in current sensors of all phases.

Similar as in the case of FC, phase current sensor noise also does not seem to affect performance much, as shown in Figure 7.10c. However, in this case it is high frequency (100 kHz), thus outside of system's bandwidth.

Figure 7.11a shows high susceptibility to rotor position error, here modelled as an

offset on the motor side (encoder still starts at zero). This is to be expected, as torque production scheme is heavily dependent on induction, which is dependent on rotor position, as described in Section 2.4.1. What is interesting is that the LOE is not symmetrical about zero error value. Response time also has some sort of plateau for low negative values, but with rapid decrease of effectiveness it is of limited use.

The viscous friction coefficient has much lower value than Coulomb friction, therefore even multiplication by 1000 does not affect the effectiveness or response time, as shown in Figure 7.11b. Pushing it even further does eventually bring LOE up, but it can be safely assumed that the friction due to windage does not affect performance of a real motor. It may be also possible to accommodate certain bearing faults or wear & tear without compromising the ability to operate.

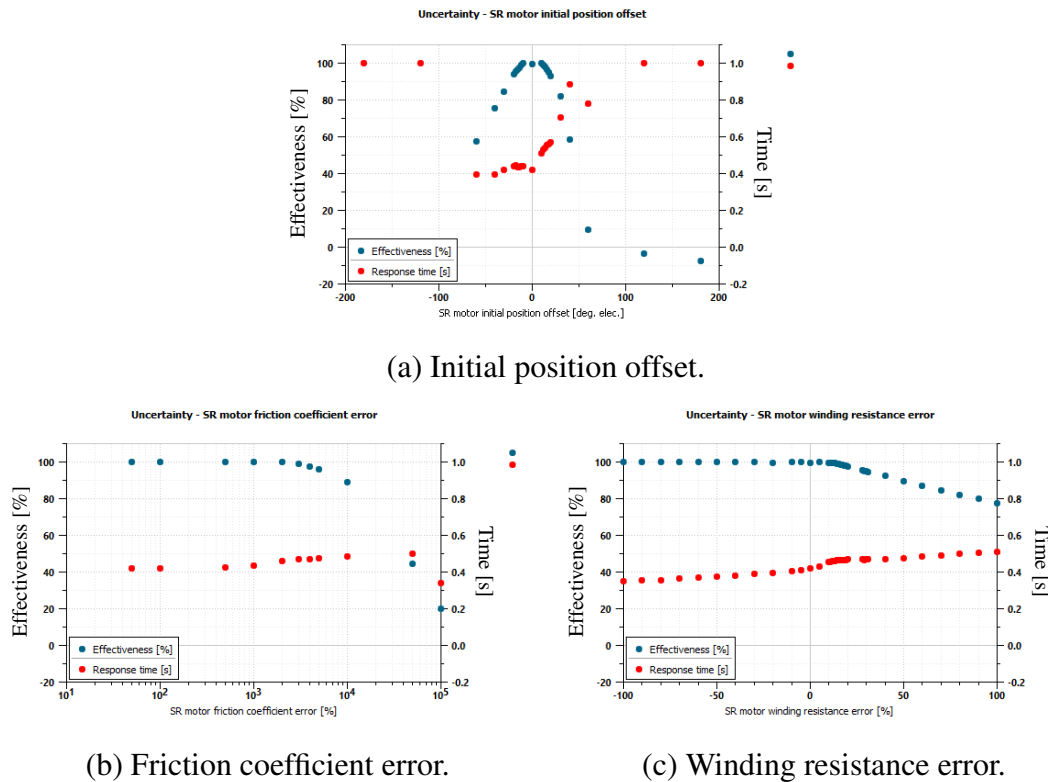


Figure 7.11: Analysis of uncertainties in SR motor.

Figure 7.11c for negative error values is self-explanatory - lowering winding resistance barely affects the ability to produce thrust (but affects copper losses and motor efficiency). However, it also shows that the resistance can still be slightly increased until

it starts affecting effectiveness. This is important, as the motor was designed with much lower resistance in mind, as explained in Section 6.3.

Inertia is not a factor during steady state, therefore it does not affect effectiveness, as shown in Figure 7.12a, while the response time linearly increases with the error value, which is to be expected. Figure 7.12b, similar to the case of the winding resistance error, shows that there is a small tolerance when it comes to increasing torque. Also similar is the fact that propeller characteristics have changed since motor design stage.

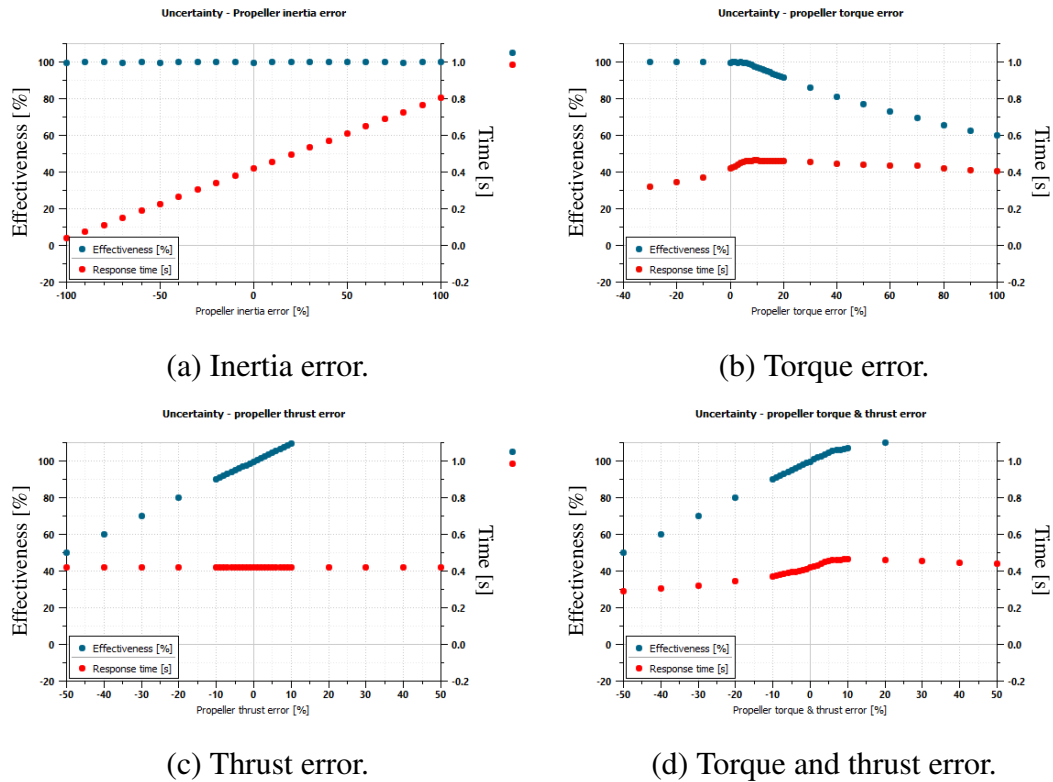


Figure 7.12: Analysis of uncertainties in propeller.

Among those is the $\omega = f(T^*)$ characteristic which is used in the speed PI controller and therefore not subject to error. Therefore, improvement in thrust characteristic shown in Figure 7.12c is unaccounted for in the motor controller. However, in real application there is another control loop present, as previously shown in Figure 4.2. Thanks to this, improvements in effectiveness are still beneficial. This is the case in Figure 7.12d, where increase in both torque and thrust (as would be the case in a real propeller, e.g. when switching to one with higher pitch) increases efficiency while only slightly altering re-

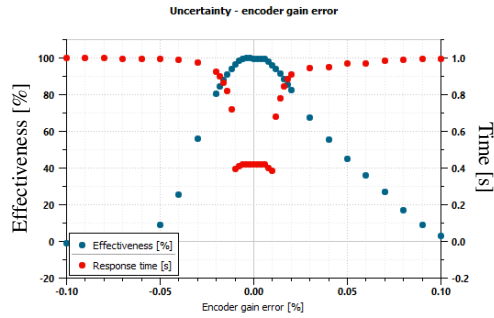
sponse time.

The signal gain is very sensitive to uncertainties, as shown in Figure 7.13a. This is to the multiplicative nature of the uncertainty, therefore the longer the motor operates, the higher the error value gets. This can be (partially) solved with an additional of obtaining position or resetting the position with every evolution. This is a feature of Heidenhain ERN 1020 acquired for the test-bench, but has not been modelled in the simulator. Similarly, Figures 7.13b and 7.13c show sensitivity to other types of uncertainties. In addition, Figure 7.13c is of similar shape as Figure 7.11a, but the use of mechanical angle shows the periodical nature of the characteristic.

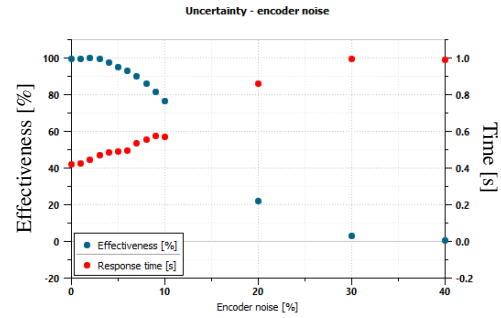
Some degree of tolerance is found in terms of the sampling period, in the form of gradual decrease of effectiveness, as shown in Figure 7.13d. The drop in response time is due to lower steady state thrust value, therefore being quicker to reach. However, what is surprising, is the fact that neither effectiveness nor response time is affected by changes in encoder resolution (with default being 2048), as shown in Figure 7.13e. Of course the value of -100 resulted in simulation not finishing, as it would equal the line count of zero.

Finally, as the battery current sensor is used only as a safety measure - limiting the current draw - its impact on the performance is low. Therefore, it can be considered to be unaffected by the signal noise, which is confirmed by Figure 7.14a. However, Figure 7.14b shows that used value of voltage of 22.2 V is very close to the limit of expected performance. Full battery (with higher voltage) can bring slight improvement in response time, while overdischarge (lower voltage) or old battery (higher internal resistance) results in gradually lower effectiveness, which need to be accounted for during maintenance.

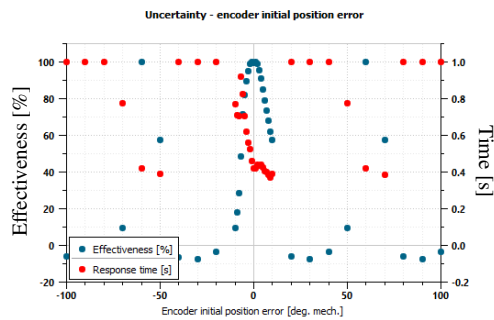
In this section numerous actuating system components were analysed in terms of sensitivity to uncertainties - deviations from baseline parameters due to improper calibration, ageing or external disturbances. This definition allows for severity of the uncertainties to be quantified and (usually) expressed as a percentage. Especially the position sensor is susceptible to this type of errors. Worth noting is the relatively low impact of friction coefficient error and winding resistance error. Overall, the actuating system should be



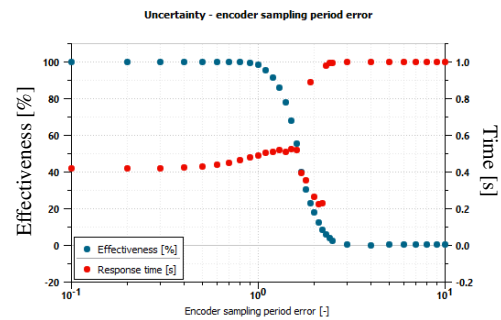
(a) Signal gain error.



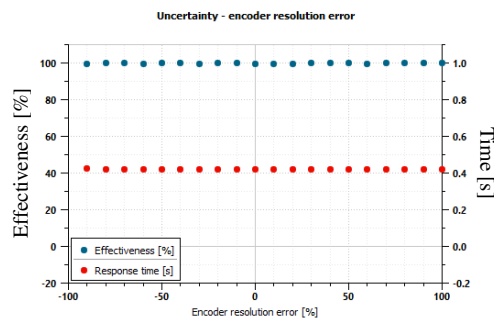
(b) Noise.



(c) Initial position offset.



(d) Sampling period error.



(e) Resolution error.

Figure 7.13: Analysis of uncertainties in incremental encoder.

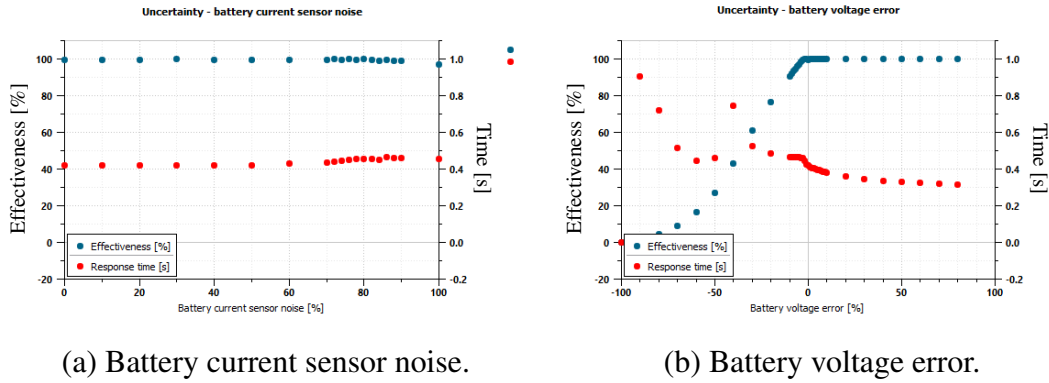


Figure 7.14: Analysis of uncertainties in battery system.

able to accommodate the tiny variances in manufactured components.

7.2.2 Faults

The faults in this section can be divided into two types: sensor faults and winding circuit faults. Sensor faults can be further divided into:

- zero signal,
- maximum signal,
- random signal,

where random signal just send a series of random values (limited by maximal and minimal sensor outputs) based on uniform distribution to emulate any other type of fault. Circuit faults are modelled mainly as open phase faults but for the battery also short circuit and arcing faults (short circuit for % of total time). Short circuit faults in motor phases (within the phase, between different phases) could not be achieved due to numerical solver used in Simcenter Amesim. Algebraic loops are created, which cannot be handled when using a fixed-step simulation.

The output of the study is the Loss of Efficiency (LOE) metric, defined as:

$$\text{LOE} = \frac{(T_{ref} - T)|_{t_{fault}+t_{recover}}}{T_{ref}|_{t_{fault}+t_{recover}}} \times 100\%, \quad (7.3)$$

where T is the output thrust, T_{ref} is the reference thrust demand, t_{fault} is the time of fault injection and $t_{recover}$ is the expected recovery time, set to 0.49 s. The faults are injected at three different times, $t_{fault} = 0$ s, $t_{fault} = 1$ s and $t_{fault} = 2.5$ s to investigate the behaviour at different speed levels (due to the nonlinearity mentioned in Section 7.1) and at start-up acceleration. The results are summarised in Table 7.2.

Table 7.2: Summary of fault simulation studies at start-up and stable conditions.

Component	Fault	0% thrust LOE	50% thrust LOE	100% thrust LOE
FC	zero value	100%	78%	87%
	max. value	-172%	-170%	-1%
	random signal	50%	77%	90%
Phase A current sensor	zero value	fail	fail	fail
	max. value	0.48%	43%	15%
	random signal	fail	0.48%	0.58%
All phases current sensors	zero value	fail	fail	fail
	maximum value	100%	78%	87%
	random signal	fail	fail	11%
Phase A	open circuit (high side)	0.33%	0.40%	15%
	open circuit (low side)	0.47%	0.42%	15%
Phases A&B	open circuit	3%	0.56%	39%
Phases A&C	open circuit	3%	0.43%	39%
Phases A&B&C	open circuit	56%	18%	63%
Encoder	zero value	101%	82%	89%
	max. value	101%	82%	90%
	random signal	100%	99%	99%
Battery current sensor	zero value	-1%	0.44%	0.22%
	max. value	100%	77%	87%
	random signal	-1%	0.44%	0.23%
Battery	open circuit	100%	68%	84%
	closed circuit	fail	fail	fail
	5% arcing	fail	fail	fail
DC-link capa- citor	open circuit	-1%	0.44%	0.22%

Although FC is not a sensor, the faults that might affect its signal are similar. Even though it is not part of the actuator on the topological level, as shown in Figure 7.15, its faults greatly affect the produced torque. In the case of zero and maximum signal, the

result is pretty obvious with no or highest allowed thrust as the output. However, it is interesting to see that a fully random signal causes the output to stabilise at a seemingly random value and even switch the steady state levels as in the case of fault injection at $t_{fault} = 0$ s. This is most likely due to the integral component of speed PI controller.

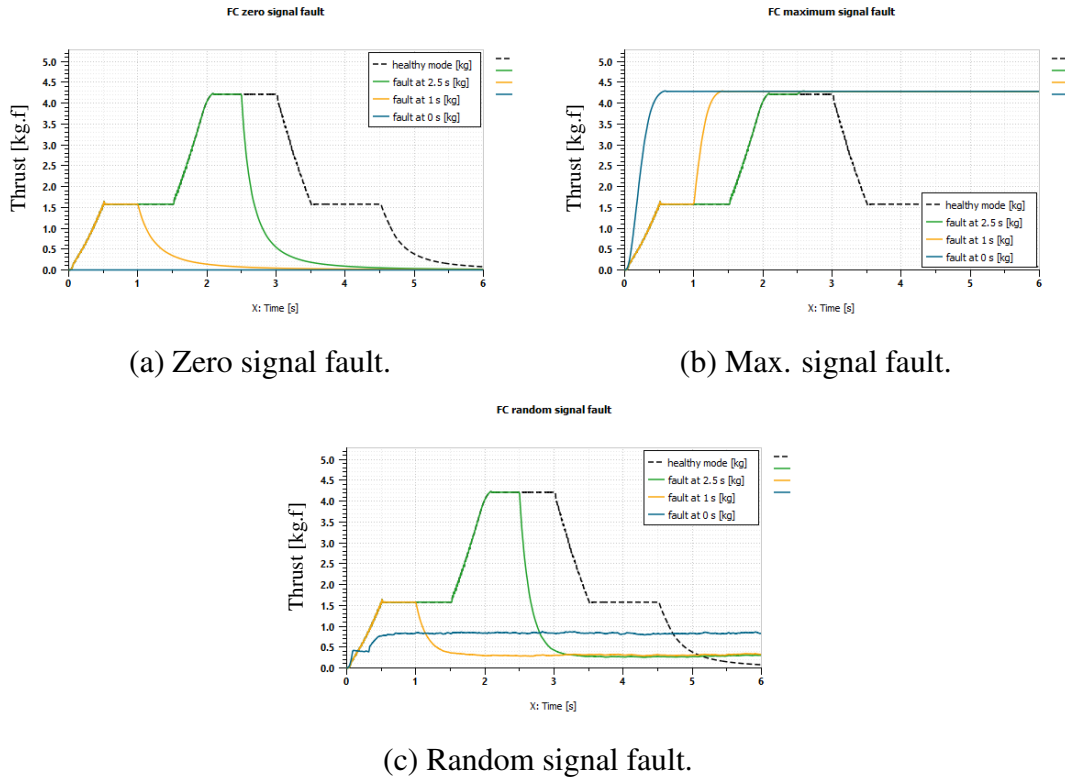


Figure 7.15: Analysis of FC faults.

Zero output of a single current sensor causes the simulation to stop due to the current value being too high, as shown in Figure 7.16. However, maximum current sensor signal tricks the controller into outputting current reducing signal. This makes that phase behave exactly like an open circuit fault (Figure 7.18b). This is important, as it shows, that no other currents are induced in this phase, eliminating the risk to other components. In addition, the recovery from the fault is very quick when injected at $t_{fault} = 0$ s (<0.1 s) and almost instantaneous when injected at $t_{fault} = 1$ s (improvement over (Tursini et al., 2017)). It seems that the only adverse effect of a loss of a single phase is limiting the thrust value to a certain level. Therefore, it is recommended to set up the current sensing system that loss of power (or other similar faults) results in sending maximum value of

a signal, to protect against overcurrent. Unfortunately, random signal fault results in an unexpected behaviour with two of the simulations failing and one completing only with slight noise in the thrust.

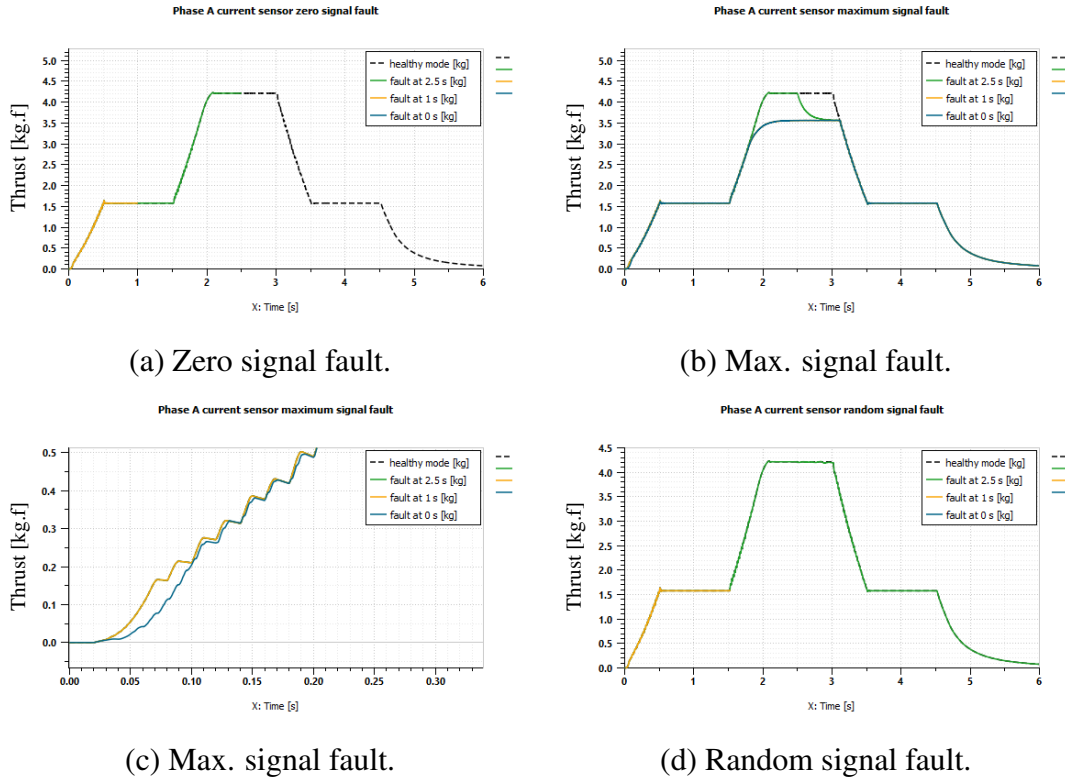


Figure 7.16: Analysis of phase A current sensor faults.

When applying current sensor faults to all phases (Figure 7.17), results for zero and random signals are repeated. However, fault-tolerance in case of maximum signal is lost, as now all phases behave like an open circuit fault, thus the motor is not supplied with any current and cannot operate.

There is a slight difference in LOE between open circuit fault on the high or low side of the converter, so this distinction is not kept for other simulations. The other characteristics of such fault were already described. However, in case of open circuit faults in multiple phases, not only maximum torque drops, but also the response time increases, which is well shown in Figure 7.19c. However, the resulting LOE in case of a loss of phase does not correspond to $25\% \times \text{thenumberoflostphases}$, but is considerably lower, as shown by (Castellini et al., 2016). This shows that the other phases can easily share part of the load.

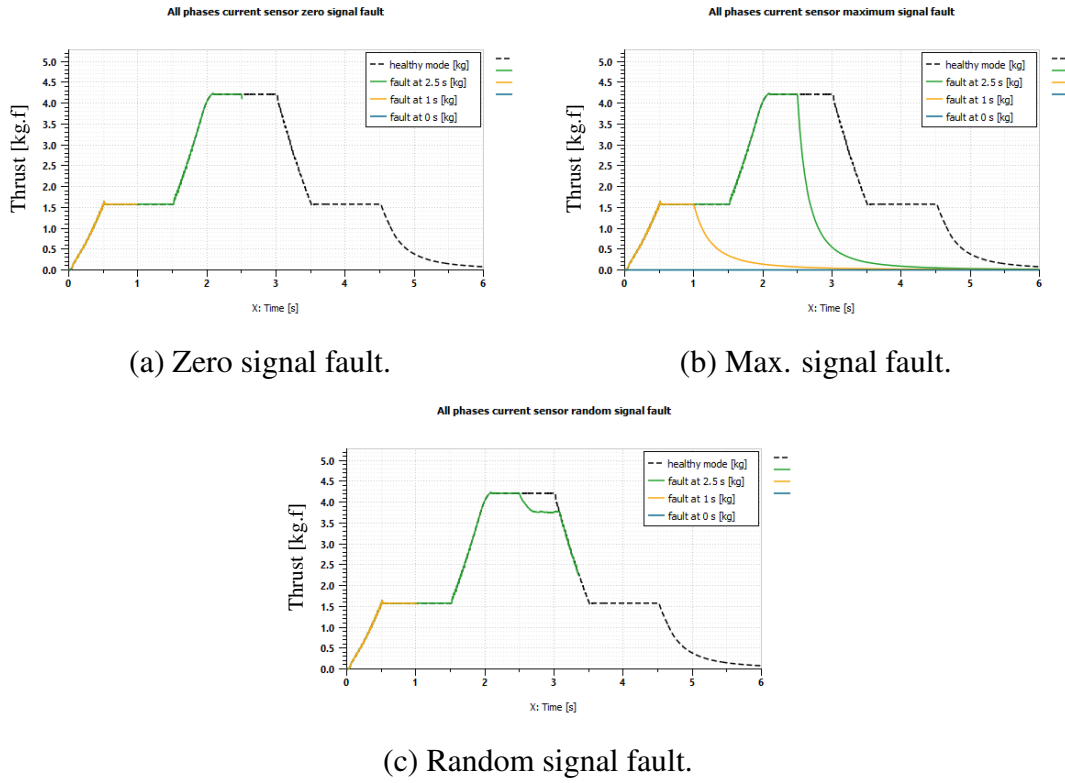
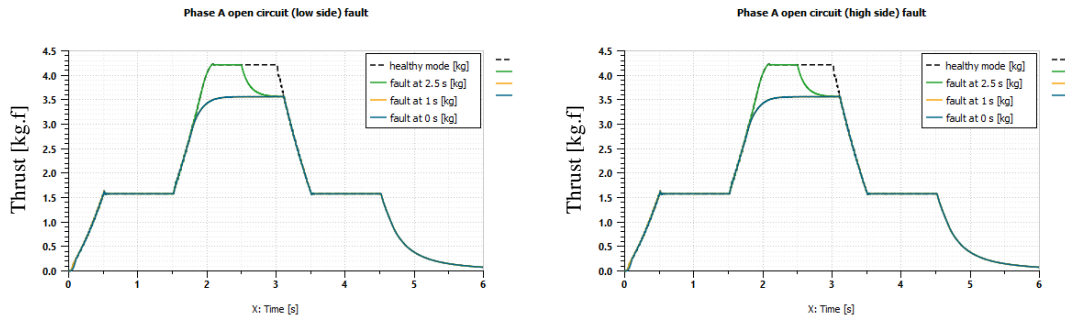


Figure 7.17: Analysis of all phases current sensor faults.

This a great benefit in terms of fault-tolerance, especially considering that thrust produced with only two phases conducting is around 2.5 kg level, so it allows for safe hover of the vehicle.

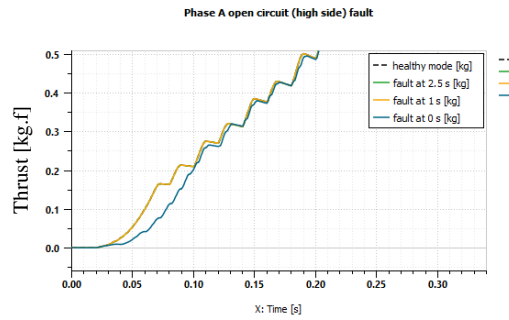
As has already been established in Section 7.2.1, encoder as a position sensor is a very vulnerable to uncertainties or other disruptions to its signal. This is confirmed in Figure 7.20, where each type of fault results in complete loss of effectiveness. Interesting is the fact, that in case of zero and max signal faults, a tiny periodic response is produced, most likely by the rotor teeth oscillating at the aligned position.

Similar to the case of encoder, a conclusion made in Section 7.2.1 is only confirmed here - battery current sensor does not actively take part in the conduction, therefore its faults do not affect the system. The only exception being the maximum signal fault, in which the sensor reports constant overcurrent, so all conduction is stopped until it passes, which in this study does not happen. Furthermore, results of battery fault simulation are also predictable:



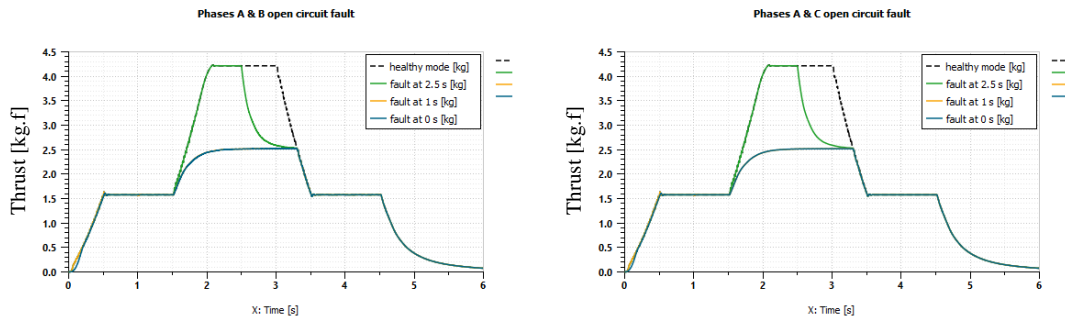
(a) Open circuit fault (low side).

(b) Open circuit fault (high side).



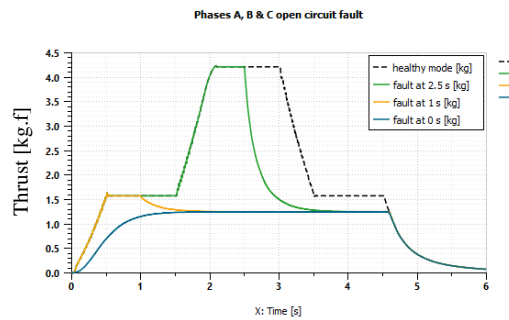
(c) Open circuit fault (high side).

Figure 7.18: Analysis of phase A faults.



(a) Phases A & B.

(b) Phases A & C.



(c) Phases A, B & C.

Figure 7.19: Analysis of multiple phase faults.

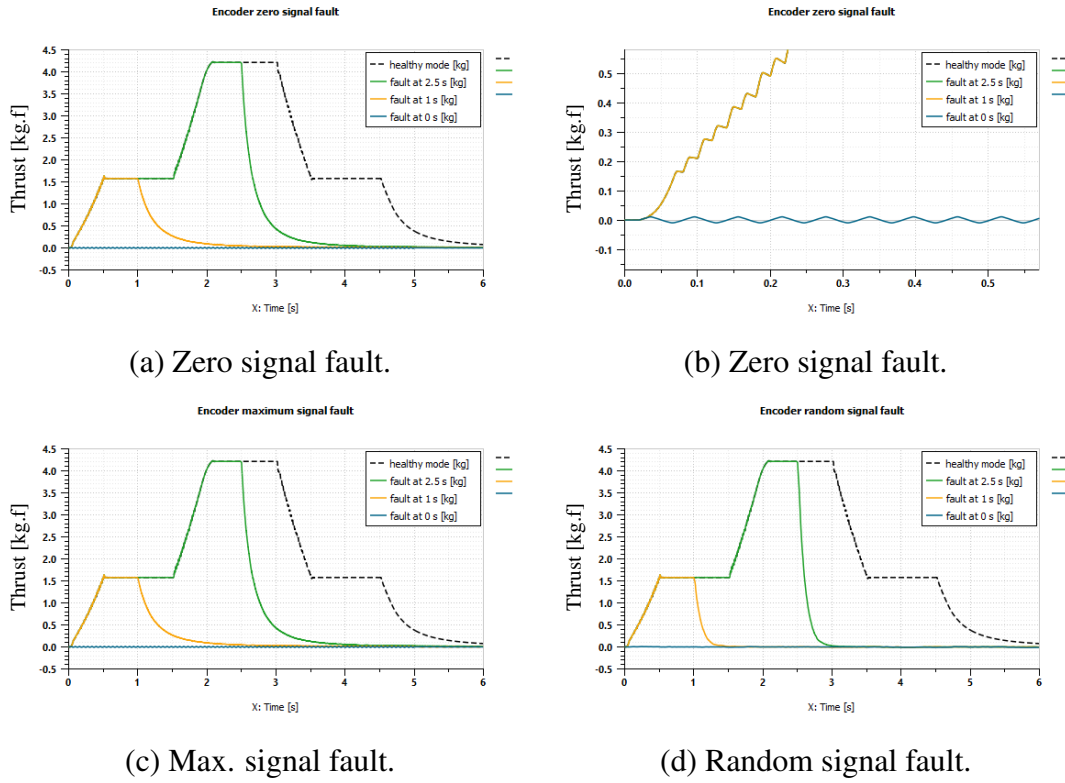


Figure 7.20: Analysis of encoder faults.

- open circuit (disconnecting the battery), stops operation and thrust generation due to the lack of power source,
- short-circuit stops the simulation due to overcurrent, and in real application would most likely lead to combustion,
- arcing (short-circuiting for short instants) also leads to stop of the simulation,
- DC-link capacitor open circuit fault has no effect, as it is mainly used for filtering purposes.

7.3 Comparison with Brushless DC drives

The fault analysis done in this work is sufficient to make a preliminary comparison with the direct competitor - Brushless DC drives. Fu, Liu and Liu (2021) divide possible faults into motor body failures (including winding failure and Hall sensor failure) and controller

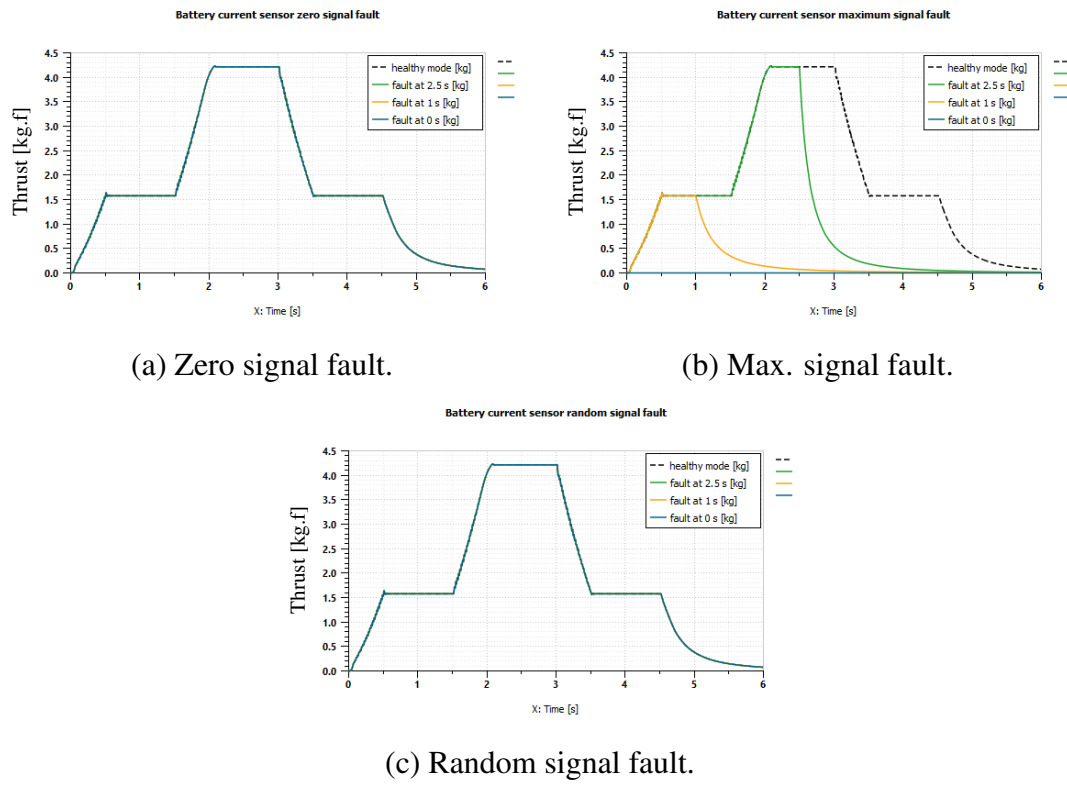


Figure 7.21: Analysis of battery current sensor faults.

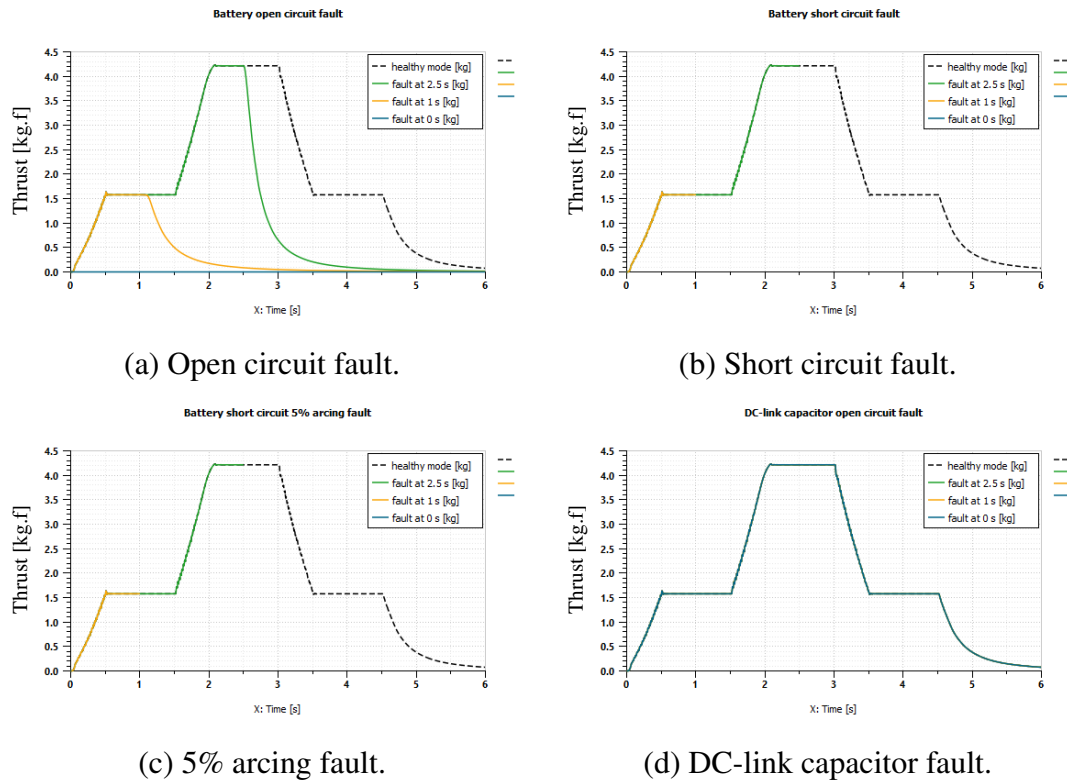


Figure 7.22: Analysis of battery faults.

failures, as shown in Figure 7.23. As this work focuses mainly on motor design, controller faults are not discussed.

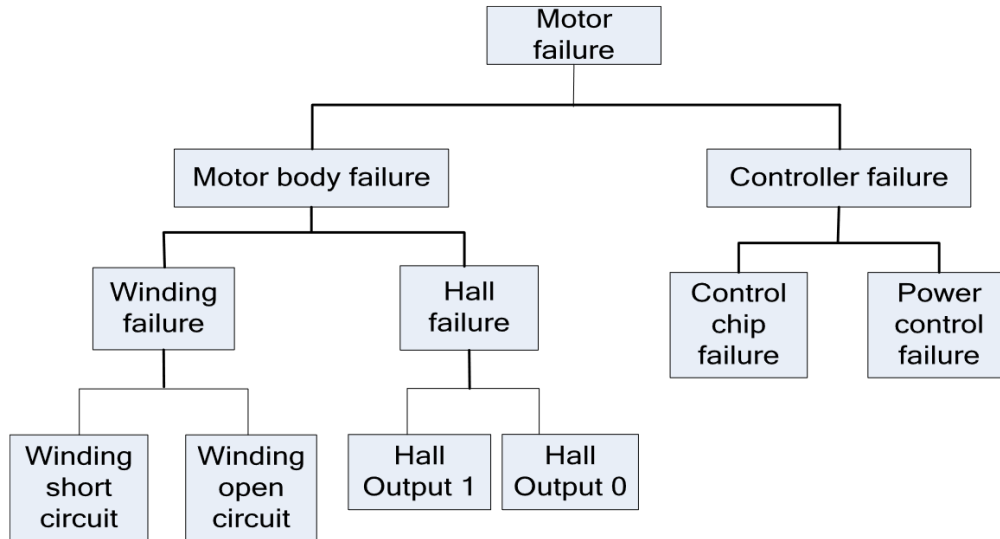


Figure 7.23: Brushless DC motor fault tree (Fu et al., 2021).

For BLDC motors, winding open circuit faults often mean whole drive failure, as the winding is connected in a wye configuration, so any fault results in the loss of at least two out of three phases (He & Yang, 2017; Spée & Wallace, 1990). A specific type of open circuit fault is an open transistor fault (Spée & Wallace, 1990) that results in a ‘ $2^{1/2}$ ’ phase operation that achieves only $2/3$ of torque output of a healthy drive. These types of faults can be protected against using a dual redundancy configuration that combines two 3-phase drive on a shared rotor (Fu et al., 2021) or an additional converter leg (Spée & Wallace, 1990). This approach, however, substantially increases the weight of the assembly, and a similar effect can be achieved with a lower cost by simply using two motors and two propellers. In this context, SR motor drives have an advantage, due to the independence of the phases, the torque capability retained after a fault is much greater, as shown in Table 7.2. Similar configuration of independent phases is also employed in multiphase machines, such as 5-phase brushless drive proposed by Villani, Tursini, Fabri and Castellini (2012). It has been shown, with one phase open, to achieve constant torque equal to that of the healthy mode. Unfortunately, no information on performance in other

operating points was provided.

This work does not analyse short circuit faults, but based on the converter design (asymmetric half-bridge), an argument can be made that SR motor drives are more advantageous in the event of transistor short circuit fault, because there is always a path provided for the circulating current to return to the supply. What is more, the phase is then still capable of operating, although without the ability for providing negative voltage, which may result in phase current never dropping to zero and continuous operation. In typical brushless drive such path is rarely available, therefore mechanisms to shut down the phase must be employed, as it can lead to the generation of uncontrolled braking torque or even a complete short circuit of the supply (Spée & Wallace, 1990).

In addition to the full phase winding failure, inter-winding open and short circuit faults may be also present. The first type can be considered identical to full winding open circuit fault. Inter-winding short circuit faults, however, are studied by Maldonado-Ruelas et al. (2016) who show that this type of fault usually results in reduction of coil turns and resistance. The motor is still able to operate (Taehyung Kim, Hyung-Woo Lee & Sangshin Kwak, 2009) and the decrease in performance can be expressed as LOE metric. Simulation study of this type of faults (or rather uncertainties as they can be of different severity) is recommended for SR motor drive as further work.

In brushless motors Hall sensors serve the role of position sensors, with a sensor dedicated to each phase. Thanks to this, the signal of a faulty sensor can be reliably reconstructed using the data from the other sensors (Q. Zhang & Feng, 2019). The signal can be reconstructed even in the case of two faulty sensors, with only minimal ripple in motor speed (X. Zhang, Lin & Zhao, 2019). SR drives on the other hand rely on a single mechanical sensor, as there are no magnets that can provide the field required for Hall sensors. In addition, the sensor is also vulnerable to faults and uncertainties, as shown in Tables 7.1 and 7.2. This enforces the need for position sensor redundancy in most applications.

One type of fault found in all PM machines (including BLDC) is the permanent mag-

net fault, more commonly known as demagnetisation. These most often happen as a result of high operational temperature, aging, corrosion or improper armature current (Da, Shi & Krishnamurthy, 2011). SR motor drives, as they do not possess any magnets, are free of such risks. Conversely, SR drives require current sensors, which introduce another possible point of failure, but as it was shown in Table 7.1 and Figure 7.16, the drive is resilient to faults and uncertainties of a singular sensor.

7.4 Summary

This chapter confirms the hypotheses formulated during the literature review in Chapter 2 - SR motor has lower power density than permanent magnet machines, requires accurate position sensing system, but is also characterised with high fault-tolerance, especially against open phase faults. In addition, the designed actuating system responds to most uncertainties (especially in current sensors) with gradual decline in effectiveness. Therefore, investigations of Laudensack et al. (2014) are complimented with tangible results. This achieves the third and fifth research objectives and concludes the extent of results of this study.

When comparing with Brushless DC drives, SR motors are advantageous in terms of open circuit faults - torque capacity available after a fault is higher than in BLDC drive. This is true both for open phase and transistor open circuit. There is possible further advantage when dealing with transistor short-circuit fault, but it was not verified in this work. However, BLDC drives possess higher fault-tolerance in regards to position (Hall) sensors, due to multiple sensors being used and the ability to reconstruct signals of faulty sensors. SR motor use only one position sensor, thus are very dependent on accurate measurements, necessitating redundancy. Permanent magnet and current sensor faults cannot be directly compared, as in a typical configuration they are specific to the drive type. The next chapter discusses the contributions and impact from the whole thesis.

Chapter 8

Discussion and Conclusions

8.1 Discussion

The research done for this project and described in this work has shown a process of design and analysis of an actuating system using SR motors and intended for use in multirotor air vehicles. The validation done in Chapter 7 has shown that the designed system has sufficient performance to be used in the application and has excellent fault-tolerance capabilities in terms of open phase and transistor faults. Although it is exceptionally vulnerable to position sensor faults and requires additional reliability measures. However, the main area requiring improvement is the weight of the system (or specifically torque density). Still, the aim of ‘showcasing SR motor actuating systems as a highly fault-tolerant solution with sufficient performance for safety-critical applications’ has been achieved.

The main contribution in this work comes from the design and validation of a complete actuating system for an aerial vehicle using motor technology that has not yet been proven for this application. This includes the design approach, parametric optimisation of the motor, manufactured motor, control solution, digital model simulator, and simulation results (performance and fault injection). In addition, it was shown that the technology and the approach applies to a range of different vehicle sizes and configurations.

Although it has been somewhat alleviated with control, SR motors (and therefore

SR motor actuating systems) are highly non-linear, especially in high-speed high-torque applications like vehicle propulsion. This makes them both hard to design and hard to control. Even their analysis in the context of the whole vehicle is challenging due to non-linear torque constant when using reduced-order models.

SR motors have only a single source of excitation - the stator windings. It is beneficial from the reliability perspective - no induced current in the unpowered winding, but results in low energy conversion ratio. Therefore, to achieve satisfactory torque, a magnetic field of high density needs to be built and then removed. With the low voltage of a battery, this often required high current, thus increasing copper losses, converter components rating and reducing efficiency and power factor. In addition, the build-up of current requires time, that limits maximum speed. These problems are especially pronounced in small machines, and in the case of multirotor applications further increased by the weight constraint.

Therefore, should SR motor actuating systems for multirotors continue to be developed, a more efficient way of building magnetic flux needs to be found. This can be achieved by modifications to the geometry in the form of segmented rotor (shorter flux paths in the SR-SRM), additional stator (DSSRM) or permanent magnets (ferrite or rare-earth) embedded in the stator. Another possibility is the inclusion of an auxiliary coil, as described in (Rain, Krebs & Marchand, 2018). However, these solution, although increasing performance, will compromise some of the advantages of SRM (most likely fault-tolerance and sustainability).

However, the two principles used in the SR motor actuating systems - reluctance torque and independent phases have the potential to transform electric machines of the future. Reluctance torque offers potentially lower losses (no copper in the rotor), but not all field energy is converted into work, which results in lower power factor and larger power stage, while to separate the phases at the motor, converter and control level, special (large) power stages need to be used. Therefore, for now, these benefits could be used only in niche applications. However, modern IPMSMs already take advantage of

reluctance torque by shaping their magnets, in addition to producing reaction torque, and combining these two types of torque may be a promising approach.

Even though it is simple and reliable, the asymmetric bridge converter suffers from the issues described above. Due to the separation of phases, the component count, and therefore weight and cost, is relatively high. However, the most reasonable way of increasing the fault-tolerance of conventional motor's converters is redundancy. Therefore, a single fault-tolerant converter might be comparable to 2 or 3 typical inverters. However, in SR motor converters, the main challenge is the heat dissipation (due to high current, low power factor and low volt-ampere rating) and the added weight of heat sinks. Therefore, increasing the number of MOSFET transistors to divide current (and reduce losses) might be beneficial for real applications. In that case, the 3-phase 12/8 configuration might bring additional fault-tolerance benefits by connecting each pair of coils (or even every coil) to a separate converter, bringing the separation further.

For small machines used in multirotors, PI controllers are simple enough and sufficient. However, the design of high performance control gets complicated, as in optimal control techniques, due to low inductance, the control variable gets much higher than available voltage, thus not achieving the control goals. In addition, the constant magnetisation angle of 180° (2-phase conduction) used in this study, makes it that only the firing position needs to be detected (and commutation angle can be calculated from speed), thus allowing for fault-tolerant techniques on the sensor level. In addition, it protects from torque dips in case of a phase fault.

It is clear that the actuating system presented in this work is not optimised. The intent was not to create the best system possible, but rather to show that SR technology can be used in multirotor air vehicle applications, and what benefits and challenges are tied to it. Even the SR motor optimisation done in Chapter 5 served only to obtain a motor with suitable power/weight ratio. The other components were designed separately (but not independently) for convenience, but enabled by the specific approach structure from Chapter 4. However, to create a system high performance that can be produced

commercially, an approach is needed that would optimise the whole drive together at the same time, due to the strong coupling between the motor, the converter and the control solution. This is a possible area for further research.

In case of multirotor vehicles reliability is of lower concern than fault-tolerance due to the low number of flight hours over the vehicle's lifespan. This is further enforced by rapid advancements of technology and older models becoming quickly obsolete. It has also been shown that possessing a degree of fault-tolerance increases the overall reliability of the vehicle. Therefore, the main focus of multirotors is retaining some degree of control authority in case of a fault (or multiple faults) to allow for safe landing. However, that is not always the case, as due to low cost, in some cases the vehicles can be sacrificed without much loss.

The motor technology is the driving force for actuating system design, that defines what power stage structure and what control is used. Therefore, the chosen motor has the most (but not fully direct) influence on the actuating system performance and behaviour during faults. In addition, as the specific actuating system components are connected in a chain, a fault in any component can reduce or remove the effectiveness of the whole system. This is especially important in case of quadrotor vehicles, where the loss of even one actuating system leg (one rotor) dramatically alters the dynamics of the vehicle. Even if fault-tolerant, adaptive control is used, the control authority over specific degrees of freedom (yaw) is removed. Therefore, there is a benefit in using fault-tolerant actuating systems that, instead of fully failing in case of a fault, gradually reduce their effectiveness.

Tying in with the development of the adaptive control methods, the possible faults and uncertainties are evaluated in terms of loss efficiency (and response / recovery time). This makes it easy to use the data generated in fault-tolerant control studies, or vice versa - based on this system, estimate performance of the whole vehicle during faults. What is more, it shows how a fault-tolerant actuating system can be combined with fault-tolerant control to create a highly resilient and safe vehicle.

Through the sets of simulations in Section 7.2.1, the position sensor has been identi-

fied as the component most sensitive to uncertainties. Therefore, it is highly recommended to adopt redundancy of some kind - whether software (additional sensorless positioning system) or hardware (additional sensors, may be of low resolution). In addition, to help protect against position offset uncertainties, absolute position sensors are preferred.

All of the analysed uncertainties have behaved predictably, following simple curves or even straight lines. Except in the case of delays, increasing the error value gradually decreases effectiveness of the system. Therefore, in case of time-varying uncertainties it allows the control system enough time to react. In addition, SR motor actuating systems have been proven to be generally tolerant towards signal noise, which is one of the more common external disturbances.

Multiple faults have been simulated, but most of them has ended with very obvious results. That being said, fault-tolerance of SR motor actuating systems in case of an open phase fault (or faults) has been validated. Not only the motor is able continue operation almost immediately after the fault, but also with two faulty phases, the produced thrust is enough for hover. This behaviour is also applicable to phase current sensors maximum signal faults, which are recommended to be set up as 'normally closed' (maximum output when unpowered or faulty).

Based on the preliminary comparison of fault-tolerance between BLDC and SR drives, SR technology seems to be more resilient. However, this answer needs to be further quantified with the probability of each type fault occurring in multirotor applications and severity (LOE) measures. Even then, the answer which drive technology is more fault-tolerant would not be complete, as fault-tolerant control systems, signal reconstruction algorithms and redundancy approach also need to be taken into account. But providing data on these drives, as this work does, is one of the steps that need to be taken to finding the answer.

In summary, multirotor air vehicles are proven to be a very challenging application. However, the designed SR motor actuating system has both reached satisfactory performance and high degree of fault-tolerance. When combined with fault-tolerant control, it

may result in a highly resilient and safe vehicle. Although the current level of SR technology cannot compete with BLDC or PMSM in this application, it is worth investigating the principles of reluctance torque and phase independence and their application to other electrical machines. However, SR actuating systems may be of interest for eVTOLs, as the weight constraints are somewhat more relaxed. The benefits of fault-tolerance and the gradual decrease of efficiency with increasing uncertainties is much more important, as there are passengers on board.

8.2 Conclusions

The developments in the electric vehicle area, motivated by the efforts to reduce emissions and increase sustainability, are transforming the transport industry. One of the outcomes of these changes is the increased interest in multirotor air vehicles. Small, unmanned vehicles are popular in the consumer sector for recreation, sport or aerial photography. Slightly larger variants are used for package delivery or in agriculture. There are even vehicles able to carry passengers being developed, to address the needs of Urban Air Mobility. However, in all of these cases high degree of safety is desired, as the vehicle itself is unstable and faults in actuators can lead to changes in vehicle dynamics. To address this, this work investigated a multirotor air vehicle actuating system using switched reluctance motors.

A pre-study was conducted that sized a conventional multirotor vehicle using a simple methodology using component databases. In it, the actuating system is treated as a dynamical model and the flow of information is reversed to obtain the sizing method. In addition, based on the sized system, flight time is calculated. The results show a sufficient accuracy against hover time values of popular off-the-shelf vehicles, especially for such a simple method. Therefore, this approach was generalised and extended to be used with motors of any type and to support the design process of a custom motor.

Based on a set of sized vehicles, a complimentary SR motor is optimised. The op-

timisation method minimises focuses on motor torque while imposing the constraints of motor weight and current density. DIRECT algorithm is used with MRVSIM software for calculation of motor flux network and performance, while the final design is additionally investigated in terms of thermal properties. Both optimised designs and the whole of generated geometries are analysed in terms of influence of optimisation parameters and the resulting performance. One motor was chosen to manufactured, but when analysed using 3D models (as opposed to 2D models of optimisation process), the performance was found to be lower than anticipated due to the influence of end windings and 3rd dimension flux leakage. Therefore, additional methods were investigated to mitigate these effects with manual modification of geometry being the chosen approach.

Along the optimisation and development of the motor, a digital model was built. It was used to develop a control solution and support the design of the actuating system. Initially, multiple optimal control solutions were investigated, but rejected due to unsuitability for this motor size and application. The model developed was also used as a simulator to asses the motor performance and investigate the effects of faults and uncertainties. The uncertainty analysis has shown high resilience of the system against error in calibration or noise. However, the position sensing system is a vital element, but its additive and multiplicative types of uncertainties can significantly degrade effectiveness of the whole actuating system. Through fault simulation, SR motor actuating systems were found to be tolerant towards open-circuit faults in one or two phases. They are quick to recover and the main symptom is maximum thrust limitation and a slight decrease in dynamical properties.

Overall, the designed SR motor actuating system has been proven to have sufficient performance for multirotor air vehicle propulsion, even when directly compared to its BLDC counterpart. Certain degree of fault-tolerance also has been proven against faults occurring during operations, as well as pre-existing uncertainties. This is a great benefit of using SR motors, especially when combined with fault tolerant control schemes. However, such systems are much heavier and more costly than currently used solutions,

mainly due to the low power factor and large size of the converters. But this is also, in part, due to the immaturity of the technology. Unless these issues are solved, SR motor actuating systems can be considered only for vehicles requiring superior fault-tolerance or to replace redundant actuating chains with singular system in low-performance applications. However, the principles of reluctance torque and independent phases are worth investigating for use in other electric machines or for eVTOL applications.

8.3 Further research

Although the results obtained in this work are certainly interesting, they do not exhaust the knowledge of the designed actuating system, not to mention about SR motors for multirotor air vehicles in general. Three directions the research can follow have been identified:

1. Design optimisation,
2. Vehicle-level analysis,
3. Experimental validation.

The influence of 3D effects has been identified only after the geometry optimisation using 2D and merely mitigated. Therefore, further work can be put creating a way of design optimisation that already takes these effects into consideration without being too computationally intensive. On the other hand, the SR motor can be investigated within the context of the whole vehicle and how it relates to control solution. For this, the reasonable first step would be preparing a non-linear (or linearised) reduced order model of the actuating system and then analysing whole vehicle dynamics. This also allows for easy comparison (in terms of bandwidth or damping) with an equivalent BLDC motor.

The most groundwork was already put into further validation of the system. BLDC motor actuating system was already tested on the ground test-bench. Using the prototype power stage and micro-controller the same can be done for SR motor system and the

results can be directly compared. This will increase the accuracy of performance validation. On the other hand, based on the data gathered, the reference BLDC motor actuating system can be modelled in a simulator, where faults can be injected and the resulting behaviour compared to that of SR motor actuating system. To increase the accuracy of the results even further, some faults (like the open phase fault) can be injected directly on the test-bench.

A step further would be to conduct the same set of experiments, but on a test-bench placed in a wind tunnel. The torque-thrust-speed characteristics of the propeller change at different airspeeds, so it needs to be investigated if sufficient thrust can still be delivered at high speeds. This study also needs to include varying angle of the propeller in regards to oncoming wind, to simulate the dynamics of flight of a multirotor vehicle.

Additional three SR motor actuating systems (including with lightweight ‘ready-to-fly’ power stages and controllers) can be manufactured and then mounted on a real vehicle. A flight of SR motor actuated multirotor air vehicle will truly validate this technology as suitable for the application. In addition, test can be carried out measuring handling qualities, endurance and maximum flight speed of such a vehicle and compared with the original values.

Finally, a similar project can be set-up, but with the aim of designing a fault-tolerant SR actuating system for eVTOL vehicles. There, it might be easier to design a well performing machine, but the constraints placed on safety are much greater, as such a vehicle would be carrying passengers.

Appendix A

Specification sets

Table A.1: Specification sets of batch 1.

l_r	τ_{spec}	ω_{spec}	Mass [g]	J_{spec} [A/mm ²]	U_{batt} [V]	I_{ref} [A]	Propeller	Reference BLDC motor
0.5	0.16	6701	128	20	22.2	9-17	11x4.5MR	Turnigy 4206 530KV
0.6	0.21	6299	128	20	22.2	11-22	12x4.5MR	Turnigy 4206 530KV
0.7	0.25	6795	128	20	22.2	13-26	12x4.5MR	Turnigy 4206 530KV
0.8	0.29	6544	237	20	22.2	12-24	13x4.5MR	iPower MultiMate MT4114-400 (415Kv)
0.9	0.36	6163	252	20	22.2	12-24	14x6E	Tarot 5008-11-340kV TL96020
1.0	0.41	6476	252	20	22.2	14-28	14x6E	Tarot 5008-11-340kV TL96020
1.1	0.38	6906	276	20	22.2	21-41	15x4E	LEOMOTION 3025- 3650/6,7:1
1.2	0.41	7194	296	20	22.2	23-45	15x4E	Derkum D-Power AL4250-09
1.3	0.45	7468	323	20	22.2	19-39	15x4E	Kontronik Kondor 25-41
1.4	0.50	6997	323	20	22.2	21-43	16x4E	Kontronik Kondor 25-41
1.5	0.53	7218	323	20	22.2	23-46	16x4E	Kontronik Kondor 25-41
2.0	0.96	5508	431	20	22.2	36-72	18x5.5MR	Kontronik Spider-XL 20-38
2.5	1.19	7325	494	20	22.2	47-95	17x6E	Torcster Red N5065/6- 390 430g
3.0	1.85	5598	531	20	22.2	57-113	20x8E	Jeti Phasor Race 2035- 2100/6,75:1
3.5	2.15	6048	668	20	22.2	70-140	20x8E	Plettenberg Dinator 30/3 Gear 5:1
4.0	3.12	5157	531	20	22.2	96-192	22x10E	Jeti Phasor Race 2035- 2100/6,75:1

Table A.2: Specification sets of batch 2.

l_r	τ_{spec}	ω_{spec}	Mass [g]	J_{spec} [A/mm ²]	U_{batt} [V]	I_{ref} [A]	Propeller	Reference BLDC motor
1.0	0.32	8214	174	20	22.2	19-38	13x4E	iPower MultiMate MT4108-580 (588Kv)
1.0	0.41	6476	252	20	22.2	14-28	14x6E	Tarot 5008-11-340kV TL96020
1.0	0.34	6581	252	20	22.2	12-24	15x4E	Tarot 5008-11-340kV TL96020
1.2	0.39	8968	296	20	22.2	21-43	13x4E	Derkum D-Power AL4250-09
1.2	0.41	7194	296	20	22.2	23-45	15x4E	Derkum D-Power AL4250-09
1.2	0.43	6478	252	20	22.2	15-29	16x4E	Tarot 5008-11-340kV TL96020
1.4	0.65	7112	323	20	22.2	28-56	14x5.5MR	Kontronik Kondor 25-41
1.4	0.50	6997	323	20	22.2	21-43	16x4E	Kontronik Kondor 25-41
1.4	0.64	5546	252	20	22.2	22-44	17x6E	Tarot 5008-11-340kV TL96020
1.6	0.55	8250	323	20	22.2	24-48	15x4E	Kontronik Kondor 25-41
1.6	0.74	5937	252	20	22.2	25-50	17x6E	Tarot 5008-11-340kV TL96020
1.6	0.77	4961	252	20	22.2	26-52	18x5.5MR	Tarot 5008-11-340kV TL96020
1.8	0.64	7880	323	20	22.2	28-55	16x4E	Kontronik Kondor 25-41
1.8	0.84	6268	396	20	22.2	35-70	17x6E	Kontronik KIRA 500- 26/6.7:1-Mezon
1.8	1.07	4750	404	20	22.2	44-87	19x8E	Hacker A40-12L V2
2.0	0.71	8273	323	20	22.2	31-61	16x4E	Kontronik Kondor 25-41
2.0	0.96	5508	431	20	22.2	36-72	18x5.5MR	Kontronik Spider-XL 20-38
2.0	1.21	4597	426	20	22.2	47-94	20x8E	Kontronik Kondor-XL 20-37
2.2	1.05	6907	462	20	22.2	41-83	17x6E	Kontronik KoraTop 20- 18
2.2	1.36	5234	458	20	22.2	56-112	19x8E	Scorpion S4020-16
2.2	1.35	4826	458	20	22.2	56-111	20x8E	Scorpion S4020-16

Appendix B

Results of SR motor optimisation using 2D model

Table B.1: Performance data of valid optimised SR motor designs at hover (nominal) operating point.

#	Size	I_{ref} [A]	θ_0 [° el.]	τ_{hover} [Nm]	ω_{hover} [RPM]	η_{hover} [%]	J_{hover} [A/mm ²]	$\Delta\tau$ [%]	$I_{DC-link}$ (peak) [A]	$\Delta I_{DC-link}$ [%]	Radial force [N]
1	50x13-26	17	-34	0.15	5867	67%	12.0	71%	13	291%	51
2	71x6-84	9	-52.9	0.18	4602	57%	9.9	109%	11	186%	35
3	43x29-26	12	-4.8	0.17	4684	69%	11.2	21%	13	268%	83
4	65x8-54	11	-33.4	0.18	4928	67%	9.1	71%	12	245%	46
5	64x8-54	11	-23.8	0.20	5138	67%	9.9	47%	16	240%	48
6	70x6-64	12	3.2	0.21	5334	62%	10.4	25%	18	178%	43
7	81x6-48	18	10.7	0.28	5087	66%	8.7	26%	24	187%	51
8	83x8-58	14	-8.4	0.38	4464	71%	8.0	30%	24	187%	69
9	3x6-54	18	-6.2	0.34	5951	70%	9.3	35%	29	195%	54
10	71x15-42	17	-3.3	0.45	3936	76%	9.1	26%	28	195%	104
11	83x9-48	19	7.3	0.45	3936	68%	8.7	29%	26	155%	79
12	90x8-48	20	-36.3	0.47	4951	74%	7.7	70%	30	227%	73

Appendix C

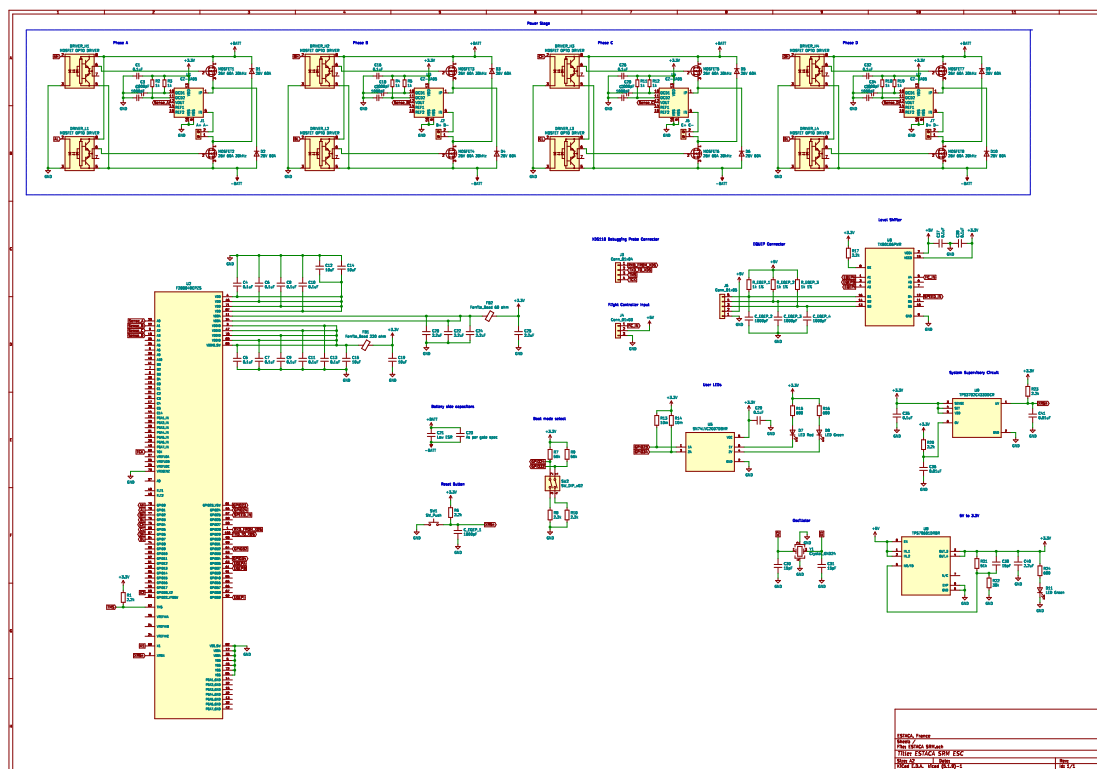
Customer-grade multirotor - motor and propeller data

Table C.1: Data of representative customer-grade multirotor vehicles (values in ‘()’ represent estimates).

Name	MTOW [kg]	Payload [kg]	No. of rotors	Battery cell count	Propeller diameter [inch]	l_r	Payload / rotor count	Motor weight [g]
DJI Mavic 2 Enterprise	1.1	0.2	4	4	8.7	0.28	0.05	(67)
Altigator OnyxStar EOS	1.8	0.5	4	(4)	(10)	0.45	0.13	(80)
Dronevolt Hercules 2	1.9	0	4	4	10	0.48	0.00	55
Multirotor Surveying Robot XL	5	2.3	6	6	(12)	0.83	0.38	(110)
Heliceo Fox 4	5	0.3	4	(6)	(16)	1.25	0.08	(141)
Altigator OnyxStar XENA	5.6	2	8	6	(16)	0.70	0.25	(99)
DJI Matrice 200V2	6.14	1.45	4	6	17	1.54	0.36	150
Prodrone PD4-AW2 BASIC	8	4	4	(6)	17	2.00	1.00	(199)
DJI Spreading wings S900	8.2	4.9	6	6	15	1.37	0.82	158
Heliceo SuperFox 6	10	4	6	(6)	(16)	1.67	0.67	(173)
DJI Spreading wings S1000+	11	6.6	8	6	15	1.38	0.83	158
Altigator OnyxStar FOX	15	5	8	6	(20)	1.88	0.63	(189)
DJI Matrice 600 Pro	15.5	6	6	6	21	2.58	1.00	250
Dronevolt Hercules 10	16.6	5	8	12	22	2.08	0.63	243
Prodrone PD6-AW2 BASIC	18	8	6	(6)	21	3.00	1.33	(275)
Altigator OnyxStar HYDRA	23	12	12	6	(14)	1.92	1.00	(192)
Prodrone SkymatiX X-F1	33.2	20	8	(6)	21.4	4.15	2.50	(363)
Dronevolt Hercules 20	34	15	8	6	26	4.25	1.88	350
Prodrone PD8-AWHR	37.5	20	8	(6)	21.4	4.69	2.50	(403)
Prodrone PD6B-AW-ARM	38.8	20	6	(6)	27	6.47	3.33	(539)
Prodrone PD6B-Type II	41.5	30	6	(6)	28.1	6.92	5.00	(573)

Appendix D

Preliminary power stage and controller schematic



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