

CRANFIELD UNIVERSITY

TIANZHI ZHOU

MODELLING AND EVALUATION OF ELECTRIFIED
REGIONAL AIRCRAFT PROPULSION SYSTEMS

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING
Aerospace

PhD

Academic Year: 2018–2023

Supervisors: Dr. Bahareh Zaghari, Dr. Panagiotis Laskaridis
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Abstract

Electric propulsion (EP) and hybrid electric propulsion (HEP) are novel concepts that significantly impact the future aircraft design and emission reduction. These novel technologies can be used to decarbonise air transportation, especially regional aircraft in short term future. Despite the potential benefits, their implementation challenges such as durability, reliability, architectural design, subsystem health state impacts, and the dynamic behaviour of various components in an integrated propulsion system have not been fully explored. The methodologies and results in literature varied significantly, they either focused on parametrically varying technology levels for aircraft weight and range sensitivity, or considered detailed subsystem design for specific purposes. Moreover, an important aspect not fully considered in most publicly available studies is to utilise fuel cell and hydrogen as the primary power supplier and energy source for future electric regional aircraft.

To fill in these gaps a modular component based simulation framework is developed in this work, aiming to model and assess the design and off-design performance of integrated hybrid electric aircraft propulsion systems by capturing the characteristics, interactions and interdependencies of its components. The developed component models include the main devices: batteries, fuel cell system, power electronics such as converters and inverters, and electric motors. Another key feature of this simulation framework is its multi-fidelity natural. The low-fidelity models enable fast system analysis and parametric studies in various aspects for holistic mission, whereas the high-fidelity ones allow detailed subsystem sizing, architectural design and evaluation, and performance assessment. In this study, power electronics and electric motors are modelled in both low fidelity

and high fidelity. For power electronics, the switching circuit elements are not included and their control mechanisms are realised by simple PI controllers for low fidelity models; whereas complete switching circuit systems are modelled to simulate their power losses and control logic for high fidelity models. For electric motor systems, dq model with PI control system are used as low fidelity models whereas a MotorCAD based PMSM performance map, with ' $I_d = 0$ ' control strategy and SVPWM modulation inverter circuit are used as high fidelity models.

The simulation framework was applied to study a 50 PAX, ATR42 like regional aircraft. Two forms of propulsion architectures were investigated: a pure PEMFC powertrain and a hybrid electric one. Based on the developed electric models and simulation framework, various cases and scenarios not studied in literature were investigated. For pure PEMFC system, the impacts of air mass flow rate and air supply pressure variation on fuel cell based system performance were investigated; The degradation impacts of fuel cell and battery on the system performance and sizing were also studied; A thorough discussion on fuel cell multi-stack architectural design was presented. Whereas for hybrid electric system, a comparative study between hybrid battery, hybrid fuel cell and hybrid battery/fuel cell propulsion system was conducted. The study evaluated key factors that can affect the electric system weight, such as mission length, hybridisation level, battery cycling number, etc. All these problems are significant and need to be solved before implementing the novel electrical propulsion technologies on regional aircraft.

Key findings and important conclusions were drawn from these case studies. For pure PEMFC system, it was found that the FC system normally exhibited higher efficiency at low power level (e.g. approximately 45% at top of climbing and 58% during descent). Therefore, a slight over-sized FC system can help improve the efficiency performance; Secondly, the effects of FC air supply pressure and mass flow rate on FC system efficiency and robustness were investigated. It was found that, although there was reduction in FC stack efficiency when keeping a relatively low FC air supply pressure, the overall FC system efficiency was improved throughout flight mission. Also, a potential risk of

low air supply rate was identified and a control strategy balancing efficiency and system reliability was proposed; Thirdly, FC degradation can cause imbalance performance of the whole multi-stack FC system. In this study, a 10% voltage and current degradation from a single FC was used, and it was found that such single cell level degradation can cause the whole FC system malfunction for some flight phases, which was detrimental. A detailed solution to avoid the malfunctioning risk was discussed in this study. For hybrid electric system, it was found that, under current and short-term technology level, FC based hybrid propulsion system generally had weight advantages over battery based one for regional aircraft. Specifically, a case study demonstrated that pack-level battery *S.E.* was expected to reach around 335-, 406-, and 543 Wh/kg to compete against the hybrid fuel cell system for 200-, 300-, and 600 nmi mission for the same power profiles. This required huge technology improvement for battery, since its cell level state-of-art *S.E.* was merely 250 Wh/kg when the research was initiated. Moreover, when battery cycling degradation was considered, further battery technology improvement was required.

Keywords

Architecture, CHARM, Degradation, Electric Propulsion, Electrical System Simulation, Hybrid Electric Propulsion, Hydrogen, Multi-fidelity Modelling, PEMFC, Regional Aircraft.

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List of Abbreviations

ACARE	Advisory Council of Aviation Research and Innovation in Europe
AFC	Alkaline Fuel Cell
AC	Alternative Current
ASM	Asynchronous Motor
BoP	Balance of Plant
B.S.E.	Battery Specific Energy
B.S.P.	Battery Specific Power
BLI	Boundary Layer Ingestion
BLDC	Brushless DC Motor
CO ₂	Carbon Dioxide
CHP	Combined Heat and Power
CHARM	Cranfield Hybrid Electric Aircraft Research Model
CIPH	Cycle-Integrated Parallel Hybrid
DoH	Degree of Hybridisation
DC	Direct Current
DMFC	Direct Methanol Fuel Cell
D-Q	Direct-Quadrature
ECM	Equivalent Circuit Model
EM	Electric Motor
EP	Electric Propulsion
eVTOLs	Electric Vertical Take-off and Landing Aircraft

EMTAT	Electrical Modelling and Thermal Analysis Toolbox
E-HEART	Enabling-Hybrid Electric Aircraft Research and Technology
EIA	Energy Information Administration
EMS	Energy Management Strategy
FOC	Field Oriented Control
FEA	Finite Element Analysis
FEM	Finite Element Method
FC	Fuel Cell
GT	Gas Turbine
GTO	Gate Turn-off Thyristor
GT-HEAT	Georgia Tech Hybrid Electric Analysis Tool
HTS	High Temperature Superconducting
HHV	Higher Heating Value
HEP	Hybrid Electric Propulsion
H ₂	Hydrogen
IGBT	Insulated Gate Bipolar Transistor
ISA	International Standard Atmosphere
Li-air	Lithium-Air
Li-S	Lithium-Sulfur
MTOW	Maximum Take-off Weight
MIPH	Mechanically Integrated Parallel Hybrid
MW	Mega-Watt
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MCFC	Molten Carbonate Fuel Cell
NASA	National Aeronautics and Space Administration
nms	Nautical Miles
NO _x	Nitrogen Oxides
NPSS	Numerical Propulsion System Simulation

PCM	Parallel Cell Module
PAX	Passenger
PMSM	Permanent Magnet Synchronous Motor
PAFC	Phosphoric Acid Fuel Cell
PMAD	Power Management and Distribution System
PEMFC	Proton Exchange Membrane Fuel Cell
PWM	Pulse Width Modulation
RPM	Revolution Per Minute
RMF	Rotating Magnetic Field
SATM	School of Aerospace, Technology and Manufacturing
SCM	Series Cell Module
SOFC	Solid Oxide Fuel Cell
SVPWM	Space Vector Pulse Width Modulation
S.E.	Specific Energy
S.P.	Specific Power
SOA	State of the Art
SOC	State of Charge
SRM	Switched Reluctance Motor
TRL	Technology Readiness Level
TMS	Thermal Management System
T-MATS	Toolbox for Modelling and Analysis of Thermodynamic Systems
VIP	Voltage/Current/Power
WRSM	Wound Rotor Synchronous Motor
YEIS	Year of Entry Into Service

Greek

α	Charge Transfer Coefficient
γ	Ratio of Specific Heats

Δ	Change Symbol
η	Efficiency
θ_e	Electrical Angular Position
θ_m	Mechanical Angular Position
θ_n	Negative Electrode State of Charge
λ	Magnetic Flux Linkage
λ_{O_2}	Oxygen Excess Ratio
ρ	Density
τ	Fuel Cell Dynamic Time Constant
Φ_{split}	Power Ratio of Battery to Whole Electric Storage System
Ω	Resistance Unit
ω_e	Electrical Rotational Speed
ω_m	Mechanical Rotational Speed

Latin

A	Tafel Slope
B	Viscous Damping
$B.S.E.$	Battery Specific Energy
Cap_{cell_ini}	Initial Lithium Cell Storage Capacity
Cap_{cell_usable}	Usable Cell Storage Capacity
CCF	Capacity Correction Factor
$c_{p,air}$	Air Specific Heat Capacity
CPR	Compressor Pressure Ratio
C_{T_L}	Long-time Transient Capacitance in Li-cell ECM RC-network
C_{T_S}	Short-time Transient Capacitance in Li-cell ECM RC-network
D	Duty Ratio
DoH	Degree of Hybridisation
$\Delta E(T)$	Temperature Correction of Cell Potential

$E_{\text{elec,mission}}$	Total Mission Energy Consumption for Battery
E_{oc}	Fuel Cell Open Circuit Voltage
F	Faraday Constant
f	PWM Carrier Frequency
ΔG	Activation Energy Barrier
h	Planck's Constant
$\Delta h_{\text{HHV,H}_2}$	Hydrogen Higher Heating Value
I_{bus}	Propulsion System Bus Current
I_{C}	IGBT Conduction Current
I_{cell}	Lithium Cell Current
i_{d}	Motor D-axis Current
i_{fc}	Fuel Cell Current
I_{inv}	Inverter Current
I_{L}	Inductor Current in Converter
i_0	Fuel Cell Exchange Current
I_{pack}	Battery Pack Current
i_{q}	Motor Q-axis Current
k	Boltzmann's Constant
K_{c}	Fuel Cell Voltage Constant at Nominal Condition
L_{d}	Motor D-axis Inductance
L_{q}	Motor Q-axis Inductance
M	Mach Number
$\dot{m}_{\text{air}}$	Fuel Cell Supply Air Mass Flow Rate
M_{air}	Air Molar Mass
$\dot{m}_{\text{H}_2}$	Fuel Cell Hydrogen Mass Flow Rate
$\dot{m}_{\text{O}_2}$	Fuel Cell Oxygen Mass Flow Rate
M_{v}	Vapour Molar Mass
$\dot{m}_{\text{v,ca,gen}}$	Water Mass Generation Rate from Fuel Cell

N	Battery Cycling Number
N_{cell}	Fuel Cell Number
n_{cell}	Battery Cell Number
n_p	Battery Cell Number in Parallel
n_s	Battery Cell Number in Series
p	Motor Pole Pair
p_{air}	Fuel Cell Supply Air Partial Pressure
P_{bop}	Power of Balance of Plant in Fuel Cell System
P_{bus}	Propulsion System Bus Power
$P_{\text{cell,loss}}$	Lithium Cell Power Loss
P_{conv}	Converter Power
p_{H_2}	Fuel Cell Supply Hydrogen Partial Pressure
P_{inv}	Inverter Power
$P_{\text{mot,mech}}$	Mechanical Power of Motor Through Mission
$P_{\text{pack,loss}}$	Lithium Battery Pack Power Loss
$P_{\text{stack,tot}}$	Fuel Cell Stack Total Power
R	Universal Gas Constant
R_0	Lumped Interconnect Resistance
R_c	Motor Armature Resistance
R_{cycle}	Li-cell Cycling Impedance in ECM RC-network
R_{ohmic}	Fuel Cell Stack Inner Resistance
R_{series}	Li-cell Internal Impedance in ECM RC-network
r_t	Battery Pack Interconnect Resistance
R_{T_L}	Long-time Transient Impedance in Li-cell ECM RC-network
R_{T_S}	Short-time Transient Impedance in Li-cell ECM RC-network
$S.E.$	Specific Energy
SOC	State of Charge
$S.P.$	Specific Power

T	Temperature
T_e	Motor Electromagnetic Torque
T_F	Motor Static Friction Torque
T_m	Motor Shaft Mechanical Torque
V_{act}	Fuel Cell Activation Over-potential
V_{bus}	Propulsion System Bus Voltage
V_{CE}	IGBT Collector-emittor Voltage
V_{cell}	Lithium Cell Voltage
V_{conv}	Converter Voltage
v_d	Motor D-axis Voltage
V_{fc}	Fuel Cell Voltage
V_{inv}	Inverter Voltage
V_{oc}	Lithium Cell Open Circuit Voltage
V_{ohmic}	Fuel Cell Ohmic Over-potential
v_q	Motor Q-axis Voltage
$W_{batt,pack}$	Battery Pack Weight
W_{cell}	Single Lithium Cell Weight
W_{conv}	Converter Weight
W_{inv}	Inverter Weight
$x\%$	Hydrogen Concentration
$y\%$	Oxygen Concentration
z	Moving Electron Number in Fuel Cell Equations

Acknowledgements

I would like to express my deepest and most sincere gratitude to those at Cranfield who offered me invaluable support and assistance with the project. Especially, my supervisors, mentors, and role models, Dr. Bahareh Zaghari and Professor Panagiotis Laskaridis. Your profound knowledge and insightful guidance gave me immense help in this research. Countless great ideas came from our meetings, seminars sessions, and workshops which made this thesis possible. I will never forget those happy times we spent together. Unfortunately, throughout the Ph.D. journey, my family faced quite an amount of challenges and life became really hard for me. I had to pause my research several times. Under enormous pressure, I even considered dropping out of the research, though reluctantly. You could really see my unwillingness and always encouraged me to give it another try. It was your full support that helped me get through all the difficulties and made this whole Ph.D. journey possible.

I wish to express my heartfelt appreciation to Dr. Devaiah Nalianda and Dr. Romano Pagliari, who took time from their busy schedules to review this research. Your review comments and advice always helped me stick to the right research direction. I greatly benefited from your critical advice and professional guidance.

I would like to gratefully acknowledge my Viva committee members, Dr. Gustavo Castelluccio, Dr. Rukshan Navaratne, and Dr. Timoleon Kipouros. Thank you for your invaluable support of this work, taking numerous hours to review this thesis. During the Viva, I really enjoyed the four-hour defense without noticing time went by. Your valuable feedback and our fruitful discussion eventually contribute to a further polished thesis.

My gratitude also goes to our lovely colleagues. We had many happy hours, not only in academia but also outside the research. In particular, I would like to thank Dr. Thomas Delaney, Dr. Evangelia Pontika, Dr. Hossein Balaghi Enalou, Dr. Yang Liu, Dr. Yize Liu, and Dr. Junjie Zhao. Your presence made this whole journey joyful.

I would also like to express my gratitude to SAS Lead Mrs. Petra Briggs, thank you so much for helping me with all the paperwork and communications during my stay. My gratitude also goes to my dearest friends: Xu Wang, Dongjin Li, Tianshu Chu and Pingyi Sun. Thank you for everything.

A special acknowledgement and miss to my best friend: Mr. Shu Han. A friend with care and passion, a scholar with talent and perseverance, a husband with responsibility and love. We miss you.

Especially, I would like to thank my rock, my girlfriend Dr. Yingjie Wang. Without you, I could not come this far. It was your patience, care, inspiration, and love that helped me through those hardest moments. Despite our four-year long distance relationship, you were always there for me. Together we overcame so many difficulties and harvested so many sweet memories. Thank you Yingjie. You finished your doctoral defense and had the graduation ceremony in late 2023. You were shining during the defense! I am so proud of you. Congratulations again for obtaining the doctoral degree!

Finally, I would like to express my deepest gratitude to my family, for everything. Words cannot express my love and gratitude to my parents, Chuner Zhou and Chaoxia Yang. I am truly blessed to be your son. It is your unconditional love, support, and sacrifice that made me the person I am now. I would also like to thank my uncle Yuru Zhou, and my brother, Tao Zhou. Your love and perseverance influence every aspect of my life. Now, I firmly believe that nothing is impossible, and never say never. I would also like to express my deepest love and miss to my late grandmother Liangxiu Zou. I can be proud to tell you, I am a doctor now. I will keep this momentum and make contributions to society, as you always taught me.

Chapter 1

Introduction

1.1 Motivation

The increasingly stringent environmental requirement motivates the research on aircraft propulsion electrification. Electric propulsion (EP) and hybrid electric propulsion (HEP) have the potential to reduce pollution and emission, enhance propulsion system performance and improve synergies between airframe and propulsion system [33]. Despite lofty promises, the EP/HEP implementation challenges such as design, sizing, and the system dynamic behaviour analysis have not been fully explored. A suitable modelling and analysis framework is desired to explore the design space and system behaviour assessment at conceptual level. Moreover, there is a great need and investment in technologies level and specific component development to facilitate their successful application in aviation sector [33]. It needs to be noted that, EP refers to all-electric propulsion in this thesis, where only batteries or hydrogen based fuel cell systems were used as the only source of propulsion power for the aircraft. Whereas HEP uses both gas turbine engines and batteries or fuel cell systems, or batteries plus fuel cell systems for propulsion during one or more phases of flight.

A range of conceptual studies have captured academic and industry interests in EP/HEP. However, they are typically relying on highly-advanced technology level assumptions,

such as extremely high battery specific energy and power, high temperature superconducting technologies and so on. These assumed technologies are unlikely seen before year-2050 time frame or even later. Moreover, some research focus on advanced future aircraft platforms which forecast ground-breaking performance. Whilst predicting the technology in long-term future, more near-term research need to be focused for decision making based on a more current technology background. This way is more likely to be the logical development pathway to market. Moreover, the lack of confidence and validation of futuristic technology may cause misjudgements for academia and industrials. For this reason, the simulation framework in this study focuses on mid-term technology levels, allowing conservative variations for year-2035-timeframe. The aircraft retrofit model is based on ATR42-like regional type, which is considered more likely to be electrified in short-term future.

For EP/HEP conceptual studies, there are two typical extremes: some studies focus more on propulsion system level with low-fidelity models for electrical subsystem. Essential component parameters are based on fixed S.E., S.P., and efficiency. Important electrical dynamic performance details are less concerned. On the other hand, some component specialised studies conducted in depth research on subsystem with high fidelity models. The integration and matching problems to more comprehensive propulsion system level are not fully explored. Whilst this aids the detailed understanding of selected component and subsystem, the complex models can be problematic when considering “modifying” them to capture technology levels impacts. Also, integrating these models to EP/HEP system level and simulate holistic aircraft mission performance is not fully addressed by these models. In this study, a modular-based simulation framework is developed, with the capability to capture missing details in the literature, as well as the availability to conduct holistic performance investigations in wider EP/HEP level.

Hydrogen based fuel cell is gradually capturing academic and industrial interest due to its zero emission nature and high S.E., but the majority e-aviation conceptual studies utilise batteries as the propulsion power without considering FC. Numerous FC stud-

ies focusing on various modelling methods and fidelity levels are available in literature [34–36]. Most studies considered land-based applications such as PEM-FC vehicles and trams [37, 38]. These studies presented insights into comprehensive land based fuel cell power-train system analysis, but the similar study on FC-power aircraft is lacking. The aviation application is so different that, there is a research need for assessment of FC system as the aircraft power-train, with a detailed and comprehensive models capturing both component and system level parameters. In this study, fuel cell system is integrated to the electric system, which offers relevant and insightful viewpoints of FC-powered aircraft. Numerous key performance parameters of fuel cell system are captured for system assessments and decision makings, which are likely to be missed in many conceptual design studies.

The subsystem components off-design and degradation performance are important to be taken into accounts. Being able to model the change in component performance, the impacts on the power-train can be assessed. These impacts often affect some key system design decision makings and performance aspects. In this study, the focus being fuel cell stack imbalance performance and its system knock-on effects, fuel cell architectural topology arrangement, better fuel cell operation strategies, avoidance of potential system malfunctions, battery system sizing, weight penalty consideration, aircraft ranges and hybrid architecture selection.

The whole study is classified into two propulsion architectures: pure fuel cell electric propulsion (PEMFC-EP) and hybrid electric propulsion (HEP) architecture. The PEMFC-EP investigates an all-electric regional aircraft powered by PEMFC solely. It provides a platform for comprehensive investigations on fuel cell propulsion system including: detailed mission-level system analysis, stack off-design assessment, fuel cell operation strategy design, stack degradation impacts on multi-stack configuration, and multi-stack configurational selection and design space exploration. However, scaling the fuel cell system and electrical systems for Mega-Watt power level regional aircraft is currently beyond the state-of-the-art fuel cell technology, especially when minimising aircraft weight

is considered. Despite the limitations, these studies are still important since they help understanding any architecture that might utilise PEMFC system for propulsion. For HEP architecture study, the regional aircraft is powered by gas turbine and electrical system. As the electric power rating is greatly reduced, the fuel cell and battery system can be investigated based on a more state-of-the-art technology level. Studying this platform provides a more mid-term look at the use of these technologies in aviation industry. It also helps decision making when considering architectural selections. Finally, with the capability to adjust power split between gas turbine, battery and/or fuel cell, the energy management strategies can be explored for different targets.

1.2 Research aim, objectives and research questions

The research aim in this thesis is: “develop a modular component based simulation framework to model and assess the design point and off design performance of integrated hybrid electric aircraft propulsion systems by capturing the characteristics, interactions and interdependencies of its components and use it to simulate and assess different energy management strategies.” To meet the research aim, the following research objectives need to achieve:

1. Evaluate the effect of various operation settings (including on and off design studies), component and subcomponent states for a given integrated propulsion system.
2. Develop subsystem models with appropriate level of fidelity to capture component performance and their interactions involved in the EP/HEP: battery pack, PEMFC system, controlled DC/DC converter, controlled three phase DC/AC inverter and PMSM in comparison with existing models for HEP.
3. Construct a pure PEMFC EP architecture to evaluate feasibility of hydrogen-fuelled PEMFC system as the primary energy storage and propulsion power supply system.

- i Identify the key parameters that influence PEMFC stack performance and evaluate their impacts on the system performance.
 - ii Explore the impact of PEMFC stack connection topology and its effectiveness in reducing the system impact of degradation and voltage/current variations in each stack.
 - iii Examine the other potential PEMFC stack configurations.
4. Construct a HEP architecture to enable hybrid battery and hybrid fuel cell performance evaluation.
 - i Investigate GT/battery and GT/PEMFC architectures in terms of weight, efficiency, and system performance, assess and compare the different characteristics of both architectures.
 - ii Explore the key factors that influence lithium battery pack performance and evaluate their impacts on the propulsion system.
 - iii Investigate the impact of flight mission range on the propulsion system performance, energy management strategies and architecture decision.

In order to achieve above listed top level research objectives, the steps can be broken down into answering the following specific research questions.

For a typical 50 PAX regional aircraft pure fuel cell propulsion architecture:

- How to develop a methodology and build a simulation framework to perform sizing, integration, subsystem interdependency and matching investigation, and holistic system performance analysis for regional aircraft pure fuel cell electric system?
- What are the key aspects of the subsystem and system parameters need to be considered?
- After identifying these effective key parameters, what fidelity level is suitable to model them?

- Are these subsystem component models validated to acceptable confidence levels?
- Which parameters can cause fuel cell system performance variations (quantitatively)?
- For these identified operation variables, is the propulsion system benefited from or detriment to them?
- By what strategies can these parameters be controlled to avoid the potential risks and improve system performance?
- What is the impact of fuel cell stack degradation on the system? Can the fuel cell stack configuration help to reduce the impact of voltage and current imbalance performance due to stack degradation?
- What are the potential fuel cell multi-stack configurations and their corresponding advantages and disadvantages for a regional aircraft propulsion system? How are these different configurations affecting the design for DC/DC converter?

For a typical 50 PAX regional aircraft hybrid electric propulsion architecture:

- How to develop a methodology and build a simulation framework to perform sizing, integration, subsystem interdependency and matching investigation, and holistic system performance analysis for regional aircraft hybrid electric system?
- How to simulate and validate the battery system from cell to pack level and enable them to capture all necessary parameters?
- What are the impacts of mission characteristics, such as power profile, mission length, and hybridisation level on the system weight and sizing?
- How does battery degradation affect the system performance, sizing and aircraft mission range?

- How to compare hybrid-battery and hybrid-fuel cell architectures in terms of sizing consideration?
- Which architecture yields lighter potential system weight, hybrid-battery, hybrid-fuel cell, or hybrid-battery/fuel cell?
- Can hybrid battery fuel cell allow more intelligent energy management strategy so that the system weight can be minimised amongst the three competing architectures?

Each of these research questions must be fully addressed to realise the objectives. A systematic, validated and reproducible methodology for propulsion system modelling, holist system on/off-design performance evaluation, system configuration assessment, and energy management implementation for electric and hybrid electric regional aircraft can be formulated by answering these questions. And finally, the research aim can be achieved.

1.3 Research contributions

1.3.1 Description of the research contribution

This work produced original understanding and knowledge in the area of pure fuel cell electric and hybrid electric propulsion system for ATR42 like regional aircraft. Novel contributions are summarised:

- In Chapter 4, the simulation framework for pure FC propulsion power-train for a typical 50 PAX regional aircraft is introduced, with appropriate fidelity modelling for subsystem components, which has several advantages compared to most existing simulation frameworks. By utilising this multi-objectives, multi-fidelity model, all relevant performance parameters of individual components, their interaction and the holistic systematic performance are captured in mission-based level. Key performance aspects, such as voltage, current, power and electrical efficiencies of FCs,

converters, bus line, inverter and motor, air/fuel flow and consumption rate for FC, mechanical performance of PMSMs are captured. Some performance evaluations and system design decision makings not seen before are now available by utilizing this simulation framework. Moreover, this framework is modular and considers component integration and electric system control and stabilization. The developed model can simulate various propulsion architectures, without redesigning the methodology framework. Modular nature enables fast studies for different cases and system configurations; control and stabilisation mechanisms enable desired operation conditions for each component. The study of air mass flow rate $\dot{m}_{\text{air}}$ and air supply pressure p_{air} effects on FC off-design operation for aircraft propulsion system is a novel work. Trade-off between system robustness and efficiency is demonstrated due to their variations. By adjusting the two operation parameters, different control strategies are proposed and assessed based on system reliability and efficiency aspects. A control strategy balancing these two aspects is obtained. The methodology of this study is generic and applicable to any system containing a PEMFC. Another novel contribution comes from investigating fuel cell stack imbalance performance impacts on the system. The V-I polarisation curve is compromised when FC stack degrades after long time usage. This can cause stack imbalance amongst FC arrays and these impacts are simulated. The potential risk due to stack imbalance performance is identified and demonstrated. It is found that carefully designed FC stack connection configuration can mitigate the potential risk due to imbalance performance. Finally, more possible FC stack configurations are analysed using a high fidelity model. More refined and detailed component and system efficiencies are demonstrated for various configurations. The contribution comes from: the set-up of high-fidelity models in an integrated way; The sizing and design process of converter considering the maximum operating points; quantitative mission-level analysis of the high-fidelity PEMFC-EP architecture model; and finally, identification of the most suitable FC stack configuration for the a typical

50 PAX regional aircraft.

- In Chapter 5, a similar framework is proposed to model hybrid propulsion power-train for an ATR-42 like aircraft. The main difference is the implementation of energy management strategy for power split between gas turbine, fuel cell and battery system, using two parameters: DoH and Φ_{split} . The characteristics of battery nominal and degrading performance are presented with validated models. A clear procedure for sizing the propulsion system is proposed based on the aircraft power requirement and battery/FC ratings and operation states. Carefully designed study cases quantitatively show that the relation between battery system weight and battery health state (cycling number degradation in this study), mission length, energy management strategy and S.E. technology level. The potential risk of battery degradation on system reliability is presented for different cycling numbers. Three competitive architectures: hybrid battery, hybrid fuel cell, and hybrid battery fuel cell are proposed and weight comparisons between them are made. It is found that, battery is not suitable for mission with long range while fuel cell is not ideal for missions with large power variation. Applying proper energy management strategy allows significant decrease in system weight. It is recommended to allocate power split such that, pure FC provides low power throughout the whole flight phase and battery works as a supplement at high power but short duration, like “Take-off” and “Climbing”. Including both battery and fuel cell, the electric system can be designed with significantly low weight. These results are presented in Chapter 5.

1.3.2 Publication

Part of Chapter 4 and 5 have been published in several conference proceedings as cited in [20, 39]. And the multi-fidelity simulation framework developed in Chapter 3 has been utilised in paper as cited in [40].

1.4 Thesis outlines

This thesis comprises six chapters and two Appendices. The series of subsections for each chapter are presented in the thesis contents. A top level summary of each chapter is listed below:

- **Chapter 1 - Introduction:** This chapter introduces the context and motivation of the research and states the overall scientific aim. The objectives and research questions that need to be addressed to deliver against the overall aim are then described. The research contributions that obtained are also summarised.
- **Chapter 2 - Review of Aviation Electrification Research:** This chapter provides a literature review on electrified aviation research and seeks answers to the research questions. Also, the research gaps are identified and the methodology to achieve the research objectives and questions are presented.
- **Chapter 3 - Methodology and Simulation Framework:** This chapter introduces the detailed simulation tools developed and its building blocks to simulate the electric and hybrid electric propulsion system for the ATR-42 like regional aircraft.
- **Chapter 4 - 50 PAX Regional Aircraft Fuel Cell Propulsion:** This chapter provides the results and their analysis to answer the research questions outlined in chapter 1 for the pure fuel cell propulsion system.
- **Chapter 5 - 50 PAX Regional Aircraft Hybrid Propulsion:** This chapter answers the research questions outlined in Chapter 1 for the hybrid electric propulsion system.
- **Chapter 6 - Conclusions and Future Work:** This chapter summarises the conclusions derived from this research project. The contributions of this work are highlighted and a list of future work is recommended.

- **Appendix:** The appendices are provided to further explain the methodology and simulation model, as well as some key Matlab codes being utilised.

Chapter 2

Review of Aviation Electrification Research

2.1 Backgrounds of aircraft electrification

The global aviation sector consumes more than 7% of oil products and produces 2.7% of in-flight combustion-related CO₂ [41]. Moreover, the global aviation sector has yet reached its full growth potential, the demand is predicted to grow at a rate of 4.8% annually [42, 43]. The U.S. Energy Information Administration (EIA) projects a greater than 60% air travel seat miles increase with a corresponding 38% increase in energy use by year 2050 [44].

Under these critical situations, many organisations and research councils have set forth regulations, and outlined environmental and performance targets. For example, the NASA ‘N+3 Strategic Implementation Plan’ outlines: by year 2035, an 80% NO_x emission, a 60% block fuel consumption, and a 52% dB noise reduction are expected to achieve, relative to the 2005 state-of-art level [45]. Also, the Advisory Council of Aviation Research and Innovation in Europe (ACARE) formulated guidelines for ‘Flightpath 2050’, targetting a 75% CO₂ and 90% NO_x emission cut and a 65% noise reduction for the aviation sector in 2050 [46]. However, the potential fuel-efficiency and emission improve-

ments achieved by conventional technology evolution approaches are already reaching a plateau, applying them alone would not meet the environmental targets [47]. Electrified aircraft propulsion technology has emerged and identified as the most suitable avenue to realise energy-efficient, sustainable and less-emission for regional air transportation aviation [48].

2.2 Overview of aircraft electrification concepts

The idea of aircraft electrification leads to the discussion of propulsion system architectures, categorised as four primary types: full electric, series hybrid electric, parallel hybrid electric, and turboelectric [41]. In this section, each architecture is introduced from the perspectives of concepts, benefits and challenges, followed by a summary of representative aircraft studies and applications.

2.2.1 Full electric

The full electric architecture is shown in Fig. 2.1a. It uses batteries or hydrogen based fuel cell system as the only propulsion power source on the aircraft. Batteries or FC system produces electricity, and electrical power propagates through power electronics and reaches to the electric motors, where it is converted to mechanical power to drive the propeller. The secondary energy for the other aircraft system is also driven from the battery or FC system. The key features of full electric are high energy conversion efficiency and zero emissions. In practice, full electric aircraft are currently feasible for short-haul flights, such as electric vertical take-off and landing aircraft (eVTOLs), general aviation aircraft, commuter aircraft, and regional aircraft. The key studies and applications are summarised in Table C.1, Appendix C.

2.2.2 Series hybrid electric

The series hybrid electric architecture is shown in Fig. 2.1b. The electrical power is either from generator driven by gas turbine or from batteries. The electrical power is distributed to motors via power electronics and electric buses. Both gas turbine engine and electrical system are electrically coupled, and this is the key feature of “Series hybrid electric” as commonly accepted by academia and industrial. In this architecture, the gas turbine can be decoupled from propulsive part, resulting in a more efficient gas turbine system. But, with the combination of generator systems, the overall weight is generally heavier than its hybrid-parallel counterpart. Moreover, due to more energy conversion stages, the series architecture exhibits lower efficiency than the parallel one. The key studies and applications are summarised in Table C.2, Appendix C.

2.2.3 Parallel hybrid electric

The parallel hybrid electric architecture is shown in Fig. 2.1c. In this architecture, the gas turbine engine and the electric motor are connected via a rigid gearbox. Both heat engine and electric system are connected mechanically instead of electrically. This is the commonly accepted key feature of “Parallel hybrid electric” architecture. Though this connection topology could need a complex gearbox system, it does not require heavy generators and corresponding power regulators, resulting in a lighter propulsion system. Moreover, it has fewer energy conversion stages, which further increases the overall system efficiency.

This architecture has fewer energy conversion stages, so that it has system efficiency and weight advantages over series hybrid system [49]. However, the control and operation aspects are relatively complicated due to mechanical coupling issues. The key studies and applications are summarised in Table C.3, Appendix C.

2.2.4 Turboelectric

The turboelectric architecture is shown in Fig. 2.1d. The electricity is provided by gas-turbine-driven generators. The electrical power is transmitted to the motor via power electronics, and finally the mechanical propulsion power is generated through electric motors. This architecture does not rely on batteries; the energy is stored in aviation fuel and converted to electrical energy.

It is predicted by the Committee that turboelectric propulsion can be introduced into service in next 10 to 30 years. It can also maximise the synergic benefits with advanced boundary layer ingestion (BLI) concepts [33]. The key studies and applications are summarised in Table C.4, Appendix C.

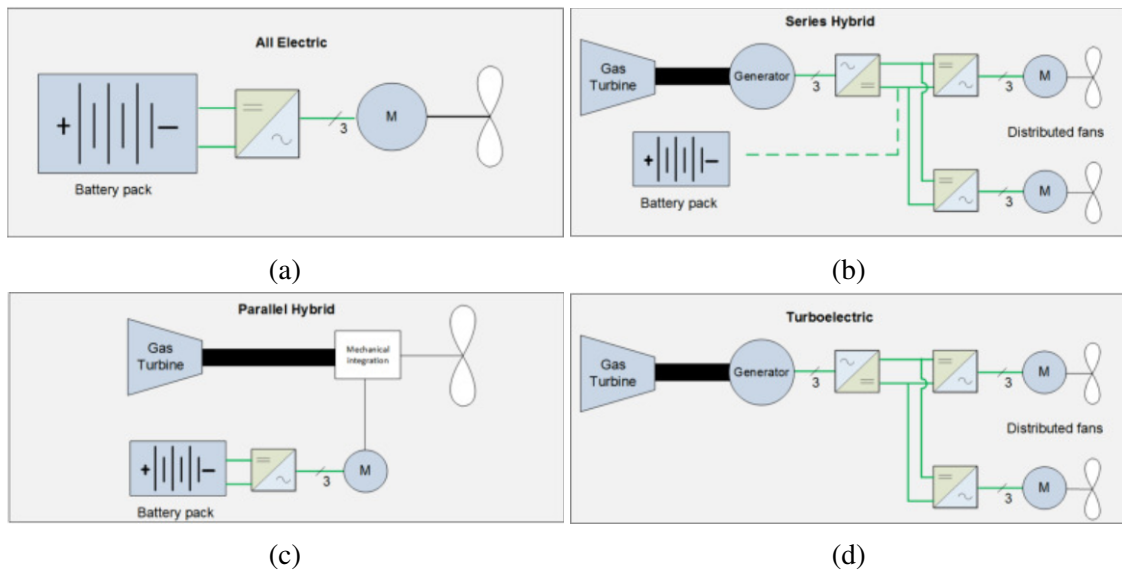


Figure 2.1: Schematic diagrams of (a) Full-electric, (b) Series hybrid electric, (c) Parallel hybrid electric and (d) Turboelectric architecture [1].

Table 2.1: Electric component technology requirements for full electric, parallel hybrid and turboelectric systems proposed by Committee on Propulsion and Energy Systems to Reduce Commercial Aviation Carbon Emissions [28].

Aviation sector	Power rates (MW)	<i>S.P.</i> (kW/kg)	<i>B.S.E.</i> (Wh/kg)
General aviation/commuter			
Full electric	EM < 1	> 6.5	> 400
Parallel electric	EM < 1	> 3	> 250
Turboelectric	EM and G < 1	> 6.5	n/a
Regional/single-aisle			
Full electric	EM 1-11	> 6.5	> 1800
Parallel electric	M 1-6	> 6.5	> 800
Turboelectric	EM 1.5-3; G 1-11	> 3	n/a
Twin-aisle			
Full electric	infeasible		
Parallel electric	n/a		
Turboelectric	EM 4; G 30	> 10	n/a

*EM: electric motor, *S.P.*: specific power, *B.S.E.*: battery specific energy, G: generator

† *S.P.* includes power electronics systems

During the comprehensive aircraft concept/design/studies literature review, three observations related to the study can be found:

- **Observation 1:** The majority of these aircraft conceptual studies focused on parametrically varying the technology levels for the range and weight sensitivity. However not many studies considered the electrical performance aspects, such as short time-scale electrical performance during mission, efficiency variation profiles, and long time-scale component degradation impacts. A consensus on how to assess the electrical systems for these novel power-trains has yet to be reached.
- **Observation 2:** Many of these studies relied on radical technology levels and concepts: high component specific energy and power, HTS technologies, boundary layer ingestions or distributed electric propulsion concepts. A more mid-term future technology was slightly overlooked.
- **Observation 3:** Battery was preferable to many studies, however the state-of-art specific energy is far from the minimum requirements proposed by the

Committee [28], especially for regional/single-aisle aviation sector. The development of energy storage of batteries is gradually reaching its limit, but alternative energy storage and energy conversion systems such as hydrogen-based fuel cells were not adequately explored or investigated for aircraft propulsion.

2.3 Overview of hydrogen fuel cell aircraft

Hydrogen is a plausible solution to achieve decarbonisation target for aviation transportation, given that the challenges of technology and implementation are addressed. Amongst various technologies, Hydrogen based fuel cell technology can promise emission free short-to-medium-range aircraft, and direct H_2 combustion in gas turbine can decarbonise longer range missions [84]. In this study, fuel cell based aircraft is considered.

2.3.1 Fuel cell overview

There are different types of fuel cells, differentiated from one another on their fuel types and electrolyte. Six representative fuel cells are illustrated in Fig. 2.2, with their advantages and disadvantages comparisons summarised in Table 2.2, and their respective state-of-art technological metrics in Table 2.3:

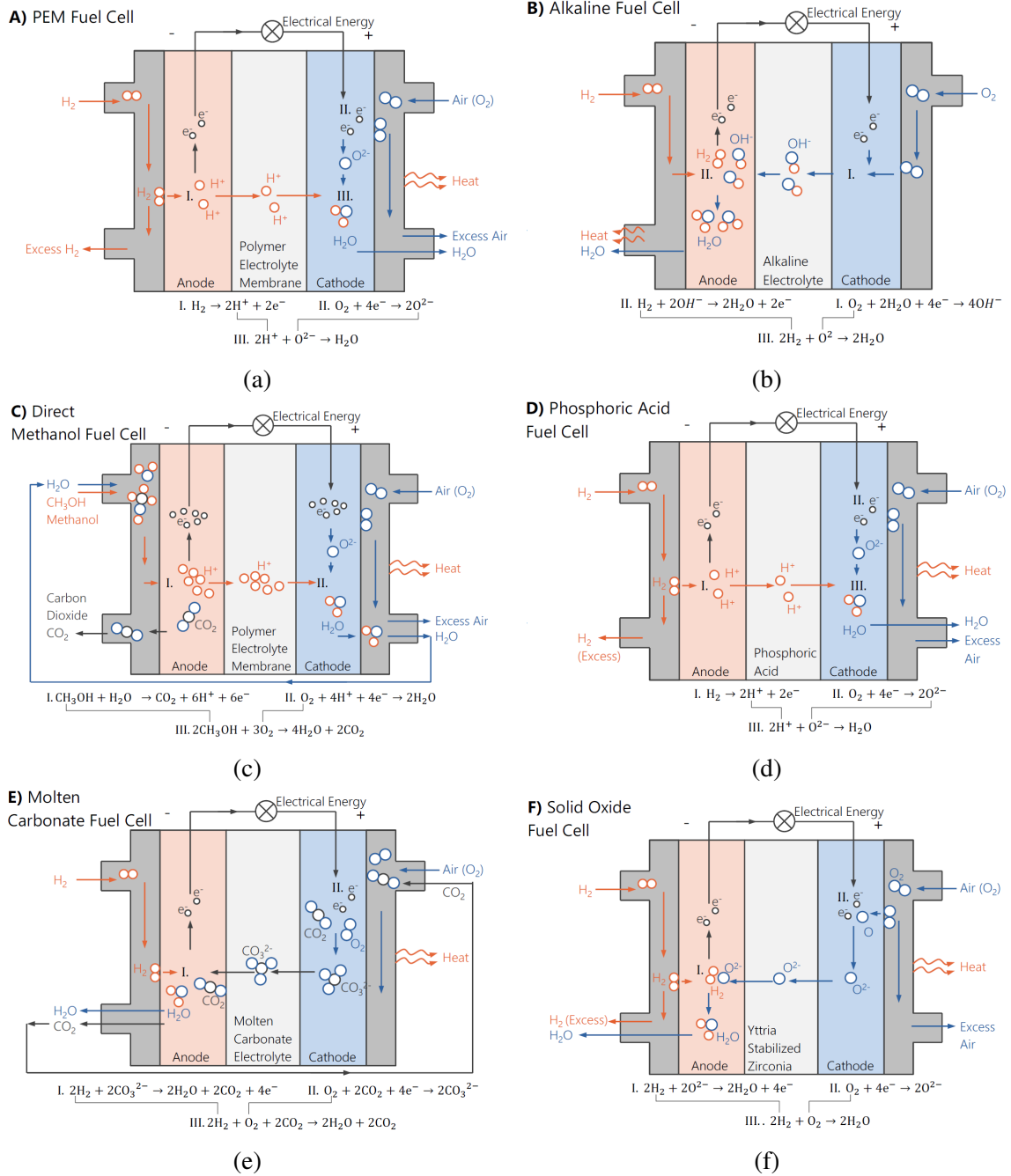


Figure 2.2: Schematic diagrams of (a) PEMFC (b) AFC (c) DMFC (d) PAFC (e) MCFC and (f) SOFC. Figures adopted from [2].

Table 2.2: Advantages and disadvantages of different fuel cell types (comparisons adopted from [29, 30]).

FC type	Advantages	Disadvantages
PEMFC	Highest specific power compared to others, high efficiency, highly modular and compact for most applications, rapid start-up time and transient response, and zero CO ₂ /NO _x emission.	Expensive catalyst and polymer membrane, complex water management required, low CO and S tolerance, and H ₂ O by-products.
AFC	High efficiency, extremely low electrolyte cost, low non-precious metal catalyst cost, and zero CO ₂ /NO _x emission.	Relatively low power density, must use pure H ₂ -O ₂ , the presence of CO ₂ degrades KOH electrolyte (cannot operate even at atmospheric CO ₂ level), low life-time, and H ₂ O by-products.
DMFC	Compact FC size, easy fuel storage and delivery, and simple thermal management and humidification system.	Low cell voltage and efficiency, low power density, poison CO is formed intermediately during anode reaction, inevitable by-products of CO ₂ and H ₂ O.
PAFC	High TRL, simple water management, small CO ₂ amount tolerance, potential CHP applications available due to high temperature, zero CO ₂ /NO _x emission.	Slow start-up time, low power density and efficiency, large system size, risk of corrosive electrolyte leakage, expensive catalyst, and H ₂ O by-products.
MCFC	Fuel flexibility, high efficiency, high contaminants tolerance, non-precious metal catalyst, and suitable for CHP.	Very high operating temperature, slow start-up time and transient response, degradation issues and low life-time, corrosive molten electrolyte, CO ₂ and H ₂ O by-products, and a recycling system needed for it.
SOFC	Very high efficiency, high contaminant tolerance, fuel flexibility, high-quality of waste heat for CHP, non-precious metal catalyst.	Extremely high operating temperature, extremely slow start-up time and transient response, high thermal stresses, complex sealing issues, low life-time, high manufacturing costs, and potential NO _x emissions due to high temperature, as well as H ₂ O by-products.

*PEMFC: proton exchange membrane fuel cell, AFC: alkaline fuel cell, DMFC: direct methanol fuel cell, PAFC: phosphoric acid fuel cell, MCFC: molten carbonate fuel cell, SOFC: solid oxide fuel cell, TRL: technology readiness level, and CHP: combined heat and power.

Table 2.3: Comparison of state-of-art technology metrics of different fuel cell types.

FC type	Efficiency [%]	Temperature [°C]	Life-time [h]	Specific power [kW/kg]
PEMFC	40 - 60 [85]	60 - 80 [86]	5000-20000 [87], > 4000 [88]	0.40 - 1.00 [86]
AFC	up to 65 [89]	60 - 120 [6]	8000 [90]	0.17 [91]
DMFC	10 - 40 [92]	70 - 100 [89]	> 4000 [88]	0.10 - 0.20 [89]
PAFC	40 - 45 [93]	220 [6]	> 50000	0.12 [89]
MCFC	60 - 70 if waste heat is used [89]	600 - 800 [94]	7000 - 8000 [89]	N/A
SOFC	50 - 65 [92], 70 [95]	800 - 1000 [96]	> 10000 [88]	N/A

From above fuel cell literature review, PEMFC and SOFC are two competitive candidates for aircraft propulsion. Firstly, the zero emission requirement rules out the DMFC and MCFC, as carbon dioxides are inevitably produced from their chemical reactions. Secondly, AFC could be challenging as atmospheric CO₂ level is not tolerable for its fuel and oxidants. This feature leads to the inclusion of complex gas treatment system and hence more weight and volume penalty in aircraft payloads. Finally, PAFCs are generally reported with lower specific power and efficiency than that of PEMFC and SOFC. Therefore, the author concluded that, PEMFC and SOFC are more suitable for aircraft propulsion system than others. It is also agreed by other studies that both PEMFC and SOFC are feasible for aviation application among the various fuel cell devices types [97]. However, it should be noted that all these fuel cells inevitably generate H₂O by-products. And water is a potential contributor for global warming due to contrail formation. Therefore, a mitigation strategy of contrails formation is also necessary to get complete benefit of fuel cells.

In this study, PEMFC is considered because the applications of SOFC involve intense investigations on combined heat and power synergy effects of gas turbine/SOFC system [97], which is not the main focus of this study.

In comparison to batteries, the hydrogen fuel of PEMFC system has much higher specific energy, and the FC system has shorter refuelling time, longer life-time, and lower

emission with non-carbon hydrogen harvest method [3]. However, the low specific power, low efficiency, high thermal losses, and lack of hydrogen refuelling station at airport still remain as considerable challenges. Only until recent years, the aviation community starts considering it as a primary power supplier. This is due to the improvement in technological readiness, especially fuel cell specific power. For example, the state-of-art off-the-shelf PEMFC stack level specific power can reach 4.7 kW/kg, but this figure only accounts for stack dry mass [98]. Also, a 2.0 to 2.5 kW/kg of PEMFC system (stack + balance of plant) and a 70% stack efficiency are predicted to reach in year 2030 [99]. The specific power of the fuel cell stack is also investigated in [100], based purely on the its active component, a 10 kW/kg is estimated for future developments. These developments gradually put the PEMFC back to the racetrack. The maximum S.P. of ATR42 equipped PW127M engine equipped is 4.3 kW/kg according to [101]. It is therefore considered viable to conduct more research on PEMFC as the primary energy source for regional electrified aircraft. The current S.E. and S.P. level comparison for different energy storage systems is shown in Fig. 2.3.

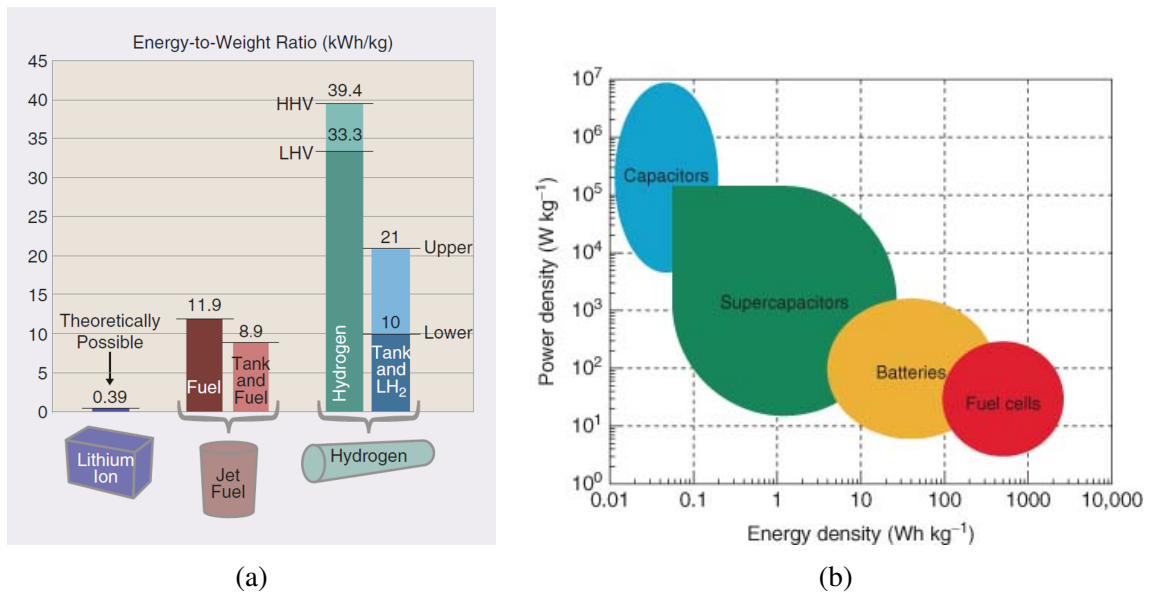


Figure 2.3: (a) Specific energy comparison between lithium ion battery, jet fuel and hydrogen from [3]. (b) Specific power comparison between capacitor, supercapacitor, battery and fuel cell from [4].

However, even though hydrogen based FCs are gradually showing their potentials

and viabilities, on board hydrogen storage still remain one of the main challenges to implement them in aircraft propulsion. The state-of-art gravimetric hydrogen storage capacity is merely 5.7% (wt) according to [160]. With such figure, the hydrogen tank would be over-weighted and aircraft payload could be limited.

2.3.2 PEMFC aircraft overview

In industrial sector, there are already some successful flights powered by fuel cell, such as a sole PEMFC-powered aircraft, developed by Boeing based on a 2-seater Diamond-DA20, flew for 20 minutes in 2008 [102]. A 4-seater aircraft developed by DLR-HY4, made its maiden flight in 2016 for ten minutes [103]. A ZeroAvia's 6-seater aircraft flew for 20 minutes in 2021 [104]. Moreover, different research institutes and leading companies also launched research projects of hydrogen aircraft concepts. DLR has been working on the BALIS project to develop Mega Watt fuel cell power-train since January 2021 (40+ seater, 1000 km and 1.5 to 2 MW) [105]. Airbus's ZEROe project has set goals to develop the world's first zero-emission commercial aircraft by 2035 with hydrogen propulsion, either with hydrogen combustion technique or fuel cells [106].

Despite the emission-free nature, fast developing fuel cell technological readiness level, there are many aspects of the fuel cell system performance, design, operation and implementation challenges yet to be explored. Therefore in academia sector, many studies are in active. Kadyk. et al [100] proposed a method for designing the fuel cell as the transportation aircraft main energy supplier with a physical-based model. They also proposed a way to size the fuel cell based on the relation between efficiency and power density. They concluded that the efficiency can be increased by over-sizing the fuel cell. And the optimal weight obtained from over-sizing benefits is not only determined by fuel cell, but also the fuel and tank. If the system is heavy in fuel and/or tank, larger over-sizing is beneficial. However, this study does not consider other important components, especially air supply and conditioning system.

There are several studies considered more detailed electrical system analysis and sim-

ulation for fuel cell aircraft: Kasim et al [107] developed a sole PEMFC propulsion system for Cessna level aircraft, where a complete fuel cell system was simulated for the holistic flight mission. They concluded that a fully hydrogen powered 8-passenger aircraft is feasible. A failure analysis of the system was also included. Zeng et al [108] also presented an integrated fuel cell and aerodynamic model for a 30kW level two-seat aircraft. However, the influence of fuel cell off-design and other detailed electrical system level analysis were neglected. Hartmann et al [109] presented a PEMFC powered system for regional aircraft, with the applications of superconducting cables and motors. They looked into the application of liquid hydrogen to provide cryogenic cooling for superconductors. It was argued by Kasim et al [107] that multi-stack configuration can not only achieve larger power requirements, but also enhance system reliability. However, there is not enough study in multi-stack configuration design and determination for aircraft propulsion applications. Apart from fuel cell applications on aviation platform, Zhou et al [110] reviewed PEM multi-stack fuel cell systems in terms of architectures, redundancy, degraded mode operation, lifetime, efficiency, and hydrogen consumption. Enlightened by them, The multi-stack related research was extended to other suitable multi-stack configurations for aircraft propulsion, considering implementation limitations of weight constraints and high voltage at high altitude in Chapter 4 and published in [20].

The hydrogen technology and PEMFC aircraft literature reviews lead to the following observations:

- **Observation 4: The rapid development in PEMFC technology makes it feasible as the primary energy supplier for aircraft propulsion system in short-term future. But the architectures with PEMFC are not commonly investigated by the study launching time. More research are required to investigate such propulsion system type.**
- **Observation 5: A comprehensive simulation framework for fully or hybrid PEMFC electric aircraft was not seen by the study was launched. The performance of PEMFC as well as the overall system depends on various fac-**

tors, such as power settings, ambient conditions, architectural selection, stack degradation level, stack reactants conditions and so on. A holistic mission level analysis considering all these factors is required to understand the system.

- **Observation 6: Battery has strength in specific power but weakness in specific energy, whereas hydrogen fuel based PEMFC has specific energy advantage but specific power shortage. It is potential to combine them to minimise the propulsion system weight with properly designed energy management strategy.**

2.4 Relevant e-aircraft simulation framework

There have been increasing number of simulation frameworks developed to study different aspects of the subsystem and system performance in differing level of details for the electrified aircraft. Some of the relevant works are briefly summarised below, with a discussion on their advantages, key features, and limitations.

S. Stückl [111] attempted to demonstrate the viability of a sole-battery-based electric propulsion system architecture for a 68 PAX ATR-72 like aircraft. In this framework, an adapted preliminary iterative sizing methodology including electric subsystem for battery-powered aircraft was proposed, as the conventional statistical-based method was not available for e-aircraft due to the lack of design data. Also, the author identified the critical components that substantially drive weight and impact safety for this type of power-train. This study also showed the practical limits of battery-based aircraft based on the foreseeable technology progress. A series of key electric subsystems were identified, modelled, and sized in the framework: storage of electric energy, electric power transmission, power switches and circuit breakers, electric motors and its drive systems, propeller and other aircraft secondary systems. Some key contributions of this paper came from the modelling of these subsystems such as the HTS cables and motors. The weight improvements brought by Li-S and Li-air battery, HTS electric motors were also

demonstrated. An interesting comparison between copper, aluminium, and superconducting materials as cable materials was also conducted and it was found that aluminium was the best suited conductor material. Although this simulation framework improved the sizing methodology for the novel e-aircraft, and included a comparison and assessment on wide range of potential technologies, there were still gaps yet to fill in. For example, many of the component used were still in early development stage, there was not enough information about more detailed operational and performance characteristics. Moreover, some key technology level assumptions were slightly ambitious, for instance the advent of commercial available battery with specific energy of 2000 Wh/kg is yet questionable. Furthermore, battery storage capacity and performance are prone to cycling degradation, but these impacts were not fully captured. Also, the specifications of HTS motor were mainly power rating and specific power, but detailed performance maps of different operation points were missing. Finally, alternative energy storage system such as fuel cell was not considered. In conclusion, the electrical models in this study were generally in low-fidelity level, mostly were based on simple mathematical correlations and physical meanings were missing, gaps on detailed mass and (off-design) performance modelling of electric architecture part remained existing.

Based on these gaps, **P. C. Vratny** [112] proposed a simulation framework attempting to close them. The framework was utilised to investigate the hybrid-electric power-train for a 180 PAX A320 like aircraft. In this framework, a more detailed electric component modelling approached was adopted to cover the relevant aspects for electric system parameters assessments. The impacts of hybridisation levels, protection systems and design voltages (values, time-varying or constant) on the system mass and design efficiency were captured. With this framework, some key findings were displayed: HTS motors provide best mass and efficiency performance for battery supplied architectures; For the considered design space, the optimum system voltage was at 2000 V driven by the electric motor voltage; a variable voltage architecture was likely an optimal design option; the sensitivity study between motor size and hybridisation level was also conducted. The key

contribution and advantage of this study comes from its electrical components modelling. All components were modelled in a way that they had common input and output parameters (power, voltage, and frequency). This way the subsystems were integrable to a wider propulsion system level. Moreover, more detailed operational and performance characteristics of them can be captured with higher accuracy. This was extremely important since the e-aircraft design was highly affected by these parameters. Before this, not many literatures systematically explored these aspects to the author's knowledge, most of them either used zero-ordered methods to cover the electrical components so that key physical terms were missing, or focused in studying components in isolation. The balance of detailed components performance and their interdependencies/integrations was realised by this study. Therefore, the methodologies developed were used by many other studies [113–115]. However, there were still limitations. For battery models the temperature, short-term cycling, long-term storage effects, cell to pack capacity reduction and internal wiring resistance were not considered. The battery design, sizing, and performance were highly affected by these factors as well. The motor model was also over-simplified by adapting a reference motor and scaling it according to designed power, rotational speed, and voltage. And the power electronics models were still adapted from first-ordered mathematical correlations. The control mechanisms of voltages or motor speeds were yet unknown and the detailed electrical operation process to realise system control was missing. Capturing them can help understanding the challenges of power electronics design, sizing, and their feasibility assessments for different application targets.

The Numerical Propulsion System Simulation (NPSS) tool is a multidisciplinary analysis environment for aircraft propulsion system assessment developed by NASA [116]. It has been the standard propulsion simulation tool used by a majority of engine and airframe OEMs as well as academia and government agencies [117]. However it is not capable of assessing novel hybrid electric architectures. **Perullo et al.** [117] attempted to extend the ability of NPSS to capture different electric elements for novel hybrid electric configurations. The key contributions are the generic features of the electrical subsystems

developed and their seamless integration capabilities. Solvers for cryocooler and superconductor were also developed and integrated within the framework enabling a design exploration on more novel technologies. However, there are still some shortcomings of this framework: Firstly, the bus voltage and total electric energy storage capacity was randomly decided, thus the sizing process of battery and fuel cell became random as well. Secondly, the fuel cell sizing was still preliminary, as only single stack was utilised in the system and the power only determined its area and cell numbers. Alternative was to use multi-stack configurations for safety and redundancy considerations. Thirdly, the energy management strategy impact on subsystems sizing and performance was not considered, which was another key factor for architectural design and decision makings. Finally, a mission level analysis was missing due to its isolation from aircraft level operations.

To fill in these gaps, **Trawick et al.** [5] proposed a simulation framework named Georgia Tech Hybrid Electric Analysis Tool (GT-HEAT). This framework was also an extension of NPSS, containing a suite of electrical components, aero analysis, and thermal management systems. Moreover, its ability to capture steady state, dynamic, and transient effects of GTs, energy storage, and aircraft in an integrative way allowed it to perform a more mission level system design and assessment [5]. The functional architecture of GT-HEAT is shown in Fig. 2.4.

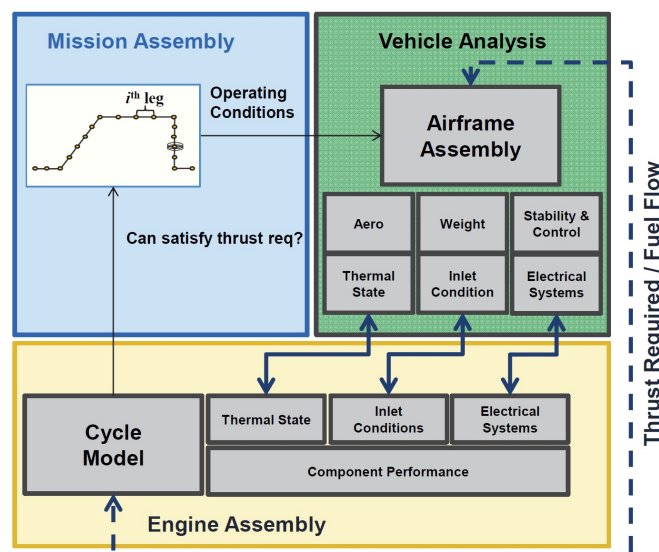


Figure 2.4: Functional architecture of GT-HEAT adopted from [5].

Its introduction was detailed in [5], the key feature was that the GT-HEAT provided an integrated sizing and synthesis platform for aircraft level operation analysis, electrical subsystem, and gas turbine engine performance evaluation for holistic missions. With these capabilities, different operation variations such as fan pitch angle, fan speed, hybridisation level were also investigated. These activities closed the gaps in [117]. However, the electrical component models were still quite basic. For instance, the battery utilised was a Thevenin-based model with equivalent resistors only to capture the waste heat for different power, a more suitable model for runtime prediction, DC response, storage degradation, temperature impacts was not seen. Power electronics were treated as black boxes with fixed efficiencies. Motors were not included in this framework. Moreover, the technology levels of most electrical components were still implicit, and their impacts on system sizing and performance were not considered.

M. E. Bell and **J. S. Litt** from NASA designed a simulation framework under Simulink environment named The Electrical Modelling and Thermal Analysis Toolbox (EMTAT) [118–120]. It was specifically designed for electric propulsion systems simulation at the level of fidelity (time scale) appropriate to capture the interaction with turbomachinery. The thermodynamic performance of turbomachinery was simulated by the Toolbox for the Modelling and Analysis of Thermodynamic Systems (T-MATS) also developed by NASA [121]. The combination of EMTAT and T-MATS enabled the creation of complex thermodynamic and electrical system simulations. The EMTAT electrical models were divided into two main libraries: power flow and physics-based. Power flow models had several characteristics: easy component adding or removal, components can be represented by equivalent circuits, and fast simulation time. While for physics-based models, specific physical performance parameters were modelled with higher fidelity level. Firstly, the internal component properties could be defined by user with their iDesign tools. Secondly, temperature feedback blocks were included for each component. This way, the components performance changes due to changing temperatures caused by their generated heat could be captured. And finally, a wide range of electrical components were available

within the libraries. However, there were still drawbacks of the framework. Firstly, the fuel cell system was not seen in their libraries. Fuel cell is considered competitive as the energy storage system and should be included. Secondly, although all EMTAT equations and default component maps were adopted from public sources, there was no validation process seen to testify the results, hence the limitations and boundaries of these models were mostly unknown. Thirdly, the sizing process for various electrical components was not clear and their property value selections were arbitrary. No concrete methodology was seen in these aspects. Finally, all EMTAT models were assumed steady state as the time-scale of electric component was negligible in comparison to that of turbomachinery. However, omitting the time-variant terms could potentially limit the design exploration space on electrical systems, especially the control systems for converters, motor drives, and power distribution systems. These explorations are significant for safety consideration such as power overshoot avoidance and ripple suppression.

The literature reviews on e-aircraft simulation framework lead to following observations:

- **Observation 7: Most of simulation frameworks assumed healthy state of energy storage system. However, their degradation impacts on system sizing and performance were not fully considered.**
- **Observation 8: A wide range of electrical component models were developed and integrated into e-aircraft simulation frameworks to capture important aspects, however a simulation framework focusing on fuel cell based propulsion system was not seen yet.**

2.5 Concluding remarks

There is an increasing need for greener or even zero emission aviation. To achieve such goals, the aviation and academia sectors are developing novel concepts such as electric and hybrid electric propulsion technologies.

The literature survey showed that many conceptual studies focused on parametrically varying technology level such as component specific energy and power for aircraft weight and range sensitivity analysis, the detailed electrical system were slightly overlooked by them. Although the number of simulation framework focusing on electrical system was gradually increasing, they all had different limitations in methodologies and findings. Moreover, a systematic analysis on PEMFC based propulsion architecture was yet to conduct. Throughout this chapter, the following observations were made:

1. The majority of these aircraft conceptual studies focused on parametrically varying the technology levels for the range and weight sensitivity. However not many studies considered the electrical performance aspects, such as short time-scale electrical performance during mission, efficiency variation profiles, and long time-scale component degradation impacts. A consensus on how to assess the electrical systems for these novel power-trains has yet to be reached.
2. Many of these studies relied on radical technology levels and concepts: high component specific energy and power, HTS technologies, boundary layer ingestions or distributed electric propulsion concepts. A more mid-term future technology was slightly overlooked.
3. Battery was preferable to many studies, however the state-of-art specific energy is far from the minimum requirements proposed by the Committee [28], especially for regional/single-aisle aviation sector. The development of energy storage of batteries is gradually reaching its limit, but alternative energy storage and energy conversion systems such as hydrogen-based fuel cells were not adequately explored or investigated for aircraft propulsion.
4. The rapid development in PEMFC technology makes it feasible as the primary energy supplier for aircraft propulsion system in short-term future. But the architectures with PEMFC are not commonly investigated by the study launching time. More research are required to investigate such propulsion system type.

5. A comprehensive simulation framework for fully or hybrid PEMFC electric aircraft was not seen by the study was launched. The performance of PEMFC as well as the overall system depends on various factors, such as power settings, ambient conditions, architectural selection, stack degradation level, stack reactants conditions and so on. A holistic mission level analysis considering all these factors is required to understand the system.
6. Battery has strength in specific power but weakness in specific energy, whereas hydrogen fuel based PEMFC system has specific energy advantage but specific power shortage. It is potential to combine them to minimise the propulsion system weight with properly designed energy management strategy.
7. Most of simulation frameworks assumed healthy state of energy storage system. However, their degradation impacts on system sizing and performance were not fully considered.
8. A wide range of electrical component models were developed and integrated into e-aircraft simulation frameworks to capture important aspects, however a simulation framework focusing on fuel cell based propulsion system was not seen yet.

In conclusion, important knowledge gaps were identified from these observations. The majority of EP/HEP conceptual design and studies for regional aircraft fell into two typical extremes. Some focused on propulsion system level and used low-fidelity electrical models. Essential component parameters were based on fixed specific energy, specific power, and efficiency. But key information were missing, such as high fidelity component electrical dynamic performance, physical parameters including component temperature, FC air supply pressure, mass flow rate, component degradation impacts, component architectural effects and etc. Whereas some component specialised studies conducted in depth research on individual components with high fidelity methods. But the problems associated with integrating components to higher aircraft propulsion system level or interdependencies amongst different subsystems seemed to be overlooked. There was a

gap between these two extremes. Further research and development are required to integrate the above-mentioned features into a multi-disciplinary simulation environment. Therefore a modular-based simulation framework and analysis methodology, capable of capturing detailed component level as well as higher propulsion system level performance evaluation is required.

Moreover, hydrogen based PEMFC system is an alternative option to battery and gradually capturing attentions from academia and industrial sectors. It can provide decarbonised electrical propulsion for aircraft and its hydrogen fuel naturally has significant advantage in terms of energy density. But the research was still at preliminary stage. An in-depth systematic investigation on PEMFC propulsion system was yet to be conducted.

Finally, there was inadequate simulation framework considering component degradations and their impacts on propulsion system performance. More investigation on this topic was required. Degradations were significant as they could hugely impact key components such as PEMFC systems and batteries. This would further lead to serious repercussions to the propulsion systems, such as power losses, efficiency drops, component malfunctions and even engine shutdowns. Degradation models need to be included in the multi-fidelity simulation framework to evaluate their impacts on the system.

Chapter 3

Methodology and Simulation

Framework

3.1 Introduction

This chapter describes the simulation framework developed for a typical 50 PAX regional aircraft electric propulsion (EP) and hybrid electric propulsion (HEP) systems. This framework helps extend the capability of the in-house CHARM (Cranfield Hybrid Electric Aircraft Research Model). Firstly, the CHARM toolkit is introduced, with applications on retrofit ATR42 aircraft model simulation for all flight mission information: power, speed, and altitude profiles. Then the proposed EP and HEP architectures for this study are presented. Next, all subsystem models are elaborated, including a PEMFC system, a lithium-ion battery pack, DC/DC converters, PMSMs and inverter based motor control systems. Finally, the complete integrated electric propulsion systems are introduced, with the mission-level performance assessment process presented.

These developed subsystems help multi-objectives, multi-fidelity level study for the electrical system, such as components and system design, on- and off-design performance analysis, and capture the interactions between the sub-system and aircraft level. The proposed electrical system design, modelling, and integration form the in-house E-HEART

(Enabling-Hybrid Electric Aircraft Research and Technology) tool, which helps extend the CHARM and becomes part of it now.

3.2 CHARM and retrofit ATR42 aircraft model

CHARM is developed in the Centre for Propulsion and Thermal Power Engineering at Cranfield University to explore key technologies and synergies for novel electrified aircraft. It enables conventional/novel aircraft configurations design and mission performance analysis [122–124], gas turbine performance simulation, novel electric propulsion architectures evaluation [20, 39], multi-fidelity electrical component and system behaviours analysis [20], motor and propeller coupling, energy management strategies exploration, thermal management system (TMS) analysis, emission calculations, system diagnostic and component life assessment [125, 126]. Fig. 3.1 shows the outline of CHARM partially.

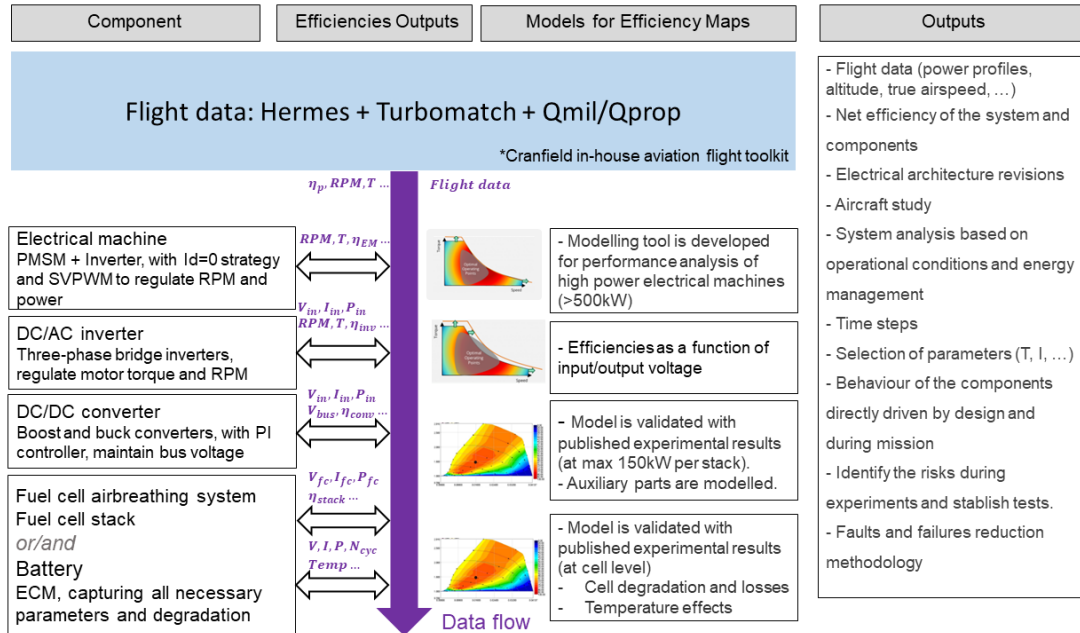


Figure 3.1: Outline of Cranfield Hybrid Electric Aircraft Research Model (CHARM).

Within CHARM, the aircraft motion simulation is performed by an in-house environment HERMES. For this toolkit, the aircraft lift and drag, climbing, acceleration and flight

path calculations are based on flight mechanisms equations and input aircraft geometry. The detailed development process can be found in [127]. The gas turbine performance is simulated by another in-house tool Turbomatch, where the development process is detailed in [128]. Turbomatch is a component-based tool for gas turbine, it resolves the engine operating point at design and off-design point, at steady and transient state, based on gas turbine component maps, thermodynamics laws, and mass, momentum and energy conservation principles. The variable pitch propeller performance is simulated by MIT's free tool Qmil/Qprop [129], where classical blade-element/vortex formulation is the main principle [130] for propeller design and performance simulation. It should be mentioned that, the detailed aircraft/gas turbine/propeller design and analysis is out of scope, and this process is conducted by Cranfield Centre for Propulsion and Thermal Power Engineering.

Using these tools, a series of retrofit aircraft model performance data are obtained. The retrofit model is based on ATR42 regional aircraft, with twin Pratt & Whitney PW127M turboprop engine models rated at 2 MW (with maximum power at 2.4 MW) each. The publicly available data [101, 131] are used in the models. The retrofit approach is considered in this study because:

1. The already wide design space of electric propulsion can be further simplified by removing aircraft geometry and configurations as variables. This way, the present analysis can focus more on electric propulsion system only.
2. Retrofitting existing aircraft with new electric propulsion systems can provide environmental benefits in a shorter time-frame as additional time and costs are required for developing, testing, and certifying brand new aircraft concepts. Even though a disruptive aircraft concept may offer optimised solutions with aerodynamics-propulsion synergic effects, the costs to overcome potential challenges will compensate the benefits. Also, the dramatic change in aircraft design could bring uncertainties for airport infrastructure, operation, and management. Therefore, retrofitting existing aircraft is likely to be the most logical pathway to market in short-term future.

For retrofit approach in this study, the same Maximum Take-Off Weight (MTOW) and fuselage volume is maintained as aircraft lifting surfaces are not changed. The additional mass and volume brought by electrical system is compensated by passenger reduction. All flight information obtained are utilised for the propulsion system performance studies.

After obtaining a series flight data, especially power, altitude, airspeed and propeller rotational speed profiles by HERMES and Turbomtach in Fig. 3.1. It is then assumed that the electric system partially or completely replace the gas turbine engines for hybrid electric or pure electric architecture. The propeller rotational speed and gas turbine power is firstly fed into the electrical machine and DC/AC inverter models where rotational speed, torque, and power profiles are required to maintain at the desire values along mission. The DC/AC inverter then acts as the motor rotational speed controller and torque by applying ' $I_d = 0$ ' strategy and SVPWM technique. Upstream the DC/AC inverter, a DC/DC converter model is used to maintain desired bus supply voltage along different mission phases. Finally, the energy storage and power system such as fuel cell and battery models are implemented. Their rating, sizing, and wiring topologies are determined based on the power requirements and research problems.

All important model outputs are propagating within the electrical systems. The bus voltage is controlled and maintaining at desired value by DC/DC converter modules; and electric machines rotational speed and torque are controlled by DC/AC inverter modules. Each of these components are outputting electrical parameters, such as voltage, current, power, and efficiency as shown in Fig. 3.1. Moreover, the system net efficiency is the product of all component efficiencies. All these outputs are collected in a data sink for further investigations.

3.3 Propulsion system architecture in this study

For this study, two groups of power-train architectures are utilised: pure fuel cell electric propulsion (PEMFC-EP) and hybrid electric propulsion (HEP) system:

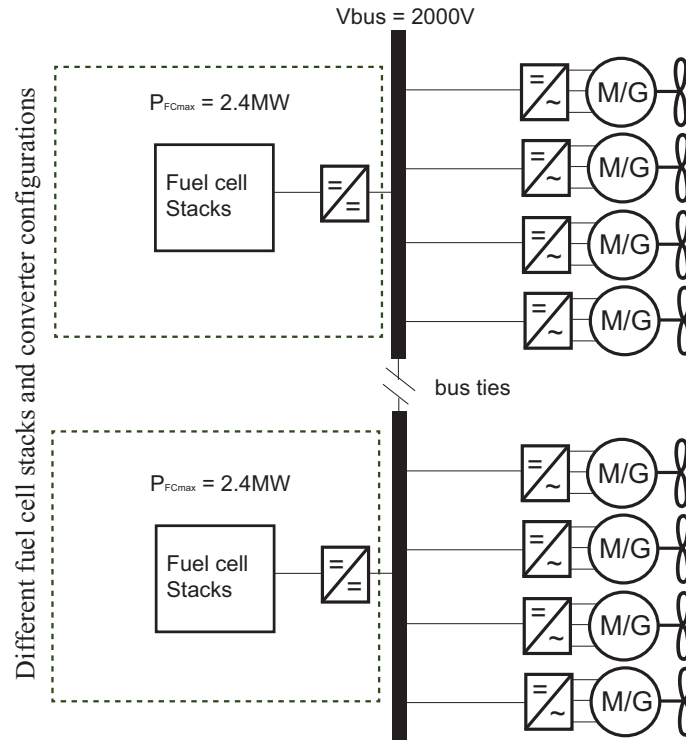
PEMFC-EP architecture

Figure 3.2: Pure fuel cell electric propulsion (PEMFC-EP) architecture.

For PEMFC-EP shown in Fig. 3.2, two DC bus are connected by bus ties, with each “side” providing 2.4 MW of power for the propulsion system. For each side, the fuel cell stack is the only source of propulsion power. For the FC stack, an air-breathing system is designed to supply air for electro-chemical reaction. Downstream the FC stack, a DC/DC converter system is utilised to maintain the bus voltage for power transmission. Eight permanent magnet synchronous machines (PMSM) designed for 500 kW at rotational speed of 2000 RPM are used for propulsion, with propeller attached. For each PMSM, a controllable DC/AC inverter is used to control the rotational speed of it under various power requirements along the mission.

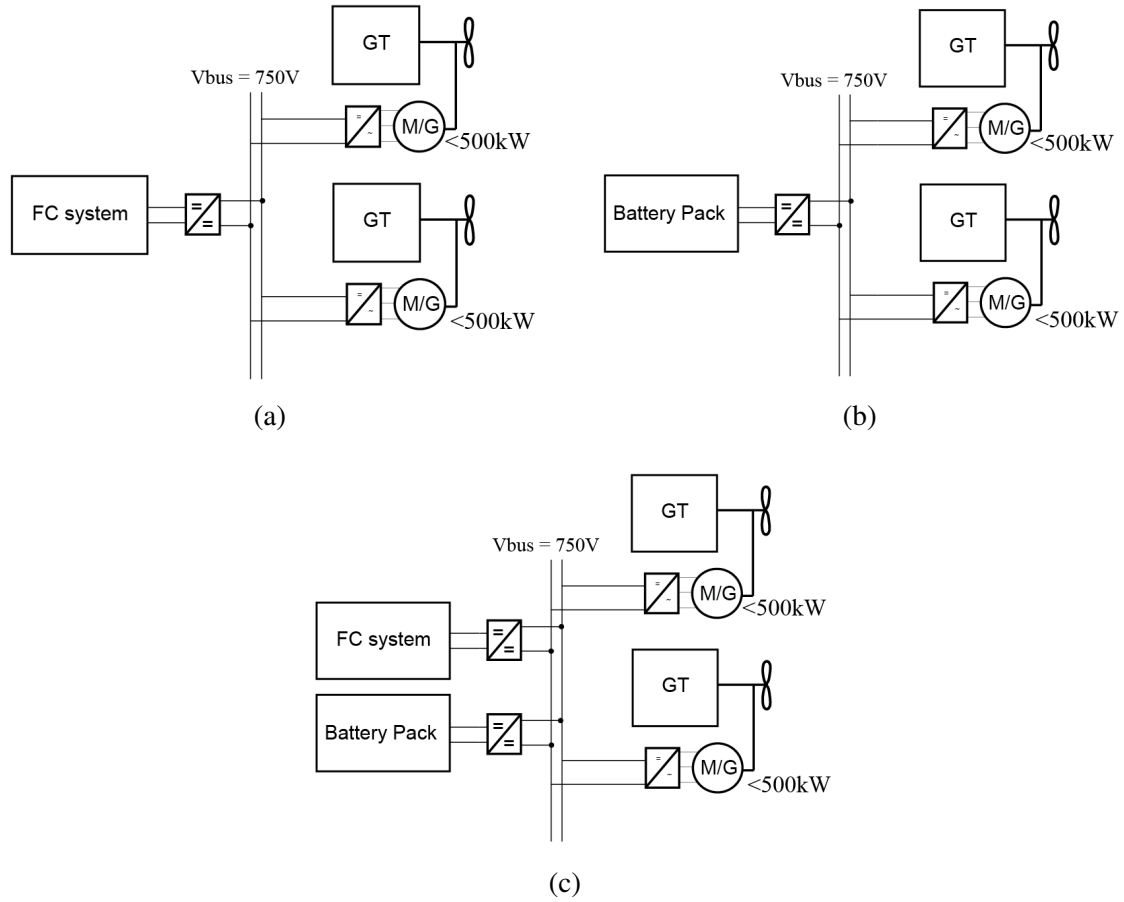
HEP architecture

Figure 3.3: (a) Hybrid FC architecture. (b) Hybrid battery architecture. (c) Hybrid FC/-battery architecture.

As introduced in Chapter 2, HEP is mainly categorised by series and parallel hybrid architecture. For series hybrid, the gas turbine can be decoupled from propulsive part, resulting in a more efficient gas turbine system. But with generator systems, the overall weight is generally heavier than parallel ones. Moreover, with more energy conversion stages, the series configuration exhibits lower efficiency than its parallel counterpart. Finally, the generator cannot charge FC system in case it is hybrid-FC configuration. This further undermines the advantages of series hybrid. For parallel hybrid architecture, the gas turbine and the electric motor are mechanically connected. Though this connection topology needs a complex gearbox system and gas turbine control system, it does not require heavy generators and their power regulators, resulting in a lighter propulsion system. Moreover,

with fewer energy conversion stages, it has higher system efficiency [49]. Therefore, a parallel hybrid architecture is used in this study.

As shown in Fig. 3.3, three architectures are proposed. The difference is in their electric energy system: with either PEMFC, battery or FC/battery combination. The energy source is connected with a DC/DC converter system to maintain the bus voltage. A DC/AC inverter is connected downstream of the bus line to control the motors. Two PMSMs with 500 kW power are mechanically connected to two gas turbines, together providing propulsion power via propellers.

It should be noted that, by the time of initiating this study, 500 kW motor is considered reasonable since motor with such power level is available in market and its specifications can be found for validations. Mega Watts motors were still under preliminary design phase by that time. Moreover, the weight and electrical performance of power cable were not considered in this model.

In order to investigate the performance of the PEMFC-EP/HEP architectures, the prominent features of their subsystems and components are studied first. Their working principles, modelling methodologies, simulation results and validation against peer-reviewed data are presented in the following contents. All these proposed and developed models will be integrated to form the complete propulsion systems.

3.4 PEMFC system model

In this section, the working principle of proton exchange membrane fuel cell (PEMFC) is firstly introduced. Its modelling methodology is then explained. Finally, the simulation validation of this fuel cell model is shown to prove the accuracy of modelling results.

3.4.1 PEMFC working principles

Fuel cells are electro-chemical devices that convert chemical energy of a fuel directly into electrical energy, rejecting only water and heat. And PEMFC is one of the most promising commercialised fuel cell types [86]. A PEMFC cell-level schematic diagram in Fig. 3.4 details the core components and working principles. There are three key components: a hydrogen fuel electrode (anode), an oxidant accepting electrode (cathode) and a proton exchange membrane electrolyte sandwiched between them. Both electrodes are covered with catalyst layer (platinum in PEMFCs) for electrochemical reaction.

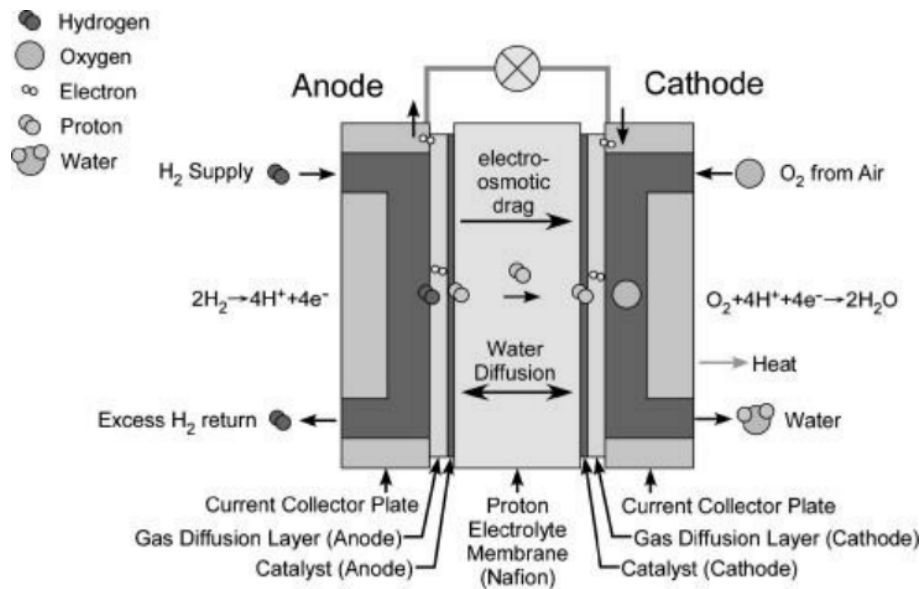


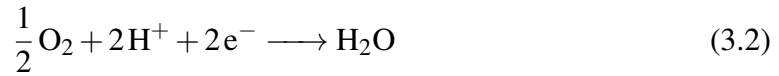
Figure 3.4: A schematic diagram of PEMFC [6].

Hydrogen fuel molecules (H₂) are delivered from a gas-flow stream to the anode and

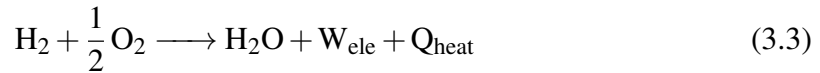
react electrochemically. They are oxidised to form ions (H^+) and electrons (e^-):



The H^+ ions migrate through electrolyte membrane and the electrons e^- are driven via an external circuit to the cathode side. The hydrogen ions and electrons react with supplied oxygen at the cathode to form water:



The overall electrochemical reaction is shown as follows, with water, heat and electric power produced:



A typical cell has a current density from 200 to 900 mAcm^{-2} , generates 0.5 to 0.8 V voltage. For an aircraft application there is a need for high current and voltage capacity. Higher current and voltage level can be obtained by connecting more cells in series with larger area. This module is known as a “fuel cell stack”. Moreover, PEMFCs normally operate at pressure higher than 1 bar, but because aircraft ambient pressure drops with altitude (decreasing to 0.5 bar at 5.4 km above the sea level), it is necessary to include a compressor model in the PEMFC auxiliary system (also known as balance of plant) to deliver and compress the reactant air.

3.4.2 PEMFC system modelling and assumptions

The PEMFC models adopted in this study is detailed by Tremblay and Dessaint [7]. This is a generic FC model that combines chemical features and electrical models, the model parameters and specifications adopted from fuel cell datasheet can be input to define the model types and characteristics. Fig. 3.5 shows a schematic diagram of this fuel cell stack model. The model is based on an equivalent circuit. Block A, B, and C calculate all

chemical features of FC, including pressures and flow rates, stack temperature and gases compositions. The equivalent circuit is updated based on these inputs. This way, FC thermodynamics and operating parameters are all captured for fuel cell electrical performance simulations.

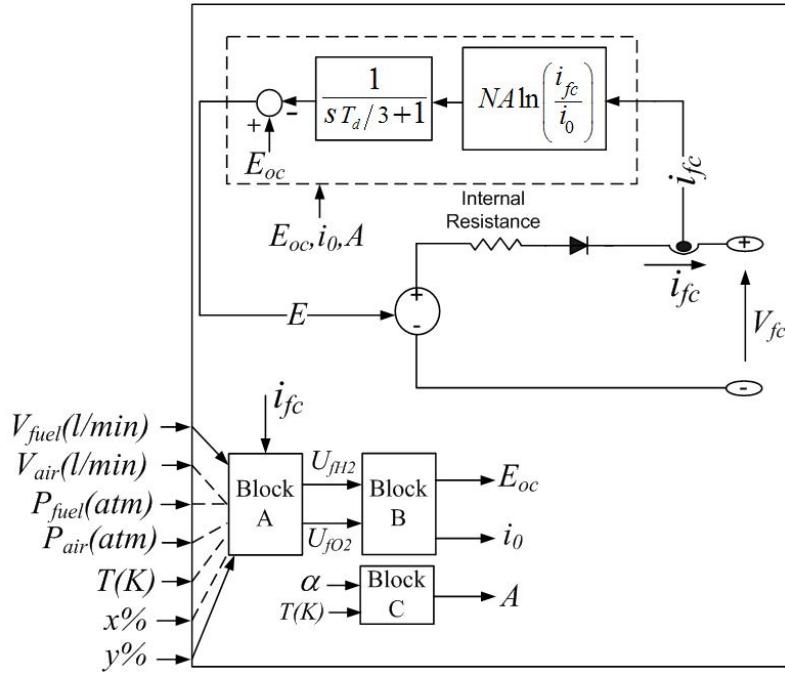


Figure 3.5: PEMFC stack equivalent circuit model adopted in [7].

A set of assumptions considered are listed below:

- (i) All gases obey the ideal gas law.
- (ii) Hydrogen and air is fed to the stack.
- (iii) An ideal thermal management system is equipped to maintain the temperatures at the cathode/anode uniform and equal to the stack temperature.
- (iv) An ideal water management system is equipped to maintain appropriate humidity level inside the stack at any load.
- (v) The total pressure inside the stack is uniform.
- (vi) The concentration losses are neglected as most fuel cells do not operate in the mass transport region.

(vii) The stack ohmic resistance is constant at any operation conditions.

Another key component is the compressor in auxiliary system. The compressor model is based on compression and expansion thermodynamic process calculation. The power consumed by compressor is determined inlet and outlet ambient conditions and isentropic efficiency. A fixed 85% compressor isentropic efficiency is considered in this model, regardless its stage number, mass flow and pressure ratio.

3.4.3 PEMFC system key equations

In the following contents, key modelling equations are introduced:

Key equations for PEMFC

The PEMFC voltage decreases from open circuit voltage (also known as reversible voltage) because of irreversible losses. The output voltage is given by [132, 133].

$$V_{fc} = E_{oc} - V_{ohmic} - V_{act} \quad (3.4)$$

where V_{fc} is the fuel cell voltage, E_{oc} is fuel cell open-circuit voltage, V_{ohmic} and V_{act} are the ohmic and activation over-potential.

Considering the temperature and gas pressure effects, the open-circuit voltage is expressed as [132, 134, 135]:

$$E_{oc} = K_c \left[1.229 + (T - 298) \frac{-44.43}{zF} + \frac{RT}{zF} \ln \left(p_{H_2} p_{O_2}^{\frac{1}{2}} \right) \right] \quad (3.5)$$

where K_c is the voltage constant at nominal condition, T is the fuel cell operating temperature, z is the moving electron number, F is the Faraday constant, R is the universal gas constant, and p_{H_2} and p_{O_2} are gas partial pressure.

The ohmic and activation over-potentials are expressed as:

$$V_{\text{act}} = \frac{1}{\tau s + 1} N A \ln \left(\frac{i_{\text{fc}}}{i_0} \right) \quad (3.6)$$

$$V_{\text{ohmic}} = R_{\text{ohmic}} i_{\text{fc}} \quad (3.7)$$

where τ is the fuel cell dynamic time constant, N is the cell number, R_{ohmic} is the stack inner resistance, and i_{fc} is the fuel cell current. The Tafel slope A and exchange current i_0 are expressed as follows:

$$i_0 = \frac{z F k (p_{\text{H}_2} + p_{\text{O}_2})}{R h} e^{(-\Delta G / RT)} \quad (3.8)$$

$$A = \frac{RT}{z \alpha F} \quad (3.9)$$

where k is the Boltzmann's constant, h is the Planck's constant, and ΔG is the activation energy barrier.

$$\eta_{\text{FC,stack}} = \frac{P_{\text{stack,tot}}}{\dot{m}_{\text{H}_2} \Delta h_{\text{HHV,H}_2}} \quad (3.10)$$

$$\eta_{\text{FC,system}} = \frac{P_{\text{stack,tot}} - P_{\text{BoP}}}{\dot{m}_{\text{H}_2} \Delta h_{\text{HHV,H}_2}} \quad (3.11)$$

where $\eta_{\text{FC,stack}}$ and $\eta_{\text{FC,system}}$ are fuel cell stack and system efficiency, $P_{\text{stack,tot}}$ and P_{BoP} are stack and balance of plant power, $\dot{m}_{\text{H}_2}$ is the supplied hydrogen fuel flow rate, and $h_{\text{HHV,H}_2}$ is the hydrogen higher heating value (HHV) [136].

Key equations for compressor

The schematic diagram of the compressor is shown in Fig. 3.6. The main function of the compressor is to increase the pressure of the flow. Generally, it accounts for most balance

of plant (BoP) work [136]. Therefore, it is assumed that all BoP power is consumed by compressor, and this compression power is directly supplied by fuel cell stacks. The compressor equations are expressed as follows:

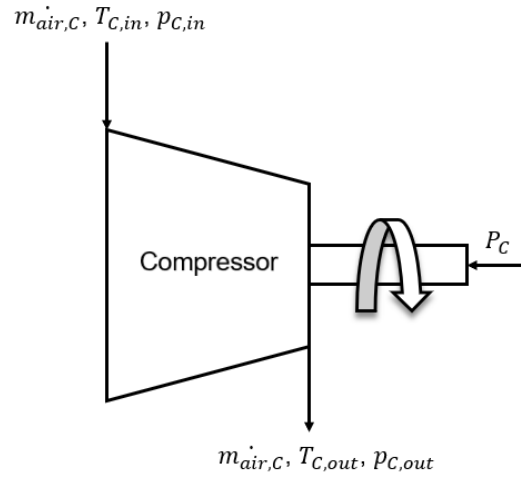


Figure 3.6: The schematic diagram of a compressor for balance of plant.

$$P_{BoP} = P_C = \frac{c_{p,air} T_{C,in}}{\eta_C} \left[CPR^{\frac{\gamma-1}{\gamma}} - 1 \right] \dot{m}_{air,C} \quad (3.12)$$

$$CPR = \frac{p_{C,out}}{p_{C,in}} = \left(\frac{T_{C,out}}{T_{C,in}} \right)^{\frac{\gamma}{\gamma-1}} \quad (3.13)$$

where P_C is the compressor power, $c_{p,air}$ is the air specific heat capacity, $T_{C,in}$ is the inlet total temperature, η_C is the compressor adiabatic efficiency, CPR is the compressor pressure ratio, γ is the air specific heat ratio, $\dot{m}_{air,C}$ is the air mass flow rate, $p_{C,out}$ is the output total pressure, $p_{C,in}$ is the inlet total pressure, and $T_{C,out}$ is the output total temperature.

3.4.4 PEMFC system specifications and key parameters

In this study, the proposed PEMFC model is based on the Ballard 150 kW FCvelocity™ HD6 datasheet [23]. The key performance specifications of this FC stack are shown Table 3.1. Also, with the PEMFC model, the key output data obtained are summarised in Table 3.2. And these specifications are used for system validation in Section 3.4.5.

Table 3.1: Specifications for modelling Ballard 150 kW FCvelocity™ HD6 FC [23].

Specifications	Values	Specifications	Values
nominal V & I	[568 V, 267 A]	cell number	762
max. V & I	[550 V, 300 A]	nominal T	330 K
nominal & max. P	[151 kW, 165 kW]	nominal $\dot{m}_{\text{air}}$	3653 lpm
nominal utilisation	[92.47%(H ₂), 54.2%(O ₂)]	nominal p_{air}	2.06 bar
nominal effi.	55%	nominal p_{H_2}	2.24 bar
reactant conc.	[99.99%(H ₂), 21.0%(O ₂)]	dynamic time const.	0.1 s

Table 3.2: Model simulation input parameters and sizing and performance outputs for the PEMFC system model.

Model simulation inputs	Sizing outputs	FC performance outputs
Single FC stack mass [kg]	FC system mass [kg]	FC voltage [V]
Ambient con. [K, Pa, kgm ⁻³]	H ₂ mass [kg]	FC current [A]
Energy required [kJ]	H ₂ tank mass [kg]	FC power [kW]
Power required [kW]	Compressor size [kg]	Compressor power [kW]
Stack temperature [K]		FC stack effi. [%]
H ₂ tank gravi. density [wt%]		FC system effi. [%]
Compressor $S.P.$ [kWkg ⁻¹]		H ₂ flow rate [kgs ⁻¹]
Compressor effi [%]		Air flow rate [kgs ⁻¹]
		H ₂ cons. rate [kgs ⁻¹]
		Air cons. rate [kgs ⁻¹]
		H ₂ O prod. rate [kgs ⁻¹]

*The mass of H₂ and fuel tank are calculated in Section 5.4.3.

The input specifications shown in Table 3.1 define the performance characteristics of the selected FC module, and the output parameters shown in Table 3.2 will be used to assess the performance of FC in aircraft application considerations. Moreover, all these component level simulation results will be used and interact with other subsystems.

3.4.5 PEMFC system validation

In order to prove the accuracy of the PEMFC system model, a series of validation tests are carried out. The simulation outcomes are compared with the experimental data presented by Li, Chen, et al [8]. The comparisons between experimental testing data and simulation polarisation curves for “Voltage-Current” and “Power-Current” are shown in Fig. 3.7a and Fig. 3.7b. The testing and simulation relations between FC air supply mass flow rate, pressure, FC output current, and power are shown in Fig. 3.7c.

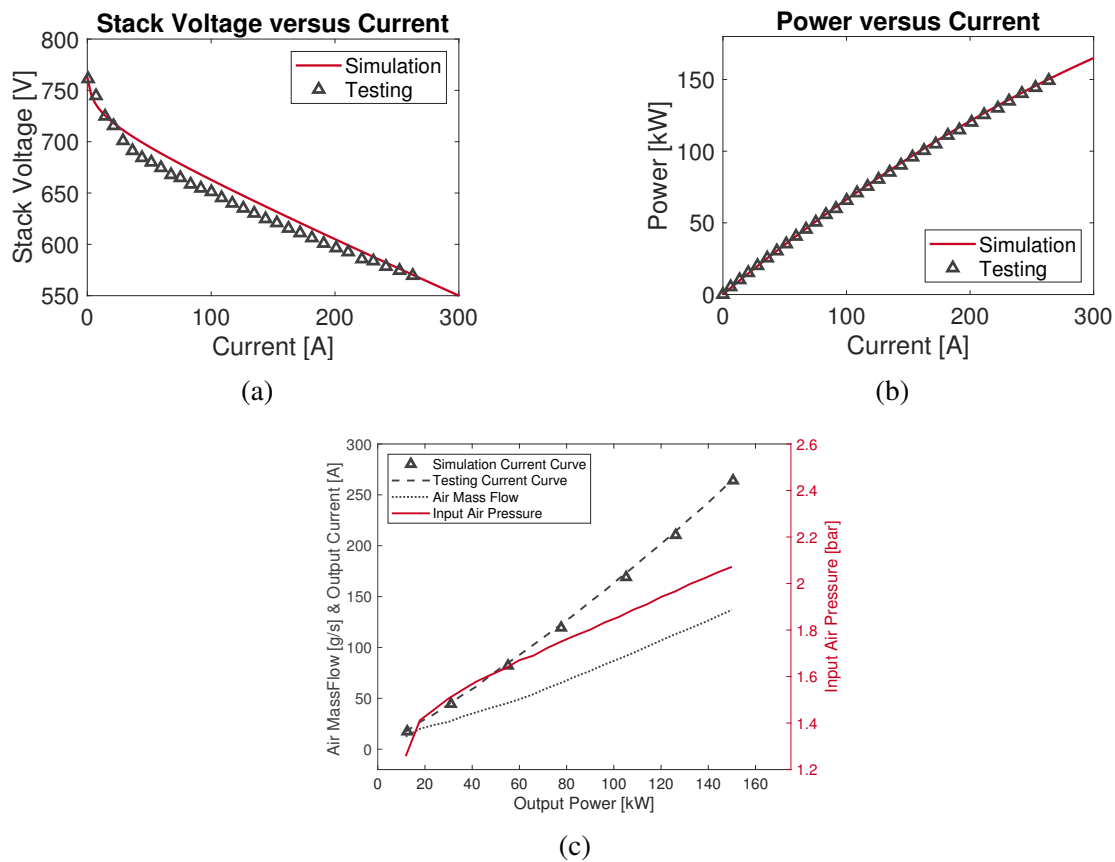


Figure 3.7: Validation of (a) voltage-current curve, (b) power-current curve, and (c) relations between air mass flow rate, air pressure and FC output current and power against reference experiment data in [8].

Despite some minute deviations, the simulated polarisation curves and $P - I$ curves against $\dot{m}_{\text{air}} - p_{\text{air}}$ are in good match with the experimental testing results. The fuel cell arrays are formed by these individual stacks, therefore this validation is considered viable for propulsion system level.

3.5 Battery model

In this section, the working principle of lithium battery is firstly introduced. Its modelling methodology is then explained. Finally, the simulation validation of this battery model is presented to prove the accuracy of modelling results.

3.5.1 Battery working principles

A battery pack is made up from one or more cells connected in parallel or in series. Cell is the smallest individual unit that stores electro-chemical energy and releases it as electrical energy. A basic schematic diagram of lithium ion cell is shown in Fig. 3.8.

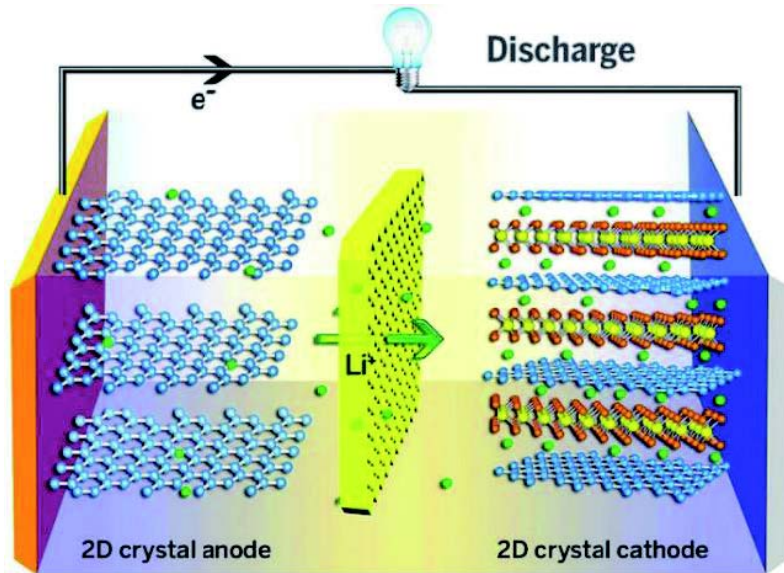


Figure 3.8: A schematic diagram of Li-ion cell [9].

The lithium is stored in electrodes as independent charge-neutral atoms, with their valence electrons loosely shared with neighbouring atoms. When discharge, Lithium atoms at negative electrode (anode) surface lose electrons and become Li^+ ions, and migrate to positive electrode (cathode) via electrolyte. Simultaneously, the lost electrons move toward cathode via external circuit. At the cathode surface, Li^+ ions accept electrons, the resulting charge-neutral Li atoms then enter the crystal structure of the positive electrode. This process is reversible, so that Li^+ ions travel back and forth between two electrodes

during charging and discharging process.

Generally, a lithium cell operates at 3.7 to 4 V, and stores about 1.8 Ah [137]. For propulsion system of regional aircraft, much higher voltage, current and energy is required. Therefore, a large number of lithium cells are connected in series and parallel to form battery packs. With battery packs, the large energy and power rating requirements can be obtained for aviation applications.

3.5.2 Battery system modelling selection

Whilst the battery working principle is established, modelling the battery performance can be complex. There are two fundamentally different models that can describe the operation of Li-ion battery [138]:

- **Physics-based models (PBMs):** PBMs usually have highest level of fidelity and accuracy and are generally used for battery research and development work. These models utilise equations of a wide range of first-principles physical laws that compute the internal cell electrochemical states and provide accurate information for battery design process, such as spatial Li-ion concentrations and spatial electric potential. However, these models are often expressed in coupled partial differential equations (PDEs), which can cause slow simulations, as well as robustness and convergence problems. Moreover, these models often require detailed macroscopic and microscopic information of battery and their outputs are not suitable for system-level studies. Therefore, these models are not considered in this study.
- **Equivalent circuit models (ECMs):** ECMs use electrical-circuit components to analogously define the cell behaviours. This is a “phenomenological” way to mimic the battery’s electrochemical performance and is most common in system-level studies. Firstly, unlike PBMs, the detailed information of battery is not required. The values of circuit element parameters can be ‘tuned’ against lab testing data so that the modelled voltage-current behaviour can be closely match the true cell.

Additional fidelity can be added depending on research needs, such as temperature impacts and cell degradation effects. However, these additional fidelity and circuit elements are semi-empirical and highly dependent on the cell types being tested. Moreover, these models cannot predict internal electro-chemical states, but they yield fast and robust simulations for input/output (current/voltage) behaviours. They are suitable for system-level studies, especially when battery management system (BMS) is considered. Therefore, ECMs are used in this study.

From above discussion, ECM is used for this study. The key features captured are cell dynamic $V - I$ performance, temperature and capacity fading effects on cell dynamics. Its detailed model developed is detailed in the following contents.

3.5.3 Battery system modelling and key equations

In this section, the cell level ECM is first introduced, then this model is expanded to battery pack level.

Lithium cell model

The cell level models adopted in this study is detailed in [137]. Fig. 3.9 demonstrates the schematic of lithium cell ECM. In this model, a controlled voltage source is connected with one temperature related potential, one series resistor, one cycle resistor and two RC branches. These components represent different features of the lithium cell. The key model equations are provided in the following contents.

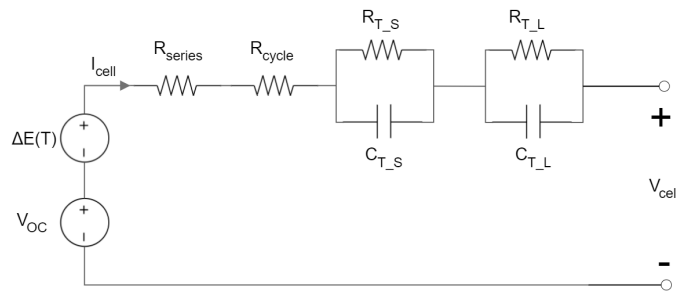


Figure 3.9: A schematic diagram of Li-ion cell equivalent circuit model.

Cell voltage V_{cell} is expressed as:

$$V_{\text{cell}} = V_{\text{OC}} + \Delta E(T) - V_{\text{series}} - V_{\text{cycle}} - V_{\text{T.S}} - V_{\text{T.L}} \quad (3.14)$$

According to Kirchhoff's law, four voltage loss terms (V_{series} , V_{cycle} , $V_{\text{T.S}}$, and $V_{\text{T.L}}$) can be found as follows:

$$\begin{aligned} V_{\text{series}} &= I_{\text{cell}} \cdot R_{\text{series}} \\ V_{\text{cycle}} &= I_{\text{cell}} \cdot R_{\text{cycle}} \\ \frac{V_{\text{T.S}}}{R_{\text{T.S}}} + C_{\text{T.S}} \frac{dV_{\text{T.S}}}{dt} &= I_{\text{cell}} \\ \frac{V_{\text{T.L}}}{R_{\text{T.L}}} + C_{\text{T.L}} \frac{dV_{\text{T.L}}}{dt} &= I_{\text{cell}} \end{aligned} \quad (3.15)$$

where, V_{OC} is the open circuit voltage; $\Delta E(T)$ is the temperature correction of cell potential; V_{series} and R_{series} are responsible for instantaneous voltage drop in cell terminal voltage; V_{cycle} and R_{cycle} are used to describe voltage drop due to cycling effects (will be discussed later); ($V_{\text{T.S}}$, $R_{\text{T.S}}$, $C_{\text{T.S}}$) and ($V_{\text{T.L}}$, $R_{\text{T.L}}$, $C_{\text{T.L}}$) are used to capture short- and long-time constants of step response for cells identified by Chen et al [11].

Another key parameter is the state of charge (*SOC*), which is the ratio of remaining capacity to nominal cell capacity. It provides information on potential runtime of the cell. Its expression is as following:

$$SOC = SOC_{\text{ini}} + \int \frac{I_{\text{cell}}}{Cap_{\text{cell.usable}}} dt \quad (3.16)$$

where SOC_{ini} is the initial state of charge and $Cap_{\text{cell.usable}}$ is the usable cell capacity.

The usable cell capacity decreases along with irreversible capacity fading due to storage time, cycle number and temperature. The loss in cell capacity occurs whether it is inactive (“calendar life” losses) or exercised (“cycle life” losses) [139]. Both calendar and cycle life losses are also affected by temperature [12]. The usable cell capacity can

be calculated by including these two losses by:

$$\begin{aligned} Cap_{\text{cell_usable}} &= Cap_{\text{cell_ini}} \cdot CCF \\ CCF &= 1 - \text{Calendar life losses} - \text{Cycle life losses} \end{aligned} \quad (3.17)$$

The semi-empirical calendar and cycle loss models adopted in [139] are expressed as:

$$\% \text{ calendar loss} = 1.544 \times 10^7 \cdot \exp(-40498/(8.3143T)) \cdot t_{\text{stored}} \quad (3.18)$$

$$-\frac{d\theta_n}{dN} = k_1 N + k_2 \quad (3.19)$$

where T is the cell temperature, t_{stored} is the storage time in month, θ_n is the negative electrode state of charge, and N is the cycle number. The values of empirical coefficients for cycling impacts adopted from [12] are summarised in Table. 3.3. With these equations, the total cell usable capacity $Cap_{\text{cell_usable}}$ and state of charge SOC can be updated with these fading and degradation effects.

Table 3.3: Values of semi-empirical temperature-dependent cycling effects coefficients adopted from [12].

Cycling temperature [K]	k_1 [cycle ⁻²]	k_2 [cycle ⁻²]	k_3 [$\Omega\text{m}^2/\text{cycle}^{1/2}$]
298	8.5×10^{-8}	2.5×10^{-4}	1.5×10^{-3}
323	1.6×10^{-6}	2.9×10^{-4}	1.7×10^{-3}

Most parameters listed in equations (3.28) are functions of cell SOC, their semi-empirical relations are given in [11]:

$$\begin{aligned}
 V_{OC}(SOC) &= -1.031 \cdot e^{-35 \cdot SOC} + 3.685 + 0.2156 \cdot SOC \\
 &\quad - 0.1178 \cdot SOC^2 + 0.3201 \cdot SOC^3 \\
 R_{Series}(SOC) &= 0.1562 \cdot e^{-24.37 \cdot SOC} + 0.07446 \\
 R_{TS}(SOC) &= 0.3208 \cdot e^{-29.14 \cdot SOC} + 0.04669 \\
 C_{TS}(SOC) &= -752.9 \cdot e^{-13.51 \cdot SOC} + 703.6 \\
 R_{TL}(SOC) &= 6.603 \cdot e^{-155.2 \cdot SOC} + 0.04984 \\
 C_{TL}(SOC) &= -6056 \cdot e^{-27.12 \cdot SOC} + 4475
 \end{aligned} \tag{3.20}$$

With k_3 shown in Table 3.3, R_{cycle} is expressed as [12]:

$$R_{cycle} = k_3 \cdot N^{1/2} \tag{3.21}$$

Finally, the temperature correction term for voltage $\Delta E(T)$ and its figure are detailed in [140]. Its semi-empirical equations can be expressed by the following piecewise functions:

$$\Delta E(T) = \begin{cases} 0.014T - 0.18 & \text{if } -20^\circ C \leq T < -10^\circ C \\ 0.018T - 0.14 & \text{if } -10^\circ C \leq T < 0^\circ C \\ 0.0061T - 0.14 & \text{if } 0^\circ C \leq T < 23^\circ C \\ 0.011T - 0.25093 & \text{if } 23^\circ C \leq T < 45^\circ C \end{cases} \tag{3.22}$$

The lithium cell model is completed, the next subsection will expand it to battery pack level model for higher voltage, current and power ratings.

Lithium battery pack model

Battery pack is often modular. That is, modules which comprising a group of cells are connected in series and/or parallel to achieve overall pack level design requirement. This allows fixed-module design and minimises non-recurring engineering (NRE) costs [10].

Two modularisation approaches for cells are possible. The examples are shown in Fig. 3.10. Cells can either be firstly wired into parallel-cell-module (PCM), then PCMs are connected in series to create pack; or firstly grouped into series-cell-module (SCM), and then connected in parallel to form pack.

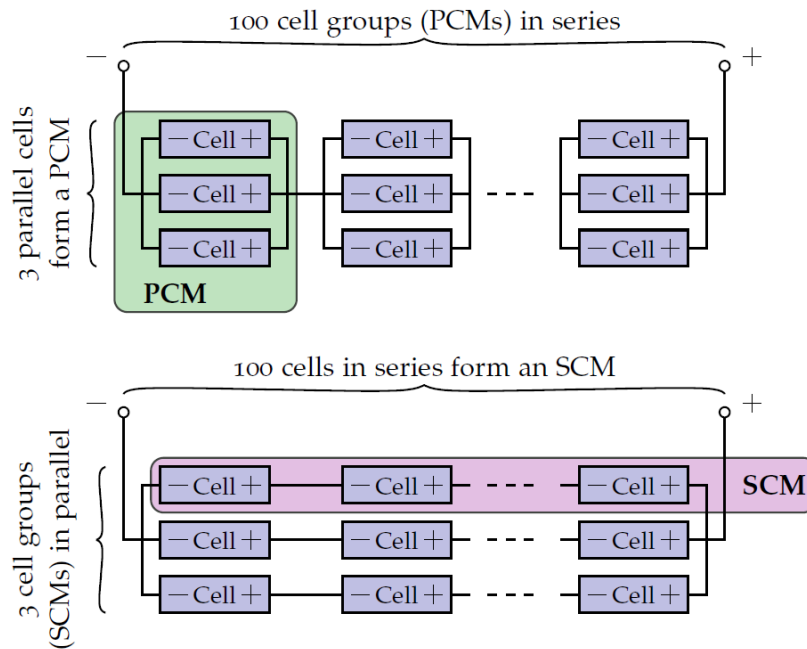


Figure 3.10: The schematic diagrams of Li-ion batter pack topologies adopted in [10].

If all cells are identical, due to topological symmetry, these two topologies provide the same pack performance, such as energy, power, voltage, current and so forth. However, if there are cell imbalance, the packs would operate differently [10]. In this study, it is assumed that all cells are the same, and the cell imbalance performance is not considered. Therefore, both modularisation approaches are fine so that the SCM topology is chosen. Moreover, the pack topology sizing is defined by n_p and n_s in this study. For example, the lower topology in Fig. 3.10 is ' $n_p = 3$ and $n_s = 100$ ', or '3P100S' in abbreviation.

Now, key battery pack modelling equations are provided. According to Kirchhoff's law, pack current and voltage are expressed as:

$$I_{\text{pack}} = n_p \cdot I_{\text{cell}} \quad (3.23)$$

$$V_{\text{pack}} = n_s \cdot \left(V_{\text{cell}} - \frac{I_{\text{pack}} \cdot R_0}{n_p^2} \right) \quad (3.24)$$

where n_p and n_s are battery pack topology sizing parameters; I_{cell} and V_{cell} are obtained in cell-level models and R_0 is the lumped inter-cell interconnect resistance [10].

The total and remaining pack usable capacity is calculated as:

$$Cap_{\text{pack.usable}} = n_p n_s \cdot Cap_{\text{cell.usable}} \quad (3.25)$$

$$Cap_{\text{pack.remaining}} = SOC \cdot Cap_{\text{pack.usable}}$$

Finally, with referring to [141], the cell and battery discharge losses due to internal resistance and their efficiencies are expressed as:

$$P_{\text{cell,loss}} = I_{\text{cell}}^2 (R_{\text{series}} + R_{\text{cycle}}) + \frac{V_{\text{T-S}}^2}{R_{\text{T-S}}} + \frac{V_{\text{T-L}}^2}{R_{\text{T-L}}} \quad (3.26)$$

$$\eta_{\text{cell}} = 1 - \frac{P_{\text{cell,loss}}}{I_{\text{cell}} (V_{\text{OC}} + \Delta E(T))}$$

$$P_{\text{pack,loss}} = (n_p I_{\text{cell}})^2 R_0 + n_p n_s \cdot P_{\text{cell,loss}} \quad (3.27)$$

$$\eta_{\text{pack}} = 1 - \frac{P_{\text{pack,loss}}}{n_p n_s \cdot I_{\text{cell}} (V_{\text{OC}} + \Delta E(T))}$$

With all key equations listed, the battery pack model is set up in MATLAB/Simulink[®]. The battery management system (BMS) is not included in this pack model. It is assumed that each cell is identical and there is no inter cell level imbalance performance. The cell identicalness assumption also extends to degradation studies in Chapter 5. The BMS weight is captured by a correction factor, which will be detailed in Chapter 5.

3.5.4 Battery model validations

It is important to test the accuracy and validity of the proposed model. To test it, several validation processes are conducted to exam its dynamic performance under different discharge current and cycling conditions.

Fig. 3.11 shows the simulation results and their validations against experimental data from Chen et al [11]. An 850 mAh TCL PL-383562 polymer Li-ion cell is tested at room temperature 25 °C. The testing discharge currents are: 80 mA continuous; 320 and 640 mA pulse; and a periodic four-step discharge current.

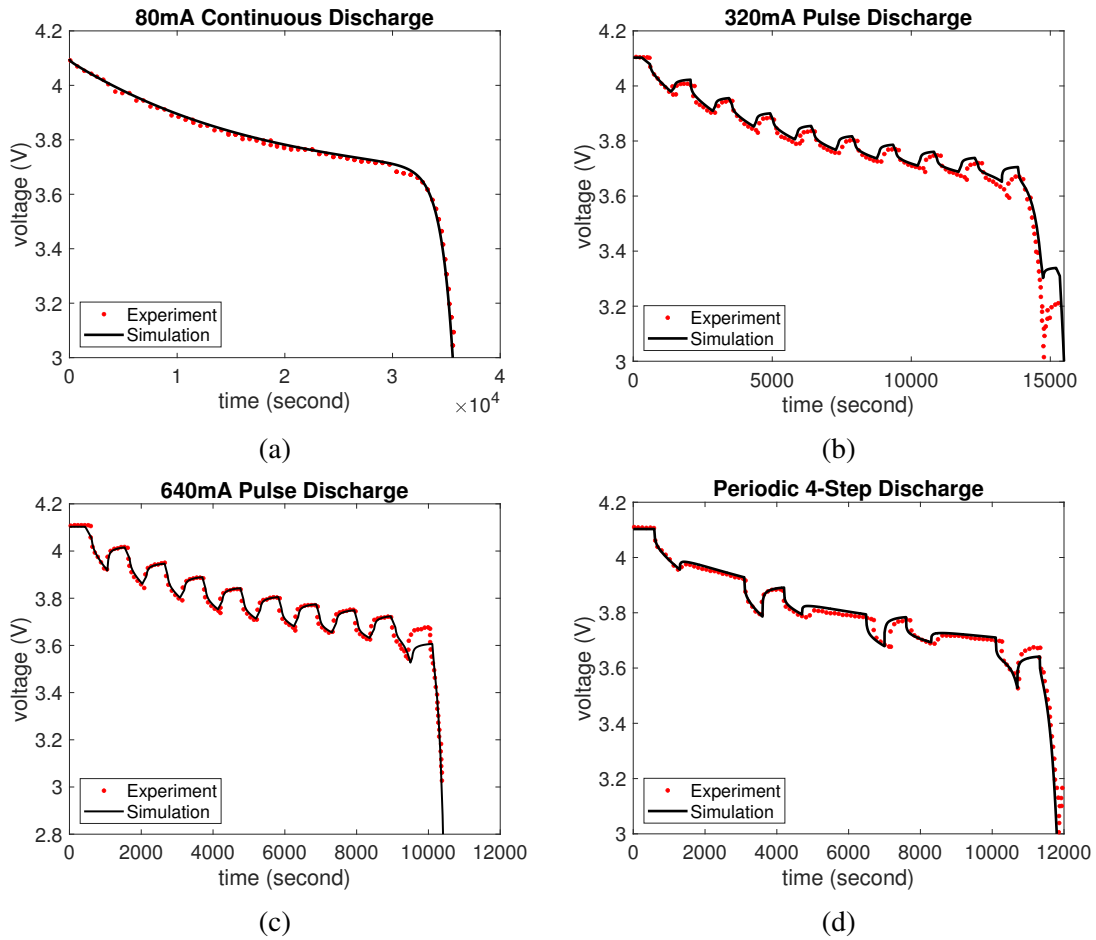


Figure 3.11: Validation of cell discharge performance of (a) 80 mA continuous, (b) 320-, (c) 640 mA pulse, and (d) periodic four-step discharge current against experiments [11].

The model errors of voltage for each test case are shown in Table 3.4. The greatest errors often occur around the end of discharge testing (low *SOC*). The close agreement

between simulated and tested data proves the reliability of the model.

Table 3.4: Values of semi-empirical temperature-dependent cycling effects coefficients adopted from [11].

Discharge current [mA]	Max. voltage error [mV]	Voltage error percentage [%]
80 - continuous	25	0.82%
320 - pulse	141	4.41%
640 - pulse	72	1.96%
Four-step periodic	31	0.84%

Similar validation process is conducted for cycling effects. As shown in Fig. 3.12, the simulated cycling effects on a 1.8 Ah Sony 18650 cell at 25 °C and 50 °C are validated against the experimental data obtained by Ramadass et al [12].

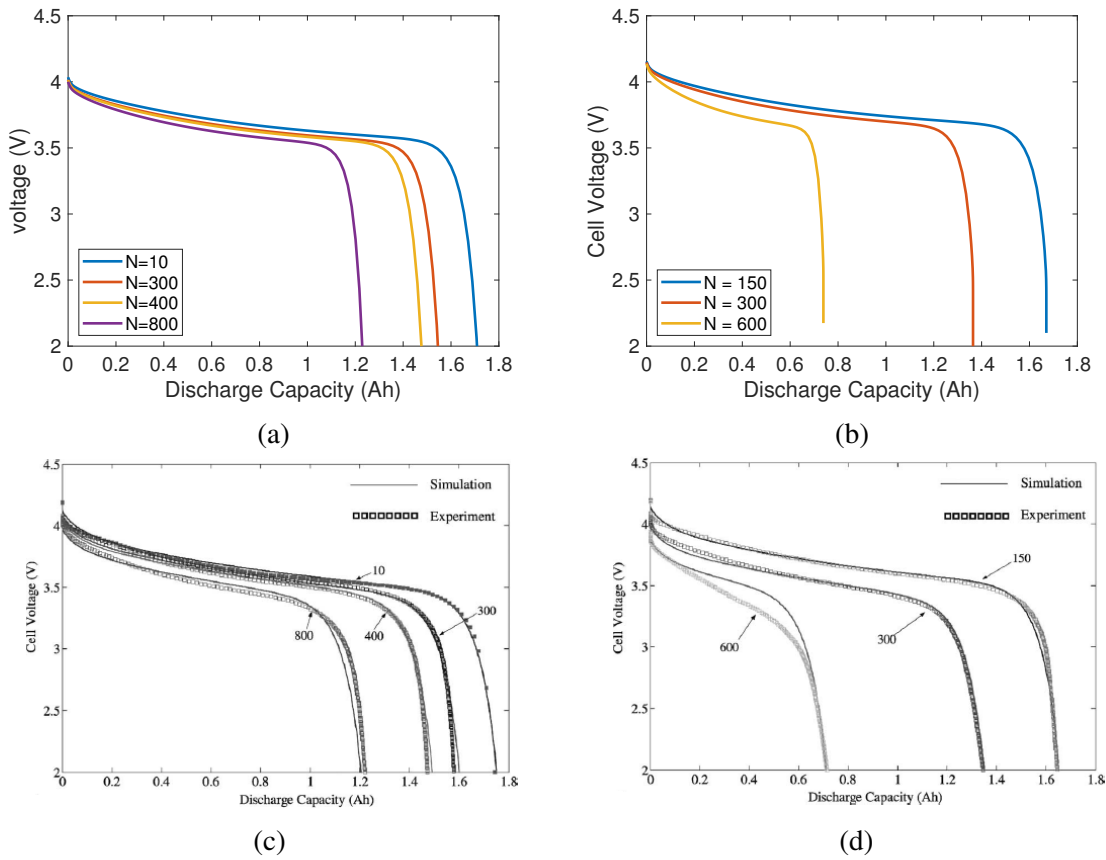


Figure 3.12: (a) and (b): Simulation results of cell discharge capacity against voltage for different cycling numbers at temperature 25 °C and 50 °C. (c) and (d): Experiment data under same cycling numbers at temperature 25 °C and 50 °C obtained from [12].

The significant impact of rising cycles and temperature on capacity degradation can be seen. Moreover, the simulation results are in good match with the experimental tested data. The slight discrepancies in absolute figures mainly come from the mismatching of semi-empirical cell equations (3.28) and cell types utilised in [12]. As long as key degradation trends are matched in high agreements, the model is considered valid for cycling impacts simulation in this study.

3.5.5 Battery system specifications and key parameters

The key model setup specifications of battery pack are shown in Table 3.5. Also, the key output data obtained from the model are summarised in Table 3.6. The battery sizing and weight estimation are highly dependent on mission characteristics, which are detailed in Chapter 5 Section 5.4.1.

Table 3.5: Key performance specifications of proposed battery pack model.

Input parameters (mission independent)	Values	Input parameters (mission dependent)
initial cell capacity (Cap_{cell_ini})	1.8 Ah	n_p
initial (SOC_{ini})	100%	n_s
minimum allowable (SOC_{final})	20%	lumped interconnect resistance (R_0)
interconnect resistance (r_t) [10]	125 $\mu\Omega$	storage time (t_{month})
		cycle number (N)
		cell temperature (T)

Table 3.6: Model simulation input parameters and sizing and performance outputs for proposed battery pack model.

Model simulation inputs	Sizing outputs	Battery performance outputs
Battery $S.E.$ [Jkg^{-1}]	Battery mass [kg]	Battery voltage [V]
Battery $S.P.$ [kWkg^{-1}]	n_p	Battery current [A]
Energy required [J]	n_s	Battery power [kW]
Power required [kW]		State of Charge [%]
Battery temperature [K]		Battery Capacity [Ah]

The output parameters shown in above tables define the sizing limitation and performance characteristics of the battery module. All these component level simulation results will be used and interact with other subsystems. The final system level decision and assessment can be made based on these data.

3.6 Power electronics: DC/DC converter model

Voltage of power source varies with time, temperature, and many other factors, especially current [142]. This phenomenon is also demonstrated in previous PEMFC and battery sections. A voltage regulator is required to keep source output voltage within acceptable ranges. Moreover, voltage regulation is also required for motor control [143]. Normally, DC/DC converters are used as the voltage regulators to convert an unregulated DC voltage to a controllable regulated DC output voltage. The voltage regulation is achieved by pulse width modulation (PWM) technique and switching devices such as gate turn-off thyristor (GTO), metal oxide semiconductor field effect transistors (MOSFETs), or insulated gate bipolar transistors (IGBTs) [143].

In this study, two fidelity-levels (low- and high-fidelity) of converter models are developed. Both of them enable: to control the voltage control function as a voltage regulator; to simulate the component performance of the converter along flight missions; preliminary weight estimation of the converter system.

The main characteristics for low-fidelity model are: the detailed physics-based switching circuit is replaced by a simple PI voltage control and an over-simplified efficiency relations; the converter weight is estimated by using system required power and converter specific power. Whereas for high fidelity one, the switching circuit is designed and the converter efficiency is calculated considering detailed power losses of PWM-based switching control circuits; most circuit elements used are based on off-shelf available products; the weight estimation is also based on these available products' ratings. The model fidelity selection depends on research objectives and simulation cases, which are discussed in details in Chapter 4 and 5.

3.6.1 Low-fidelity converter model

Three aspects of proposed model are introduced: component performance, voltage regulation function, and weight estimation. The schematic diagram of a DC/DC converter is shown in Fig. 3.13.



Figure 3.13: A schematic diagram of the low-fidelity DC/DC converter model.

Converter performance modelling

The component performance is given by the following equations for Fig. 3.13:

$$\begin{aligned}
 P_{\text{conv,in}} &= I_{\text{conv,in}} \cdot V_{\text{conv,in}} \\
 P_{\text{conv,out}} &= I_{\text{conv,out}} \cdot V_{\text{conv,out}} \\
 \eta_{\text{conv}} &= \frac{P_{\text{conv,out}}}{P_{\text{conv,in}}}
 \end{aligned} \tag{3.28}$$

where the converter efficiency is proposed by following equation, with a principle that: higher discrepancy between input/output voltage, less efficiently the converter performs.

$$\eta_{\text{conv}} = 1 - 0.9 \left| \log_{10} \left(\frac{V_{\text{conv,in}}}{V_{\text{conv,out}}} \right) \right| \tag{3.29}$$

Voltage regulation

The purpose of a converter is to maintain the output voltage at desired values for different input/output conditions. The output voltage is controlled by a closed-loop control system with a PI controller. The closed loop control schematic diagram and its implementation in MATLAB/Simulink® are shown in Fig. 3.14.

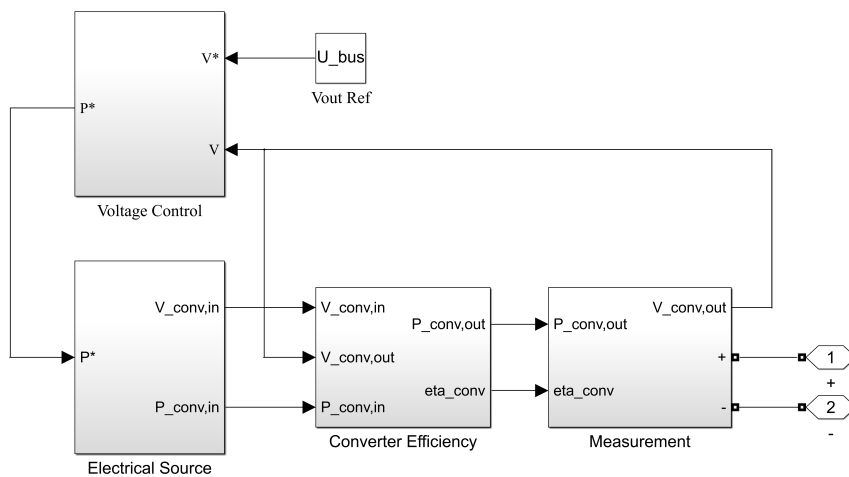


Figure 3.14: The MATLAB/Simulink® implementation of the low-fidelity DC/DC converter model with control loop.

The voltage control module takes the converter output voltage $V_{\text{conv,out}}$ and compares it with desired voltage V^* . A PI controller takes their difference and outputs the power P^* command signals for electrical source to achieve the target converter output voltage. The measurement block collects all necessary data for the control system and calculates the converter efficiency η_{conv} .

Weight estimation and model parameters

The key model input parameters and output data are summarised in Table 3.7. The equation of converter weight is also presented.

Table 3.7: Model simulation input parameters and sizing and performance outputs for proposed low-fidelity converter model.

Model simulation inputs	Sizing outputs	Converter performance outputs
Converter $S.P.$ [kWkg^{-1}] $I_{\text{conv,in}}$ [A] $V_{\text{conv,in}}$ [V]	Converter mass [kg]	$I_{\text{conv,out}}$ [A] $V_{\text{conv,out}}$ [V] η_{conv} [%] $P_{\text{conv,loss}}$ [kW]
$W_{\text{conv}} = P_{\text{conv,peak}} / S.P._{\text{conv}}$		

In this subsection, the low fidelity converter model is presented. It is a “black-box” like model and capable to output preliminary data. In the next sections, a more detailed high-fidelity converter model will be introduced.

3.6.2 High-fidelity converter model introduction

In this section, a high-fidelity converter model is introduced. The converter is no longer treated as a black box and instead, the switching elements characteristics are modelled for more accurate efficiency calculation. Moreover, a higher fidelity sizing method considering capacitive and inductive elements rating current and voltage is utilised to replace specific power based method given in Table 3.7. This way, a more realistic design space

exploration for power electronics system can be achieved. The proposed detailed model is of significant importance for fuel cell configuration studies detailed in Chapter 4 and a publication by the author [20].

Pulse width modulation (PWM)

Before introducing the converter working principle, it is necessary to illustrate the concept of pulse width modulation (PWM) technique. Most converters use it to regulate their output voltages and this study also utilises this technique.

A typical PWM signal is shown in Fig. 3.15a. Within a period T_p , the duration for “ON” time is T_{ON} . The ratio between “ON” time and period is called the duty ratio. The peak amplitude for the pulse voltage is indicated as V_{pk} . When applying a series of square wave pulses to an L-C filter, a DC output voltage V_{out} can be obtained. The average value of this output voltage is the product of duty ratio and voltage signal amplitude, as shown in Fig. 3.15b. This way, the output voltage can be controlled by changing the “ON” time. This is the key process for step down the voltage in buck converters, which is called a “chopper”. Similar principles are applied for boost converter, which will be detailed later.

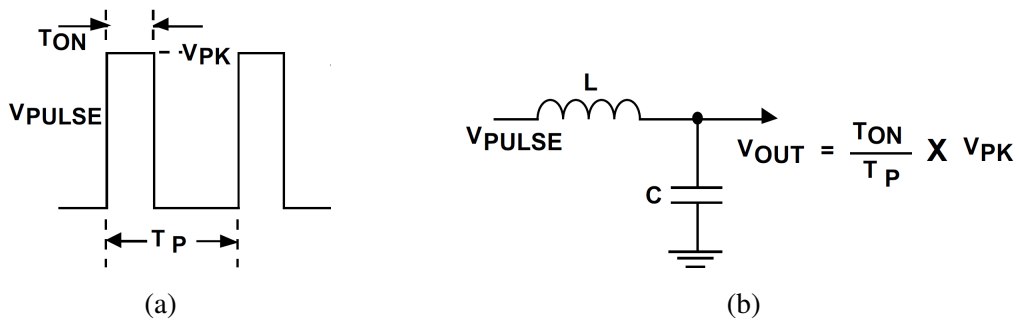


Figure 3.15: Example of a PWM signal and its averaged output amplitude [13].

The converter working principles will be introduced. The schematic diagram of a buck and a boost converter is shown in Fig. 3.16.

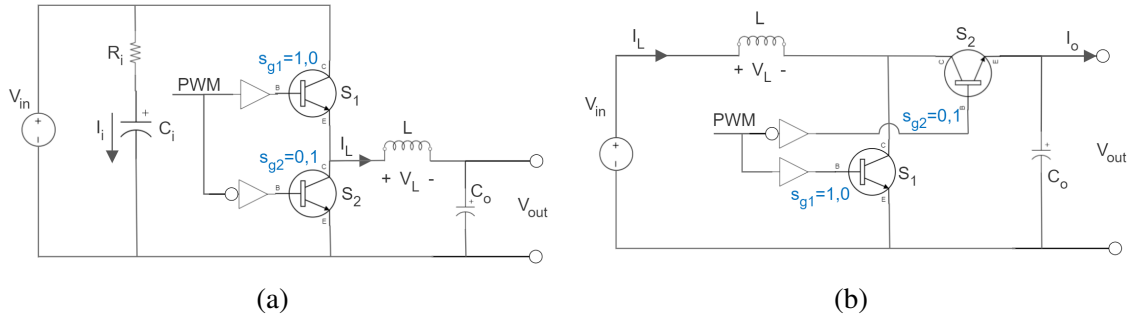


Figure 3.16: Schematic diagram of (a) buck converter and (b) boost converter.

Buck converter working principle

For a buck converter, the dc voltage is stepped down from input to output terminal. The circuit operation is controlled by the conduction state of the two IGBT switches (S_1 and S_2). This is achieved by feeding them with controlled PWM signals. Note that, the signals for S_1 and S_2 are normally opposite. signal 1 and 0 represent “On” and “Off” states of the switch respectively. Within a converter operation period T_p :

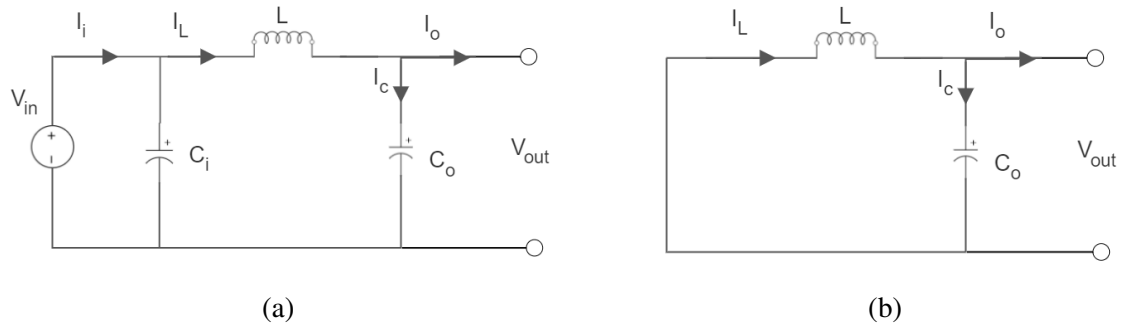


Figure 3.17: (a) S_1 On S_2 Off and (b) S_1 Off S_2 On buck converter operation mode.

S_1 On S_2 Off: The converter circuit is equivalent to Fig. 3.17a. The DC voltage source provides energy through S_1 to inductor L and capacitor C_i and C_o . The inductor and capacitors store energy in magnetic field and electric field respectively.

S_1 Off S_2 On: Now the converter circuit is equivalent to Fig. 3.17b. Energy stored in inductor L is transferred to capacitor C_o and output terminal.

The ratio between $T_{S_1, \text{on}}$ and T_p is the duty ratio D , which is also the ratio between output and input voltage, expressed as: $V_{\text{conv, out}}/V_{\text{conv, in}} = D$. The inductive and capacitive elements within the buck converter circuit are important for smoothing out V-I ripples, providing current flowing channels and protecting the circuit from large V-I slope damage at switching on/off moments.

Boost converter working principle

For a boost converter, the dc voltage is stepped up from input to output terminal. Similar to buck converter, there are also mainly two operation modes in a period, but the working principle is different:

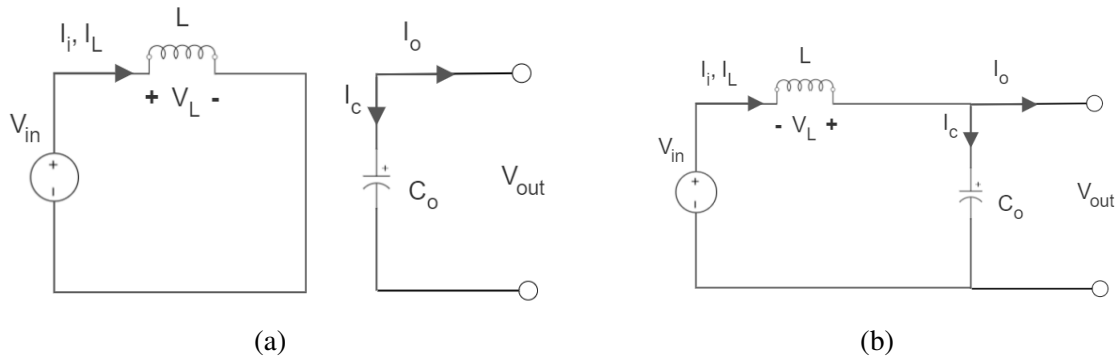


Figure 3.18: (a) S_1 On S_2 Off and (b) S_1 Off S_2 On boost converter operation mode.

S_1 On S_2 Off: The converter circuit is equivalent to Fig. 3.18a. The DC voltage source charges inductor L via closed switch S_1 . The inductor current increases and energy is stored in the form of magnetic field. According to inductor equation: $v = L \frac{di}{dt}$, the polarity of left side of the inductor is positive. The capacitor C_0 releases its energy to output load.

S_1 Off S_2 On: The converter circuit is equivalent to Fig. 3.18b. Both voltage source and inductor transfer energy to the output load. The current will be reduced as the impedance of the load is higher. However, since current through inductor cannot abruptly change, the magnetic field produced previously is decreased to maintain current. As the term $\frac{di}{dt}$ is negative, the polarity is reversed for the inductor. Now

right side of the inductor is positive. As a result, the output voltage can be increased due to the series connection of two energy sources. The energy flows to the output load and capacitor C_o .

Unlike buck converter, the ratio between output and input voltage of boost converter is expressed as: $V_{\text{conv,out}}/V_{\text{conv,in}} = 1/(1 - D)$. The inductance here resembles a secondary energy source to increase output voltage.

3.6.3 High-fidelity converter modelling: switching elements

The power transistors are used as switching elements as they have controlled turn-on and turn-off features [143]. There are different possible candidates available. Fig. 3.19 shows a classification of different switching elements, depending on the switching frequency, power and voltage.

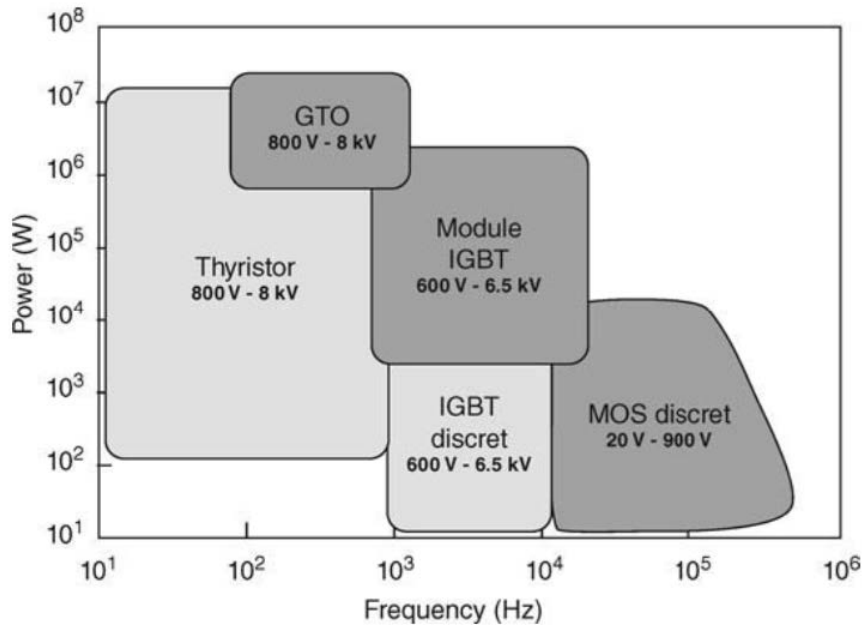


Figure 3.19: Classification of different switching elements [14].

It can be found that both thyristor and GTO can satisfy the power and voltage requirement, but their operation frequencies are too low for aircraft propulsion system. MOSFET can switch at highest frequency but its operating power is too low. Also the high frequency

of MOSFET could cause higher switching losses. Therefore, the IGBT is most suitable in terms of switching efficiency, power and voltage consideration for aircraft applications. Many studies [31, 144] also agree that IGBTs are most appropriate option as switching elements. Therefore, an IGBT model is selected and modelled for converter and inverter in this study.

The IGBT model is based on ‘Infineon (model: FZ1500R33HL3)’ datasheet [16]. This element has relatively low switching losses and also can work under voltage higher than 2000V when collector-emitter voltage $V_{CES} = 3300V$. It also provides high continuous DC collector (conduction) current $I_{C,nom} = 1500A$ while keeping high DC voltage stable. To simulate the performance of IGBT, both I-V and switching on/off characteristics are modelled as they directly determine the component conduction and switching losses. The losses transfer to heat and affect the component efficiencies. The typical patterns of these two characteristics are shown in Fig. 3.20. Although there are other power losses for an IGBT, such as blocking losses and driving losses, they are negligible according to [144].

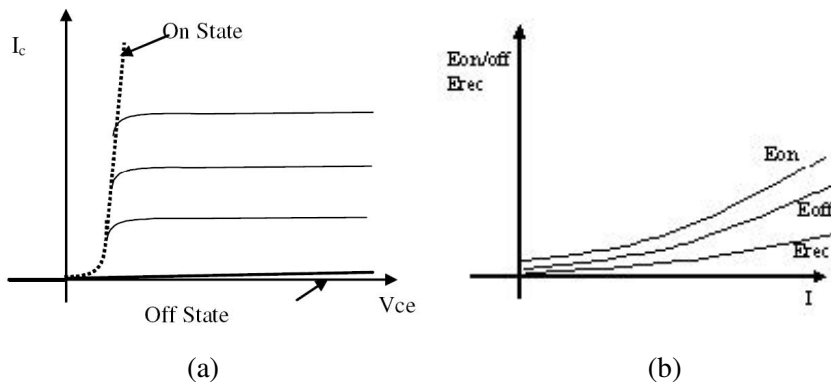


Figure 3.20: Typical patterns of (a) IGBT current against voltage diagram (b) IGBT switching energy against current [15].

IGBT I-V curve and conduction losses modelling

The I-V characteristics of the selected IGBT component is shown in Fig. 3.21a. It can be seen that the collector-emitter voltage V_{CE} increases with conduction current I_C . Their relation also depends on operation temperature, as temperature increases, the $I - V$ curve

shifts rightwards. This means that, with higher conduction current and temperature, the conduction power dissipated in the IGBT increases.

These characteristics are implemented and simulated in MATLAB/Simulink[®]. Linear interpretation method is used to emulate the $I - V$ curves. Notice that, the characteristics are not strictly linear and the interpretation is a simplified method. Fig. 3.21b demonstrates the simulation results for the $I - V$ characteristics of the proposed IGBT model, which has high agreement with the Infineon datasheet [16].

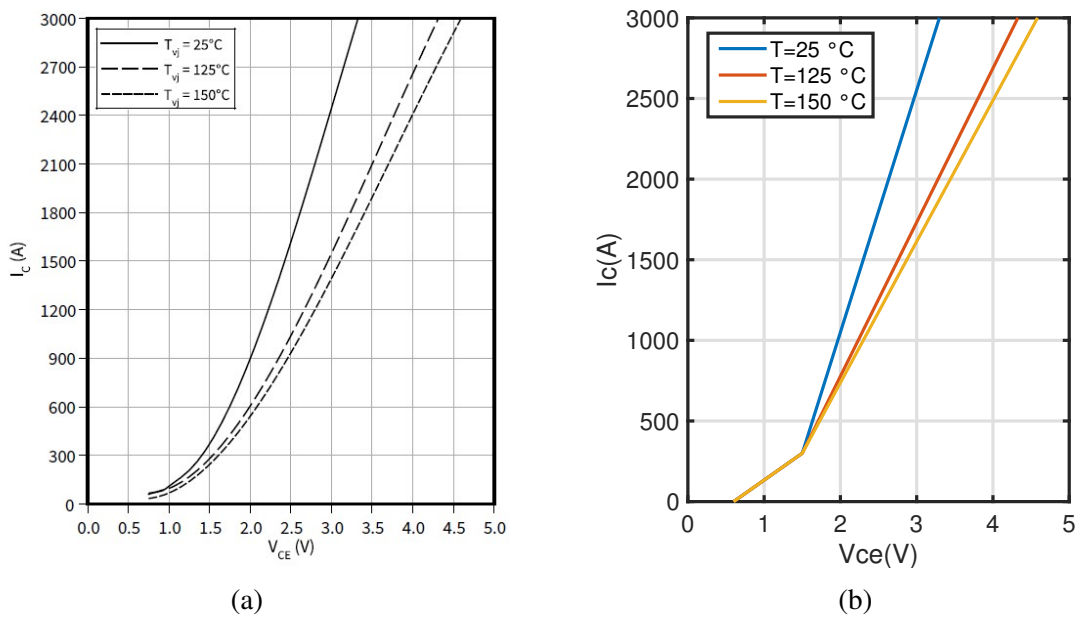


Figure 3.21: Typical current against voltage characteristics diagrams of (a) IGBT datasheet [16] (b) IGBT model simulation result.

IGBT switching losses modelling

The switching loss of selected IGBT is shown in Fig. 3.22a. The energy of switching loss increases with conduction current. Also, a typical power and energy transient loss of IGBT switching operation is shown in Fig. 3.22b. To emulate the loss characteristics, two small durations of pulse power dissipation signals are utilised after each switching on and off operation.

Fig. 3.22c shows an example of simulated switching losses output at conduction current $I_C = 1000\text{A}$. The IGBT is switched on and off at 2×10^{-5} and 6×10^{-5} second. At

this current, the energy dissipated for switching on and off are around 2100 mJ, given by the datasheet. This value matches the energy loss values calculated by the model, shown in Fig. 3.22c. Also, the simulated energy dissipation curves have similar trends of general IGBT characteristics predicted by other study (Fig. 3.22b). This developed IGBT model is utilised to simulate the switching components inside the converters.

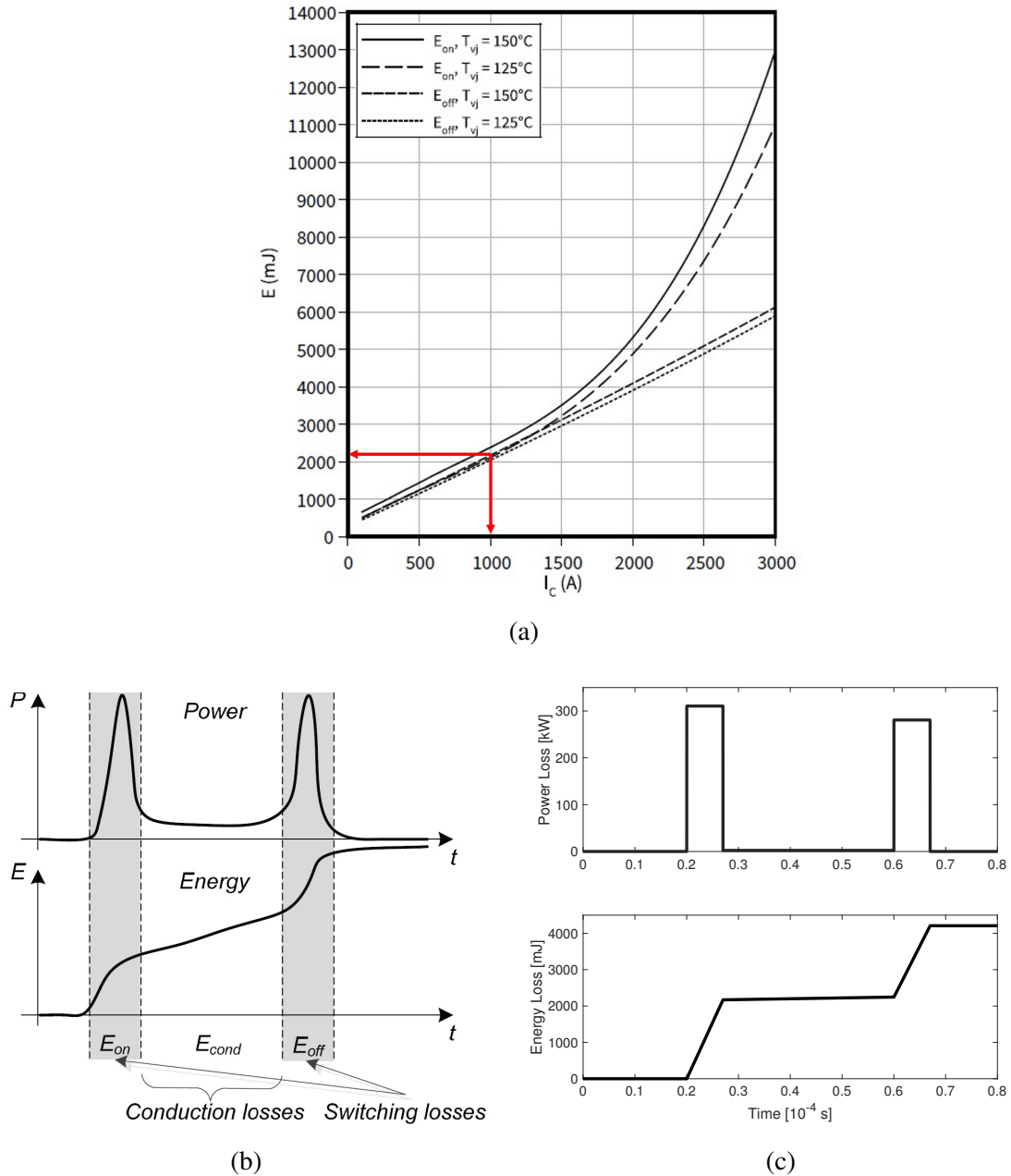


Figure 3.22: (a) IGBT switching losses characteristics from datasheet [16], (b) IGBT general performance characteristics from [17], and (c) IGBT switching loss simulation results for 1000-Ampere conduction current at operation temperature 125°C .

3.6.4 High-fidelity converter modelling: voltage regulation

The conduction and switching losses are modelled, the next step is to realise the voltage control function of the DC/DC converter. Fig. 3.23 shows the schematic diagram of cascade control system for converter. This control strategy, together with the converter models, are implemented in MATLAB/Simulink®.

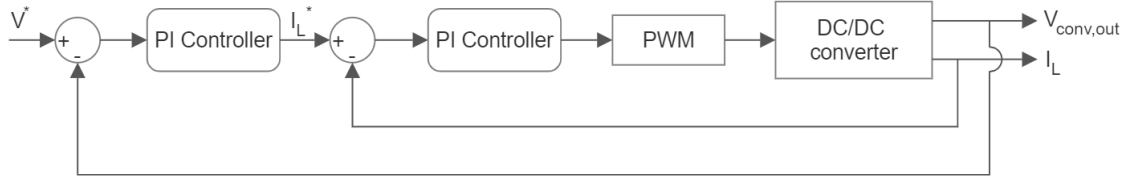


Figure 3.23: The schematic diagram of the cascade control system for the DC/DC converter.

In this control strategy, two PI controllers are used. One for inner inductor current control loop and the other for outer voltage control loop. For the outer loop, the converter output voltage is measured and compared to the desired voltage V^* , the error signal is fed to the first controller to generate a reference inductor current signal I_L^* . This signal is fed into the inner current loop where inductor error signal is produced by comparing with measured value I_L . This error signal is used to command the operation of the two IGBTs by producing controlled PWM signals. According to [145, 146], the cascaded control strategy has advantages over single PI voltage control in terms of stability, fast response and robustness.

In order to assess the robustness of the control system, simulation tests under varying output power are carried out. In the test simulation, a step output power from 50- to 200- and 100-kW is applied from time 0- to 0.4- and 0.8-s. The converter input voltage $V_{\text{conv,in}} = 3000V_{\text{DC}}$ and the converter output voltage is set to $V_{\text{conv,out}} = 2000V_{\text{DC}}$. And Fig. 3.24 shows the applied power variation, the output voltage response, inner inductor current and duty ratio.

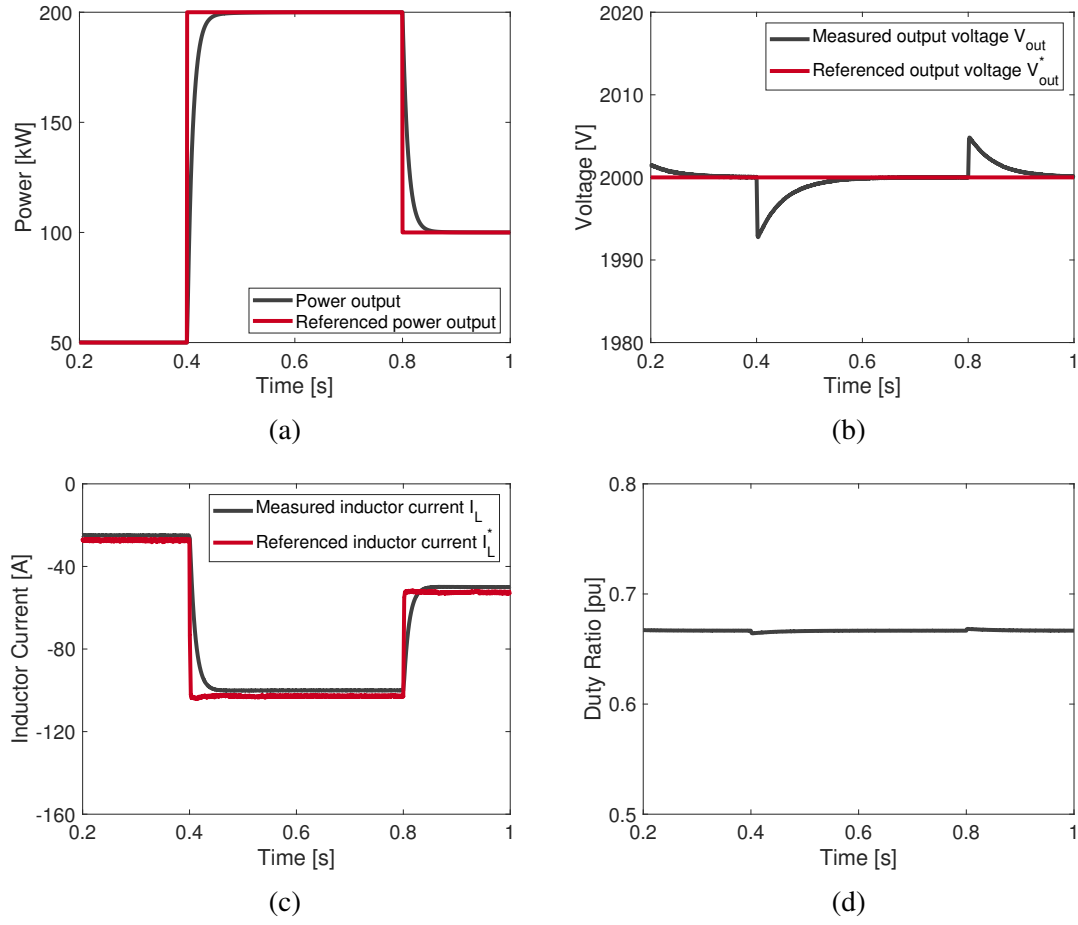


Figure 3.24: (a) Converter output power, (b) converter output voltage, (c) inductor current variation, and (d) duty ratio.

It can be seen that both output voltage and power quickly follow the desired values. The inductor current also follows the output of first PI controller I_L^* along the test. Also, the duty ratio has small disturbance at power change points and rapidly stabilises. These tests verify that the simulated data can reach to the reference values rapidly and smoothly. Therefore, the voltage regulation function is achieved by this proposed model.

3.6.5 High-fidelity converter modelling: LC sizing

This subsection discusses the sizing consideration for the capacitive and inductive components for the converter. The high power capacitor and inductor are adopted from available off-shelf products, with their datasheet in [147, 148]. The sizing of LC components follows the principle that: the maximum voltage and current across the each LC component

must be within the safety range (i.e. smaller than the component maximum allowable voltage and current). Wiring inductors/capacitors in series and parallel can increase their maximum acceptable voltage and current. Therefore, an array of inductors and capacitors can be lumped together to represent the LC components shown in the converter schematic diagrams (Fig. 3.16). The calculation of the maximum voltage and current across them are shown below:

Buck converter

Capacitor C_i : According to Kirchhoff's Law, the peak current and voltage across this capacitor are the maximum input current and voltage of electric source: $I_{C_i, \max} = I_{in, \max}$ and $V_{C_i, \max} = V_{in, \max}$.

Inductor L : The peak inductor current is given by: $I_{L, \max} = I_{out, \max} + \frac{V_{in, \max} D(1-D)}{2fL}$, where $I_{out, \max}$ is the maximum converter output current, D is the duty ratio, f is the PWM carrier frequency and L is the lumped inductance. Whereas the peak inductor voltage is: $V_{L, \max} = \max \{|V_{in} - V_{out}|, |V_{out}|\}$

Capacitor C_o : The peak current is the maximum output current $I_{C_o, \max} = I_{out, \max}$. Whereas the peak voltage is: $V_{C_o, \max} = V_{out, \max} + \frac{V_{in, \max} D(1-D)}{16LCf^2}$, where C is the lumped capacitance.

Boost converter

Inductor L : The peak inductor current is: $I_{L, \max} = I_{out, \max} + \frac{V_{in, \max} D}{2fL}$. Whereas the peak inductor voltage is similar to buck case: $V_{L, \max} = \max \{|V_{in} - V_{out}|, |V_{out}|\}$.

Capacitor C_o : The peak current is: $I_{C_o, \max} = \max \{|I_{L, \max} - I_{out, \max}|, |I_{out, \max}|\}$. Whereas the peak voltage is given by: $V_{C_o, \max} = V_{out, \max} + \frac{I_{out, \max} D}{2fC}$.

All above equations and their derivations can be found in [143, 149]. Moreover, the sizing of lumped LC components also impacts the inductance and capacitance values in

the above equations, an iteration process is utilised to size these components. The configurations of them are dependent on electric source architecture, and the electric propulsion system architectural studies will be detailed in Chapter 4 Section 4.7.

3.6.6 High-fidelity converter: model parameters and assumption

The key model parameters and output are summarised in Table 3.8. It is worth noting that, the converter efficiency for this model is directly obtained by following equation:

$$\eta_{\text{conv}} = \frac{P_{\text{conv,out}}}{P_{\text{conv,in}}} \quad (3.30)$$

Table 3.8: Model simulation input parameters and performance outputs for proposed high-fidelity converter model.

Model simulation inputs	Sizing outputs	Performance outputs
IGBT & LC component datasheet	Inductor topology	$I_{\text{conv,out}}$ [A]
Reference output voltage [V]	Capacitor topology	$V_{\text{conv,out}}$ [V]
Required output power [kW]	Converter mass [kg]	$P_{\text{conv,out}}$ [kW]
Temperature [K]		η_{conv} [%]
PWM carrier frequency [kHz]		$P_{\text{conduction,loss}}$ [kW]
$I_{\text{conv,in}}$ [A]		$P_{\text{switching,loss}}$ [kW]
$V_{\text{conv,in}}$ [V]		$P_{\text{converter,loss}}$ [kW]
$P_{\text{conv,in}}$ [kW]		

Finally, the switching elements of this converter model are based on ‘Infineon (model: FZ1500R33HL3)’ and LC components are selected from off shelf products (Section 4.7.2), which means the converter model setup is only suitable for the selected power rating in this study. Also, an ideal thermal management system is equipped to maintain the temperature of the converter. There is no temperature feedback mechanism in this model, which means the heat generated is dissipated instead of affecting the converter.

3.7 Electric motor model

Electric motors convert electrical energy into mechanical energy. Their high specific power and superior efficiency are two main features [33]. For example, Honeywell developed a 540 kW motor for aircraft propulsion, with specific power of 7.9 kW/kg and efficiency of 97% [150]. Also, their efficiencies are not sensitive to operational altitude, providing an advantage over conventional gas turbine engines [151].

There are many motor comparison research conducted. For example, [31, 152] qualitatively assessed the advantages and disadvantages of three types of motors in terms of efficiency, mass, torque density and inverter complexity. The selected motors are: asynchronous motors (ASM), switched reluctance motors (SRM) and permanent magnet synchronous motors (PMSM) machines. Moreover, [32] quantitatively investigated eight motor types for a 1.5 MW/1kV aircraft propulsion system for wider criteria. The candidate motor types are: inductionmotor (IM), switched reluctancemotor (SRM), wound rotor synchronous motor (WRSRM), PM synchronous motor (PMSM), slotless PMSM, PM-assisted synchronous reluctance motor (PM-assisted SynRM), brushless DC (BLDC) motor, and brushless doubly fed reluctance motor (BDFRM). Table 3.9 and 3.10 summarise the comparison results of these studies. According to these studies, permanent magnet synchronous motor (PMSM) lead in terms of efficiency and specific power for aircraft applications. Therefore, a PMSM motor is selected for this study. It should be noted that, the selected PMSM is radial flux instead of axial flux given the time available for this research. In the future, the simulation framework will include the flexibility of integrating axial flux motors for “high torque low speed” scenarios.

Table 3.9: Overview of electric motors provided by [31].

Electric Motor	ASM	SRM	PSM
<i>Efficiency</i>	0	0	+3
<i>Mass</i>	0	0	+1
<i>Torque density</i>	0	+1	+3
<i>Inverter Complexity</i>	0	-3	-1
-3 strongly negative; -1 negative ; 0 neutral; +1 positive; +3 strongly positive			

Table 3.10: Overview of electric motors provided by [32].

Criterion	IM	SRM	BDFRM	WRSM	PMSM	SI-PMSM	SynRM	BLDC
Rotor losses	H	M	M	H	L	L	M	L
Stator losses	M	M	H	L	L	L	M	L
Losses at high speed	M	H	H	M	M	L	M	M
Partial-load efficiency	L	M	M	M	H	H	M	H
Torque ripple	M	H	M	M	L	L	M	H
Rotor thermal limits	M	H	M	M	M	M	L	M
Cooling complexity	H	M	M	M	M	L	M	M
Rotor mechanical integrity	M	H	M	M	M	M	L	M
Manufacturing tolerance	L	M	M	M	M	H	M	M
Short-circuit behavior	H	M	H	H	M	L	M	M

L, low; M, medium; H, high.

Green, favorable; yellow, moderate; orange, unfavorable.

For the following sections, a brief introduction of the PMSM working principle is introduced. Then, two sets of PMSM models (low- and high-fidelity) are developed and introduced. The model fidelity selection depends on the research objectives, which will be detailed in Chapter 4 and 5.

3.7.1 Working principle of the PMSM

Fig. 3.25 shows the structure of a PMSM and its stator winding. A three-phase voltage source is connected to stator windings, when energised, a rotating magnetic field (RMF) is generated. The RMF interacts with the magnetic field from the rotor-mounted permanent magnets. The rotor then rotates and outputs mechanical power. With PMSM, there is zero speed difference between the rotor and stator magnetic fields.

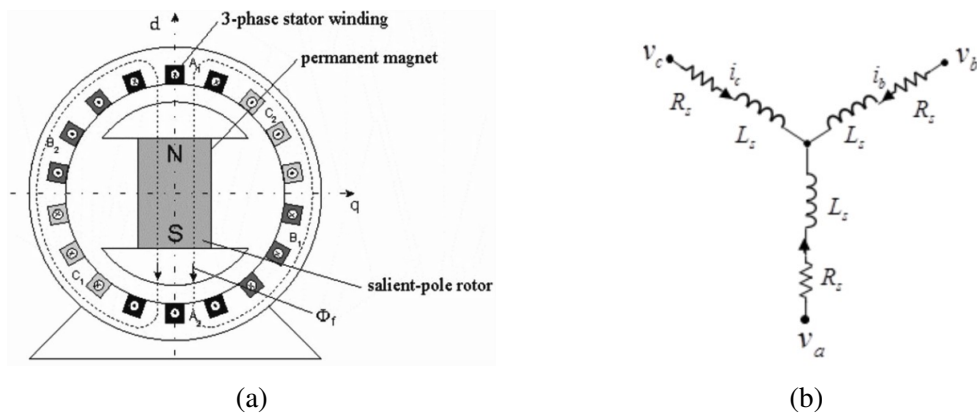


Figure 3.25: (a) A schematic diagram of the PMSM structure [18] (b) PMSM three-phase wye-connected stator.

3.7.2 Low-fidelity PMSM mathematical model

In this section, the three phase natural reference frame model of the PMSM is firstly introduced. Then the necessity and importance of transforming it to direct-quadrature (dq-) model is explained, with a presentation of Clarke-Park's transformation matrix. Finally, the dq- PMSM model is introduced.

Three-phase equivalent circuit model

An equivalent circuit (Fig. 3.26) is used to model the PMSM electrical performance. With the electrical quantities obtained, the electromagnetic torque and mechanical equations are obtained. Together with voltage equations, the low-fidelity PMSM mathematical model is constituted. The following assumptions are made to simply the model.

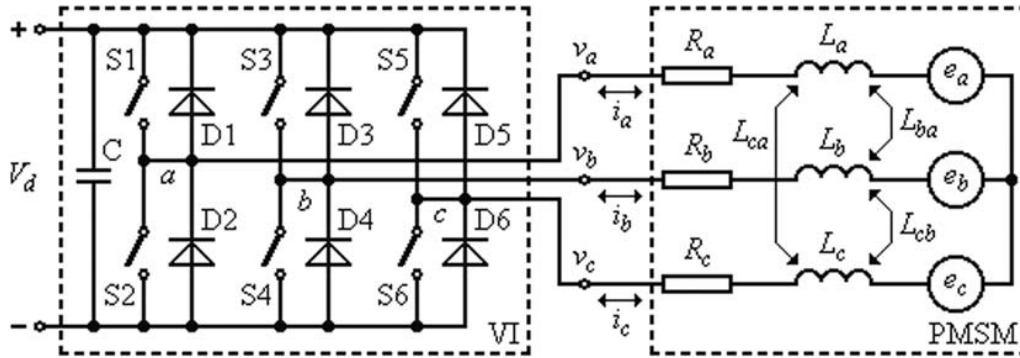


Figure 3.26: The three-phase equivalent circuit model of PMSM [19].

- (i) Ferromagnetic saturation effects are neglected.
- (ii) Eddy current and hysteresis losses are neglected.
- (iii) Input current/voltage are three phase sinusoidal waveforms.
- (iv) Stator winding resistances and inductances are identical and constant.

Therefore, in natural frame of reference (ABC frame), the voltage equations of PMSM can be expressed in matrix form

$$\begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} = \begin{bmatrix} R_c & 0 & 0 \\ 0 & R_c & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_A \\ \lambda_B \\ \lambda_C \end{bmatrix} \quad (3.31)$$

where, v_I is the phase voltage, i_I is the phase current, R_c is the winding copper resistance, and λ_I is the total magnetic flux linkage, where subscript ' $I = A, B, C$ '.

Due to Wye-connection topology of motor winding, the phase currents have following property:

$$i_A + i_B + i_C = 0 \quad (3.32)$$

The total flux linkage is further expressed as

$$\begin{bmatrix} \lambda_A \\ \lambda_B \\ \lambda_C \end{bmatrix} = \begin{bmatrix} L_{AA} & L_{AB} & L_{AC} \\ L_{BA} & L_{BB} & L_{BC} \\ L_{CA} & L_{CB} & L_{CC} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} \lambda_{mA} \\ \lambda_{mB} \\ \lambda_{mC} \end{bmatrix} \quad (3.33)$$

where, L_{II} is the self-inductance of the stator windings, L_{IK} is the mutual inductance of the stator windings, and λ_{mI} is the permanent magnet fluxes linking the stator windings, where subscript ' $I, K = A, B, C$ '. These inductances in the stator windings are functions of rotor electrical angle, and defined as:

$$\begin{aligned}
\theta_e &= \frac{p}{2}\theta_m + \theta_{e0} \\
L_{AA} &= L_s + L_m \cos(2\theta_e) \\
L_{BB} &= L_s + L_m \cos(2(\theta_e - 2\pi/3)) \\
L_{CC} &= L_s + L_m \cos(2(\theta_e + 2\pi/3)) \\
L_{AB} &= L_{BA} = -M_s - L_m \cos(2(\theta_e + \pi/6)) \\
L_{BC} &= L_{CB} = -M_s - L_m \cos(2(\theta_e + \pi/6 - 2\pi/3)) \\
L_{CA} &= L_{AC} = -M_s - L_m \cos(2(\theta_e + \pi/6 + 2\pi/3))
\end{aligned} \tag{3.34}$$

where θ_e and θ_m are rotor electrical and mechanical angles; θ_{e0} is the rotor offset electrical angle, its value is either 0 or $-\pi/2$, depending on whether electrical angle is referred to d-axis or q-axis; p is the motor pole pair; L_s is the stator self-inductance per phase, its value is the averaged self-inductance of each stator windings; L_m is the stator inductance fluctuation; and M_s is the stator mutual inductance.

The linked motor flux is expressed as:

$$\begin{bmatrix} \lambda_{mA} \\ \lambda_{mB} \\ \lambda_{mC} \end{bmatrix} = \begin{bmatrix} \lambda_m \cos \theta_e \\ \lambda_m \cos(\theta_e - 2\pi/3) \\ \lambda_m \cos(\theta_e + 2\pi/3) \end{bmatrix} \tag{3.35}$$

According to [153], the electromagnetic torque T_e is the partial derivative of magnetic energy stored of mechanical angle:

$$T_e = \frac{p}{2} \left\{ \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix}^\top \frac{\partial}{\partial \theta_e} \begin{bmatrix} \lambda_{mA} \\ \lambda_{mB} \\ \lambda_{mC} \end{bmatrix} \right\} \tag{3.36}$$

With the electromagnetic torque expression available, the complete mechanical equa-

tion of PMSM can be obtained and defined:

$$J \frac{d\omega_m}{dt} = T_e - T_F - B\omega_m - T_m \quad (3.37)$$

where, J is the combined inertia of rotor and load, ω_m is the mechanical speed, T_F is the static friction torque, B is the viscous damping of rotor and load, and T_m is the motor shaft mechanical torque.

It can be seen that, the total flux linkage (and thus the electromagnetic torque) is a function of stator angle θ_e . Moreover, the torque equation (3.36) is also over-complicated. Usually, the PMSM model can be simplified by transforming it from the natural reference frame (ABC-axes) to the synchronous rotating frame (dq-axes). This is realised by Clarke-Park's transformation [154].

Coordinate transformation: ABC- to dq- reference frame

Clarke-Park's transformation is commonly used in PMSM modelling and control design. The Clarke's transformation converts three phase system (ABC frame) to two components in an orthogonal stationary $\alpha - \beta$ frame. Park's transformation converts stationary $\alpha - \beta$ frame to a rotating orthogonal $d - q$ frame. By applying them consecutively, the three phase AC voltage and current signal can be converted into DC signals. The voltage, current and electromagnetic torque expression are all decoupled from stator angle θ_e .

Clarke-Park's transformation matrix is expressed as:

$$\mathbf{T}_{ABC/dq0} = \frac{2}{3} \begin{bmatrix} \cos \theta_e & \cos \left(\theta_e - \frac{2\pi}{3} \right) & \cos \left(\theta_e + \frac{2\pi}{3} \right) \\ -\sin \theta_e & -\sin \left(\theta_e - \frac{2\pi}{3} \right) & -\sin \left(\theta_e + \frac{2\pi}{3} \right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (3.38)$$

DQ- equivalent circuit model

Applying Clarke-Park's transformation to the voltage, current and electromagnetic torque equations, the PMSM model in dq reference frame is obtained and expressed as:

$$\frac{di_d}{dt} = \frac{1}{L_d}v_d - \frac{R_c}{L_d}i_d + \frac{L_q}{L_d}p\omega_m i_q \quad (3.39)$$

$$\frac{di_q}{dt} = \frac{1}{L_q}v_q - \frac{R_c}{L_q}i_q - \frac{L_d}{L_q}p\omega_m i_d - \frac{\lambda p\omega_m}{L_q} \quad (3.40)$$

$$T_e = 1.5p[\lambda i_q + (L_d - L_q)i_d i_q] \quad (3.41)$$

where i_d and i_q are motor dq currents, v_d and v_q are motor dq voltages, and L_d and L_q are motor dq inductances, expressed as $L_d = L_s + M_s + 3/2L_m$ and $L_q = L_s + M_s - 3/2L_m$ respectively. As a result, the equivalent circuit of PMSM in dq reference frame is shown in Fig. 3.27.

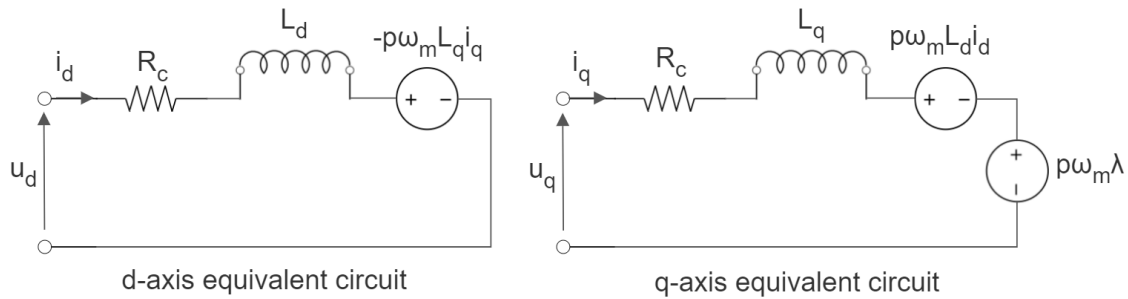


Figure 3.27: The dq equivalent circuit model of PMSM [19].

Finally, the efficiency is given by the ratio of output mechanical power to input electrical power, in dq axis, it is expressed as:

$$\eta_{\text{motor}} = \frac{T_m \omega_m}{1.5(v_d i_d + v_q i_q)} \quad (3.42)$$

Eqn.(3.39) to (3.41) form the dq-model of PMSM. With dq-model, the motor simulation can be significantly simplified. Moreover, the field oriented control (FOC) can be

easily implemented to regulate the motor rotational speed under different load conditions.

The key modelling input parameters and output simulation data of this low-fidelity model are summarised in Table 3.11. The results are important for motor torque and speed control, which will be detailed in motor control and DC/AC inverter model section. They are also used to assess the PMSM performance along flight missions.

Table 3.11: Model simulation input parameters and sizing and performance outputs for low-fidelity PMSM model.

Model simulation inputs	Performance outputs
Number of phases	Stator current (d-q axis) [A]
Rotor type	Stator voltage (d-q axis) [V]
Pole pair	Actual rotor mechanical speed [rads ⁻¹]
Stator phase resistance [Ω]	Actual rotor electrical speed [rads ⁻¹]
Inductances (d-q axis) [H]	Electromagnetic torque [Nm]
Flux linkage [Wb]	Motor mechanical power [kW]
Inertia [kgm ²]	Motor power loss [kW]
Static friction torque [Nm]	Motor efficiency [%]
Viscous damping [Nms]	
Initial rotational speed [rads ⁻¹]	
Initial angle position [rad]	
Required rotational speed [rads ⁻¹]	
Required mechanical torque [kW]	

3.7.3 High-fidelity PMSM model

The high-fidelity PMSM FEA (finite element analysis) model is built in ANSYS Motor-CAD. With FEA method, the accurate electromagnetic and electrical performance can be simulated for different motor types and designs across the full operating range. There are four key modules in ANSYS Motor-CAD [155]:

1. **EMag:** In this module, a 2D FEA method and analytical algorithms are utilised. A range of electromagnetic performance results are generated for different motor designs, such as torque, power, losses, voltages, currents, inductances, flux linkages and forces. The motor types, geometries, windings, and motor component materials are specified in this module.
2. **Therm:** Thermal performance of different motor components are modelled, as well as the cooling design is assessed. Extensive outputs are obtained, including component temperature, axial temperature distribution, thermal losses, heat transfer coefficients and thermal resistances.
3. **Lab:** With FEA in EMag and Therm modules, the analysis of any motor design over full operating envelope is enabled. Representative outputs are efficiency and loss maps, peak torque/speed characteristics, drive cycle efficiency and thermal maps.
4. **Mech:** 2D FEA method is used to analyse mechanical stress/strain and displacement for rotors during operation. Various mechanical outputs are generated, including averaged and maximum Von-Mises stress, radial direction displacements, and safety ratio of rotor yield strength.

The design and simulation workflow of ANSYS Motor-CAD can be found in [155]. In comparison to low-fidelity models, the FEA method greatly enhances the simulation accuracies and modelling details. The assumptions of low-fidelity model in p. 76 are relaxed, as EMag captures detailed magnet B-H curves, magnet saturation impacts, iron losses, eddy current and hysteresis effects, field-weakening effects, geometry-specified

copper losses and so on. The accurate electromagnetic field distributions and flux linkages are also captured by FEA methods. Moreover, the coupling impacts of thermal and electromagnetic are also simulated. All these capabilities can help enhance the fidelity level of PMSM model.

In this study, a high fidelity PMSM model for aircraft propulsion is adopted from [20], with its modelling method and shown in Fig. 3.28. It should be noted that the modelling development is out of the scope of this study and the model was adopted to use in this simulation framework. Based on the flight mission data, the maximum torque and rotational speed for each motor are calculated and they normally occur at Take-off stage. The Take-off torque and rotational speed are considered as the design parameters for the motor. An Interior Brushless Permanent Magnet Motor is considered (Fig. 3.29). Once all the motor design parameters such as torque, rotational speed, supply voltage, motor geometry, size, component materials properties, and cooling method are setup and identified by the model, FEA-based methods with motor fundamental equations are used to simulate its performance over pre-defined operation range.

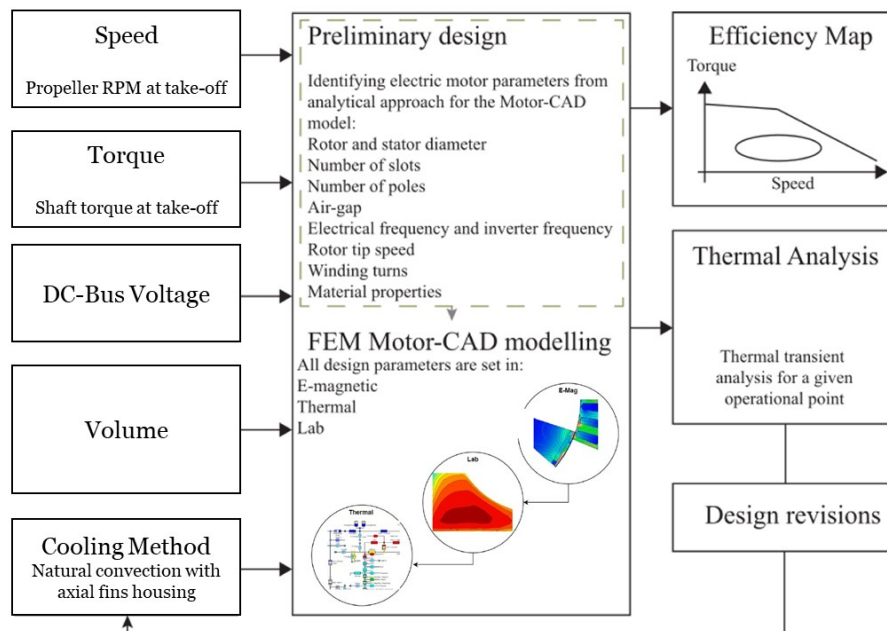


Figure 3.28: PMSM design process for the baseline flight mission requirements adopted in [20].

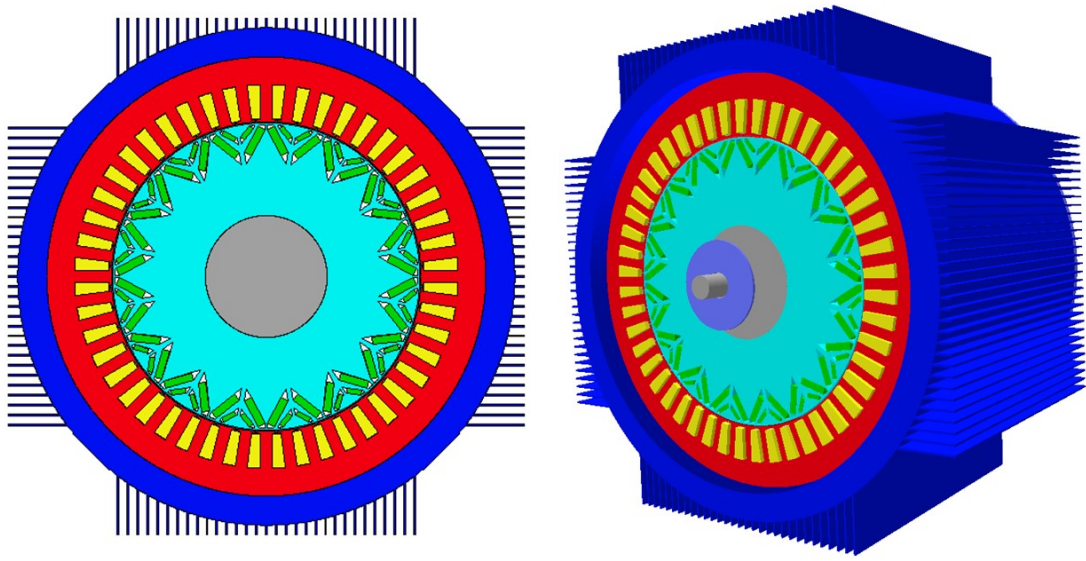


Figure 3.29: The front view and side view of PMSM designed in Ansys MotorCad adopted in [20].

Table 3.12 and Table 3.13 show examples of motor design parameters under 2000 V_{dc} bus voltage for this study. Table 3.14 shows the outputs obtained from the FEA analysis. The power losses are comprised of: copper losses, iron losses, frequency-related losses in the winding, eddy current losses, and mechanical friction and windage losses.

Table 3.12: Radial design parameters for high-fidelity PMSM model.

Radial parameters	Value/type	Radial parameters	Value/type
Slot number	18	Pole number	16
Stator lam- diameter	450 mm	Slot depth	38 mm
Tooth width	12 mm	Slot opening	1.5 mm
Slot type	Parallel tooth	Rotor type	Interior V (web)
Coil style	Stranded	Winding turn	10
Winding throw	3	Winding type	Lap
Divider type	Overlapping	Wire gauge	AWG 17
Wire slot fill	0.494	Winding connection	Star connection
Magnetisation	Parallel	Airgap	1.25 mm
Magnet width	Layer 1: 30 mm Layer 2: 15 mm	Magnet thickness	Layer 1: 8 mm Layer 2: 5 mm
Shaft diameter	125 mm	Magnet layer	2
Phase number	3	Lam- material	25PNX1250F_raw
Cooling method	Air cooled		

*lam- means lamination.

Table 3.13: Axial design parameters for high-fidelity PMSM model.

Axial parameters	Value	Axial parameters	Value
Motor length	370 mm	Stator lam- length	300 mm
Magnet length	300 mm	Magnet segments	12
Rotor lam- length	300 mm	Stator bore diameter	317.5 mm
Cooling method	Air cooled		

*lam- means lamination.

Table 3.14: Output parameters from high-fidelity PMSM model.

Output parameters	Value/type	Output parameters	Value/type
Motor weight	400.2 kg	Motor volume (with housing)	Diameter $\times$ length 510 by 370 mm
Mechanical torque	Speed-torque plane contours	Mechanical power	Speed-torque plane contours
Power losses		Efficiency	
DQ- voltage		DQ- current	
DQ- flux linkage		DQ- inductance	
DC current		Back EMF	

The results are used to assess PMSM performance, also the dq- current and voltage outputs for different operating points are fed to inverter-based motor control system. Finally, Fig. 4.26 in Chapter 4, Section 4.7.5 is a typical performance map obtained from Ansys MotorCAD software. The map will be used to carry out system performance evaluation in that section.

desired one. The error signal is fed into a speed controller to output instant reference q-axis current command signal. This reference q-axis current is then compared against measured q-axis current. The error signal is fed into another current controller to output q-axis voltage.

4. Block 4: for current loop, the measured d-axis current is compared to reference value. The error is fed to a current controller to generate d-axis voltage. The reference d-axis current value is normally set to “0”. Notice that, for surface mounted PMSM type, because d- and q- axis inductance are identical [156], the torque in Eqn.(3.41) can be simplified as: $T_e = 1.5p\lambda i_q$, so that it is only a function of q-axis current. Therefore setting d-axis current to zero can minimise unnecessary ohmic loss. Moreover, a zero reference d-axis current can decouple dq-axes currents and voltages in Eqn.(3.39) to Eqn.(3.40), which provides a more stable control strategy. For interior PMSM, although torque is not maximised, the decoupling of dq-axes quantities are desirable.
5. The obtained dq-axes voltages are required by the PMSM at this instant. Shown in block 5, 6: these voltages and angle position are fed into inverse Park’s transformation to obtain voltages in stationary orthogonal $\alpha - \beta$ reference frame.
6. Block 5, 6: the $\alpha - \beta$ voltages signals are sent to PWM based DC/AC inverter. The required three phase AC voltages are generated based on the PWM waveforms. The output three-phase voltage from the inverter is supplied to the PMSM and the speed control is realised.

Physically, The controlled PWM signals are generated by Space Vector Pulse Width Modulation (SVPWM) technique. These signals are fed to the switching components of the DC/AC inverter to control their on/off states and ultimately generate required three-phase AC voltage. Detailed SVPWM techniques and their implementations in MATLAB/Simulink® are introduced in Appendix A.

Another key component in Fig. 3.30 is the DC/AC inverter system . In this study, a low- and high-fidelity inverter models are developed. Both of them can: regulate the voltage output for motor requirement; simulate the inverter performance, especially its efficiency along flight mission; provide preliminary inverter weight estimation. The selection of them depends on the research objectives, which will be detailed in Chapter 4 and 5.

3.8.2 Low-fidelity motor drive system and inverter model

For low-fidelity motor control and inverter model, the block 5, 6 in FOC schematic diagram (Fig. 3.30) is replaced by an inverse Clarke-Park's transformation. The required dq-axes voltages are directly transformed to three-phase ABC-axes voltages. They are directly fed into the PMSM model using ideal “controlled voltage sources” in Simulink®. The detailed DC/AC inverter operation is omitted and the power losses is replaced by a fixed 98% efficiency. The simplified FOC schematic of low-fidelity motor control system is illustrated in Fig. 3.31.

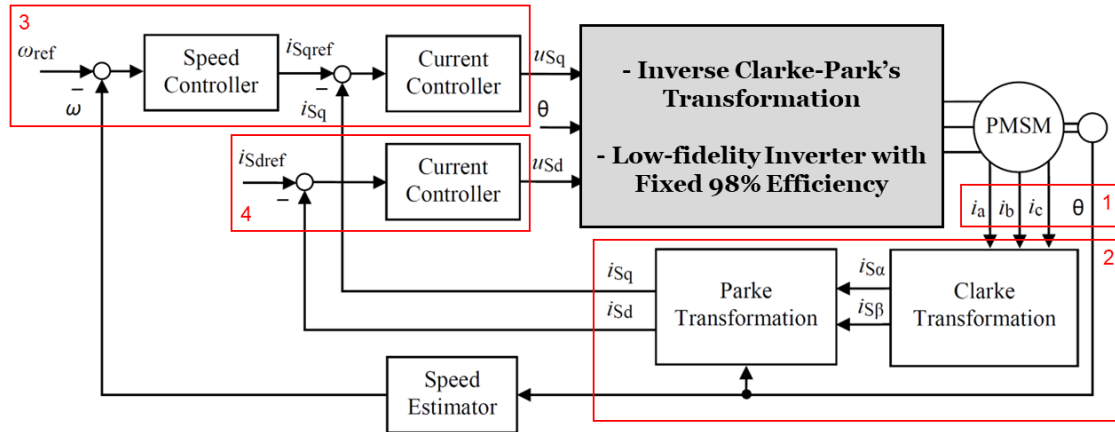


Figure 3.31: The simplified Field Oriented Control (FOC) algorithm schematic diagram with implementation steps [21].

The model parameters, sizing and performance outputs for this low-fidelity AC drive model is summarised in Table 3.15. The low-fidelity motor control and inverter model enables fast mission-level analysis. Especially for research cases that detailed power electronics performance is not of priority.

Table 3.15: Model simulation input parameters and sizing and performance outputs for proposed low-fidelity converter model.

Model simulation inputs	Sizing outputs	Converter performance outputs
<div>Inverter $S.P.$ [kWkg⁻¹]</div> <div>$I_{\text{inv,in}}$ [A]</div> <div>$V_{\text{inv,in}}$ [V]</div> <div>η_{inv} [%]</div>	<div>Inverter mass [kg]</div>	<div>$I_{\text{inv,out}}$ [A]</div> <div>$V_{\text{inv,out}}$ [V]</div> <div>$P_{\text{inv,loss}}$ [kW]</div>
<div>$W_{\text{inv}} = P_{\text{inv,peak}}/S.P._{\text{inv}}$</div>		

3.8.3 High-fidelity motor drive system and inverter model

The high-fidelity motor control model is used for high-fidelity PMSM. The flow chart (Fig. 3.32) shows the setup of high-fidelity PMSM control model. All important PMSM parameter outputs form a set of lookup tables for a range of torque and rotational speed variations. The key parameters bridging the PMSM and motor drive system are dq- voltage and current. The motor drive system operation is designed to generate the required voltage and current for any given torque-speed points of the motor maps. The off the shelf IGBT model is introduced previously. Finally, the motor control system performance map are obtained in the torque-rotational speed plane.

In order to generate required voltage and current, and to assess the performance of the motor drive system, a control strategy high-fidelity SVPWM+inverter system is proposed (Fig. 3.33) and the realisation steps are summarised as:

1. The dq-axes currents i_d^* and i_q^* are transformed to ABC-frame to generate a three-phase current sink. This three phase AC current sink is used to simulate the current consumption of the motor under given loads.
2. The dq-axes voltage v_d^* and v_q^* are measured as reference voltage values.
3. The upstream DC voltage is connected with an H-bridge DC/AC inverter to generate three-phase AC voltages. This AC power is consumed by the current sink.
4. An inverse Clarke-Park's transformation is applied to convert the three-phase voltage to two phase dq- reference frame.
5. The measured dq- voltages are input to a Space Vector Pulse Width Modulation (SVPWM) module to generate six PWM gate signals
6. The six gate signals are input to the inverter so that the required three phase voltages can be obtained.
7. The inverter output and reference dq- voltages are compared to ensure that they are identical.
8. Finally, the inverter efficiency is obtained by comparing the input power (upstream of the inverter) and output power (downstream of the inverter). The efficiency is expressed by: $\eta_{inv} = P_{inv,out}/P_{inv,in}$.

Notice, an open-loop control is adequate for this study. Because the PMSM performance map is already provided and no system disturbance is applied.

A key component in this system is the DC/AC inverter. An inverter changes a DC input voltage to an AC output voltage [143]. In this study, a 6-IGBT H-bridge DC/AC inverter model is utilised. Its schematic diagram is shown in Fig. 3.34.

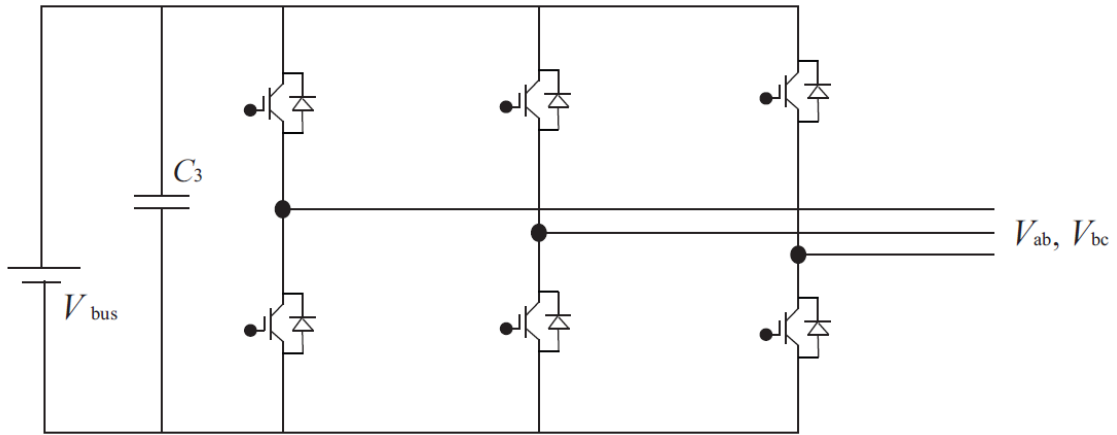


Figure 3.34: The schematic diagram of a three phase H-bridge DC/AC inverter for PMSM. The six Infineon FZ1500R33HL3 IGBTs modules indicated in this image are chosen based on the bus voltage and load current requirements.

The IGBTs utilised are the same as high-fidelity level converter model (Section 3.6.2). By appropriately firing on/off signals to these IGBTs, the inverter can output three-phase voltage and current with desired amplitude, frequency and phase. This is achievable by SVPWM techniques, which will be detailed in Appendix A. The inverter efficiency map is calculated for the variation of motor torque and rotational speed.

Response of the motor control system

In order to assess the reliability of the motor control system, simulation tests under different motor loads are carried out. Motor torque steps from 0- to 1948.6- and 1417.0-Nm (Fig. 3.35a); rotational speed steps from 0- to 2424- and 1988-RPM at time 0.5- and 1.0-s (Fig. 3.35b). The two non-zero selected points correspond to motor operation conditions at “Take-off” and “Cruising”. The input voltage of motor drive system is $V_{inv,in} = 2000V_{DC}$. The motor reference dq-voltage v_d^* , v_q^* and inverter output dq-voltage v_d , v_q are shown in Fig. 3.35c. And the reference current i_d^* , i_q^* and inverter output current i_d , i_q are shown in Fig. 3.35d.

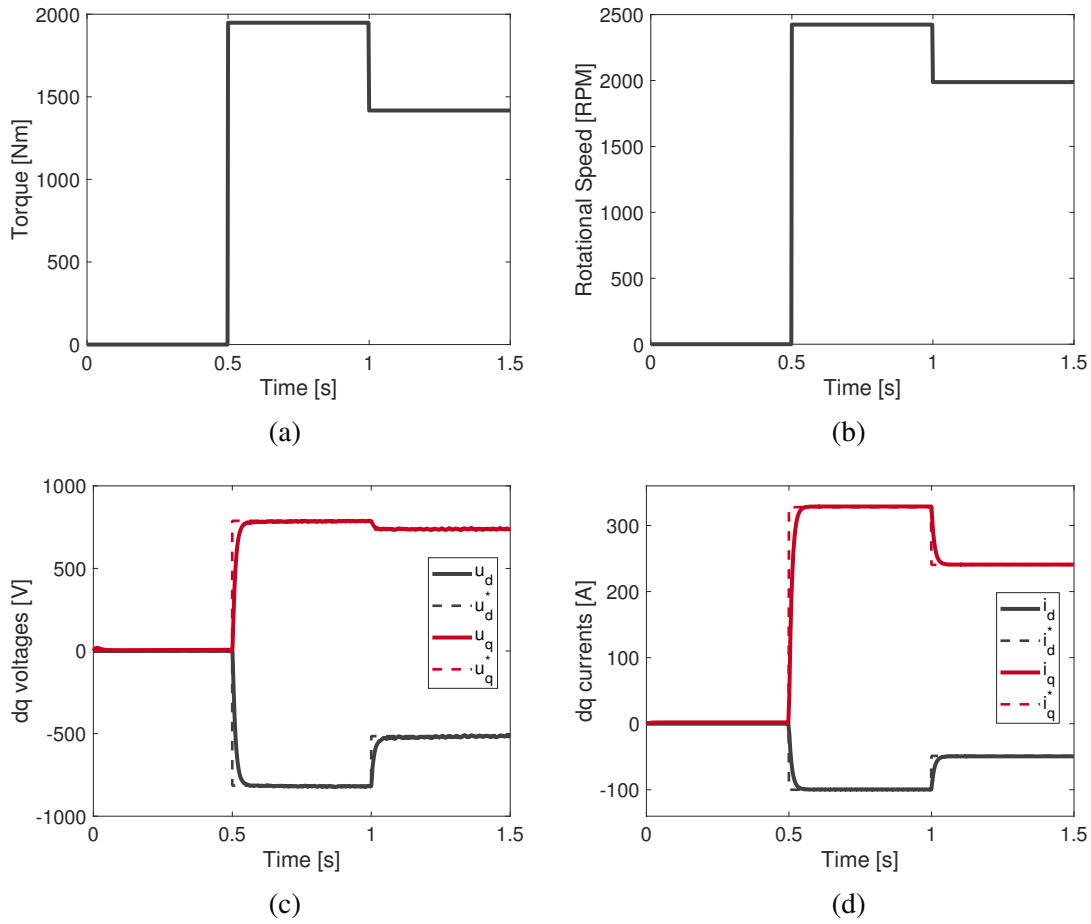


Figure 3.35: (a) Motor required torque, (b) motor required rotational speed, (c) dq- referenced and simulation output voltages, and (d) dq- referenced and simulation output currents.

It can be seen that, even for large step change (zero motor power to full take-off power) the inverter output dq voltages and current v_d , v_q , i_d , i_q can follow up the motor required dq- voltages and current v_d^* , v_q^* , i_d^* , i_q^* . Therefore, the motor control function is achieved by this proposed model.

High-fidelity motor control system parameters

Finally, all necessary input and output parameters of the proposed motor drive system are summarised in Table 3.16.

Table 3.16: Model simulation input and performance outputs for high-fidelity motor control system.

Motor control system inputs	Performance outputs
IGBT datasheet	Inverter three-phase output voltage [V]
PWM carrier frequency [kHz]	Inverter three-phase output current [A]
Input DC voltage [V]	Inverter power loss [kW]
Motor speed [rads ⁻¹]	Inverter efficiency [%]
Motor electric angle [rad]	
Motor torque [Nm]	
Reference motor voltage (d-q axis) [V]	
Reference motor current (d-q axis) [A]	

3.9 Mission performance analysis

To conduct different mission level analysis for this study, three key steps need to be realised:

1. Obtain the performance maps of high-fidelity component models of converter, motor drive system, and Permanent Magnet Synchronous Motor (PMSM) for a range of operation points.
2. Integrate all components to form the complete simulation framework, with appropriate fidelity levels.
3. Input and incorporate aircraft level performance data to the simulation framework, including power profiles, speed profiles, propeller rotational speed profiles, altitude profiles, ambient temperature, pressure and density variations.

3.9.1 Obtaining performance maps of high-fidelity models

For low-fidelity power electronics models, the voltage regulations and motor control functionalities are realised by PI controllers. Their electrical performance are emulated by either simple mathematical equations or fixed values; And for low-fidelity PMSMs, the performance is simulated by simple dq-models. These models often provide rapid and low-cost simulation. Therefore, they can be used directly for the complete mission-level analysis.

However, for high-fidelity power electronics models, the control functionalities are obtained realised by high frequency switching circuits with PWM techniques. The operating IGBT frequency ranges from 10 to 50 kHz [157], and the simulation time-step sizes must be small enough to coordinate with this value. Hence, the simulation time-step size is in the order of 10^{-5} second. With this time-step, it is time-consuming and memory costing to run the complete 1.5 to 3 hours flight mission. On the other hand, due to the high-frequency characteristics, the power electronics and motor control system have fast

response time (in the order of 10^{-2} second). Therefore, the transient response of these electric components can be treated as quasi-steady for mission level analysis. Given this situation, the author decided to output steady-state performance map for all high-fidelity models. The detailed simulation process is introduced as follows.

DC/DC converter performance map

As illustrated by Fig. 3.36, an input voltages $V_{i,1}$ and load power requirements $P_{o,1}$ are input to the converter models and the converter efficiency $\eta_{1,1}$ is obtained, after completing one step, the next pair of $V_{i,2}$ and $P_{o,1}$ are input and $\eta_{2,1}$ is obtained. By repeating this process, the complete voltage $V_{i,n}$ and power $P_{o,m}$ range are swept and a matrix of converter efficiency is obtained. This matrix corresponds to the converter efficiency map. Moreover, the simulation time is set to 0.5 seconds to ensure the converter reaches to steady-state for each loop. The realisation Matlab code is included in Appendix B.

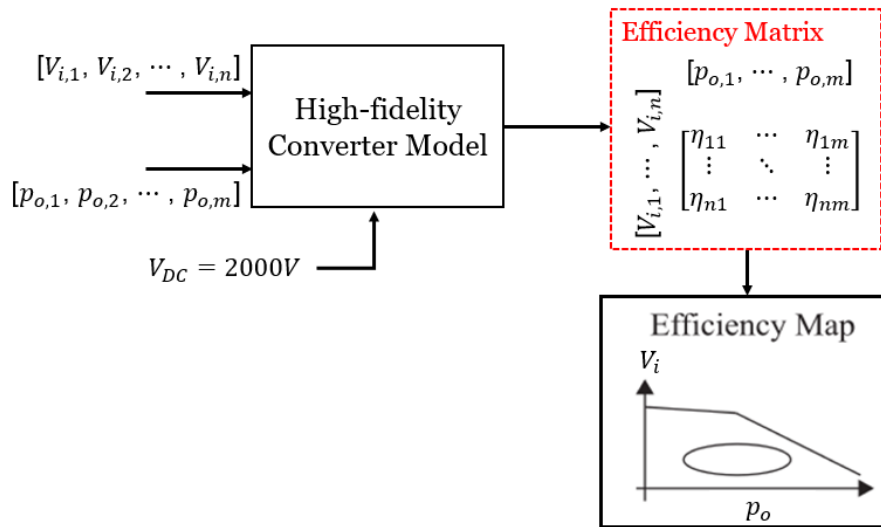


Figure 3.36: Obtaining the performance maps of high-fidelity converter model.

This way, the high-fidelity converter model is transferred to a rapid look-up table method for mission level analysis. Meanwhile, the model can still maintain high accuracy over different operation ranges (input voltages and load powers).

PMSM

The performance maps of PMSM obtained from finite element method can be directly used in mission level analysis, with torque and rotational speed as inputs.

Motor control system performance map

Similar to converter, the motor control system performance map is swept over motor torque and rotational speed. As illustrated by Fig. 3.37, The performance map is obtained in the ‘Rotational Speed - Torque’ plane. The simulation time is also set to 0.5 seconds for system to stabilise. The Implementation Matlab code is in Appendix B. This process enables rapid mission level analysis for high-fidelity motor control system.

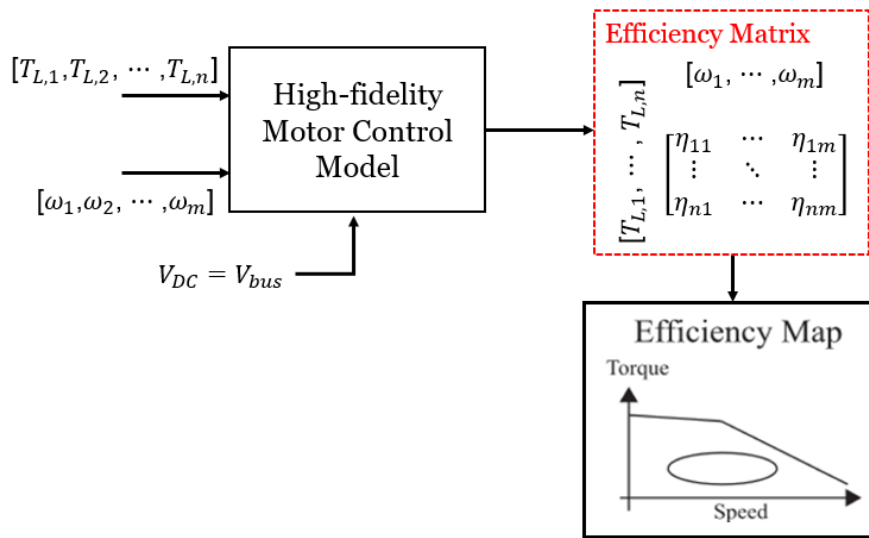


Figure 3.37: Obtaining the performance maps of high-fidelity motor control system model.

3.9.2 Integration of components in Matlab/Simulink® and aircraft performance data input

Low-fidelity integration example

The key modules of low-fidelity PEMFC-EP propulsion system (half side) are illustrated below. As shown in Fig. 3.38, the mission power profile and motor torque and rotational speed obtained in Section 3.2 are input as three time-variant 2-D lookup tables, and these data (red tags) are fed to the PMSM modules as performance requirements. Upstream the motors, the FC and its control system is connected to provide the electric power. The referenced bus voltage (blue tag) is maintained as 2000-Vdc throughout the mission via a low-fidelity converter model (detailed in Section 3.6.1).

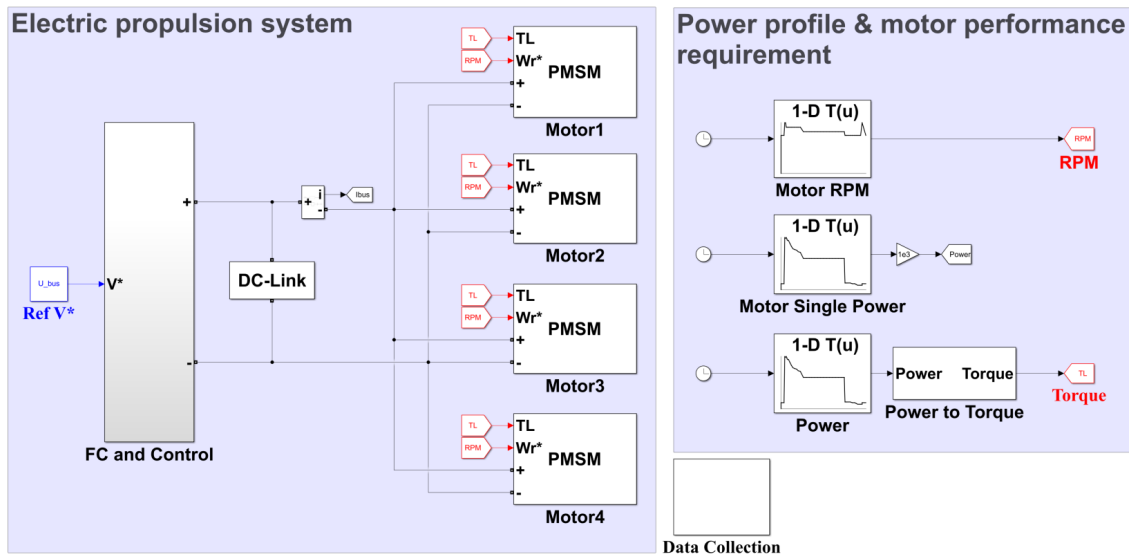


Figure 3.38: The Matlab/Simulink® implementation of half-side of the PEMFC-EP propulsion system.

The low-fidelity motor model and its control system are integrated via Fig. 3.39. The PMSM dq model outputs the performance parameters under ' $I_d = 0$ ' strategies for mission torque T_L and rotational speed W_r^* (red tags). The power required for the motor (blue tag) is forwarded to the lower 'power exchange' block, after multiplied by an inverter efficiency, the required input power for motor and its control system then propagates to the upstream via bus line.

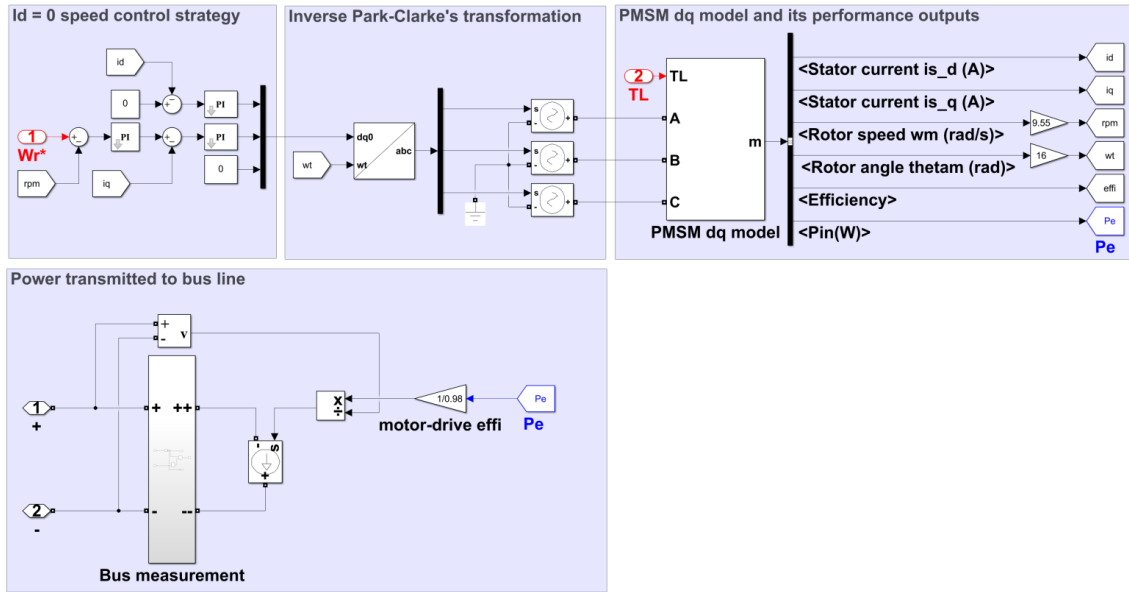


Figure 3.39: The Matlab/Simulink[®] implementation of PMSM dq model and low-fidelity motor control model for the PEMFC-EP propulsion system.

For fuel cells another module is the ambient conditions calculation, as shown in Fig. 3.40. The time-variant altitude and Mach number (speed) are obtained via 2-D lookup tables for the mission. The instantaneous altitude is fed to international standard atmosphere (ISA) table, where the ambient air temperature, static pressure and density along the mission are obtained.

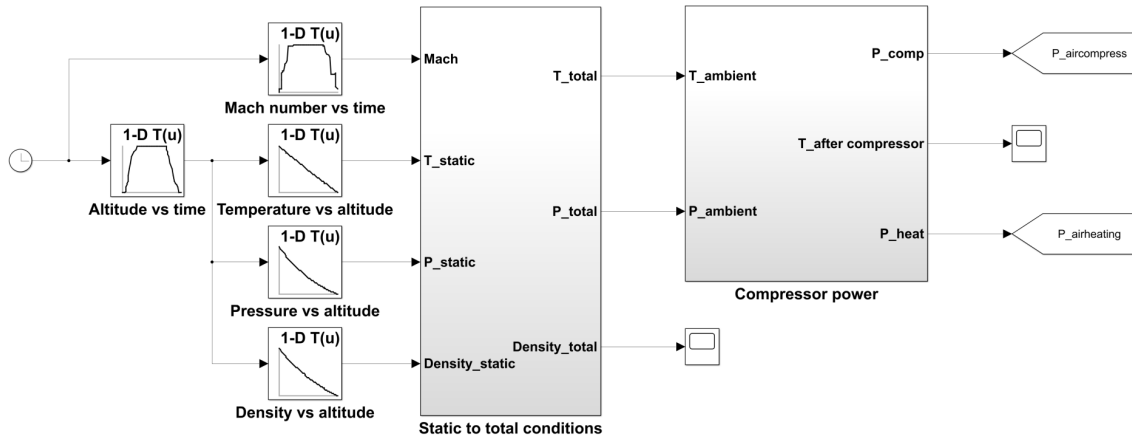


Figure 3.40: The Matlab/Simulink[®] implementation of ISA table for the PEMFC-EP propulsion system.

The static ambient conditions and instantaneous flight speed are used to calculate the

total conditions via following isentropic flow equations:

$$\frac{p}{p_{\text{tot}}} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{-\gamma}{\gamma-1}} \quad (3.43)$$

$$\frac{T}{T_{\text{tot}}} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{-1} \quad (3.44)$$

$$\frac{\rho}{\rho_{\text{tot}}} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{-1}{\gamma-1}} \quad (3.45)$$

The total atmospheric conditions are forwarded to compressor power calculation module, which is detailed in Section 3.4.3. The compressor power is directly provided by the PEMFC. This way, all developed low-fidelity subsystems are integrated to form the complete propulsion system for the PEMFC-EP architecture. All subsystem and system level simulation results are collected in the ‘Data Collection’ block in Fig. 3.38.

High-fidelity integration example

The integration process is similar to that of low-fidelity, the main difference is to use by high-fidelity converter, motor control and motor maps to simulate their performance.

As shown in Fig. 3.41, the converter integration is similar to low-fidelity case (Section 3.9.2). The only difference is that the converter efficiency calculation is obtained by performance map. The power output of the converter is fed to the bus line via electric ports (blue tags). Fig. 3.42 illustrates the integration of high fidelity motor drive and PMSM systems. Torque and rotational speed (red tags) along mission are input to ‘motor map’ and ‘motor control system map’ so that the motor mechanical power, motor efficiency and motor drive system efficiency are obtained. Then the input electric power to the motor drive/PMSM system is obtained by dividing the motor mechanical power by these two efficiencies. This required input power (blue tag P_e) is then forwarded to the ‘power transmission’ block, drawing electric power from fuel cells system via bus line.

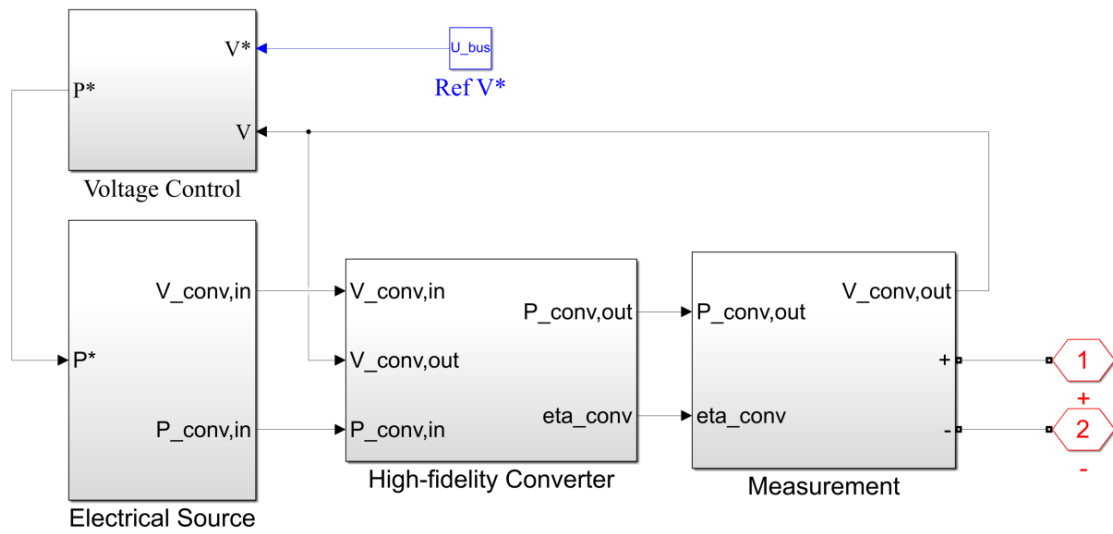


Figure 3.41: The Matlab/Simulink[®] implementation of high-fidelity converter model for the PEMFC-EP propulsion system.

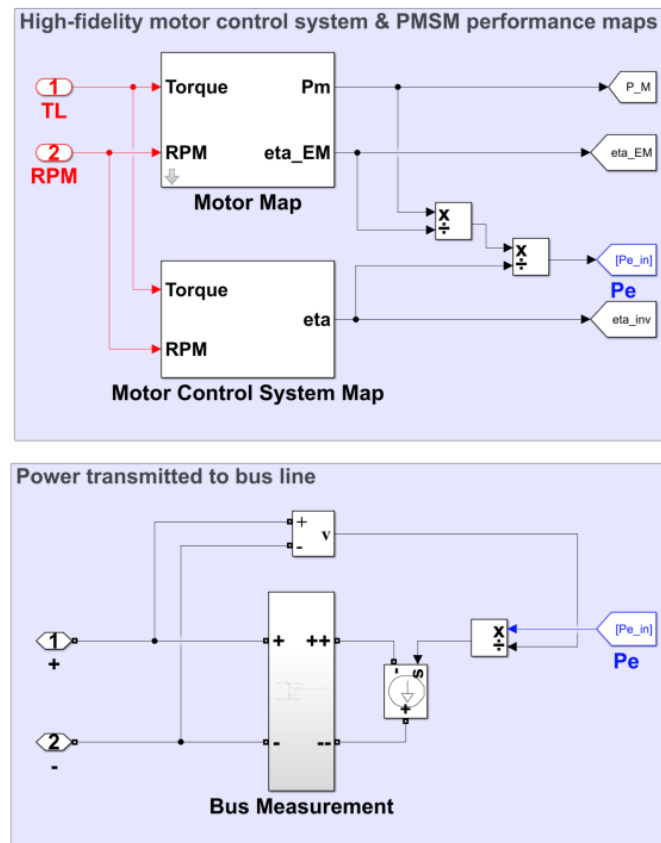


Figure 3.42: The Matlab/Simulink[®] implementation of high-fidelity motor control and PMSM model for the PEMFC-EP propulsion system.

3.10 Concluding remarks

Firstly, the aircraft retrofit model is introduced. With HERMES and Turbomatch in CHARM, a series of aircraft level profiles are obtained: altitude, speed, power, propeller rotational speed, and propeller propulsion power. These profiles are key baselines for component subsystem and propulsion system sizing and power rating considerations.

The working principles and modelling methodologies for each components (PEMFC, battery, converter, motor control system, and PMSM) are described in this chapter. Their key modelling input and output parameters are presented, and the validations are conducted. For PEMFC and battery models, they have the capabilities of simulating on- and off-design performance. And for power electronics and PMSM subsystem modelling, multi-fidelity/disciplinary models are developed. These model features can address the limitations of methods seen in literature and enhance the capability of the simulation framework. These developed subsystems are modular, scalable, and physics-based, which enable the simulation of the most prominent characteristics of the novel electric propulsion systems and the possible application scenarios they will face.

The integration and matching of subsystem modules to the complete propulsion system is then discussed. Different control strategies are utilised during integration process, including closed-loop PI control, cascade dual closed-loop control, ' $I_d = 0$ and SVPWM' control, and open loop controls. After testing, these developed control strategies are considered reliable and robust. These components and control systems are integrated to different electric propulsion architectures: PEMFC-EP, hybrid fuel cell, hybrid battery and hybrid fuel cell/battery. These methodologies together form the in-house E-HEART (Enabling-Hybrid Electric Aircraft Research and Technology) tool.

Finally, the communication and data flow between the retrofit aircraft model and propulsion system is introduced. The mission-level evaluation of system performance, architecture, energy management strategy, design, sizing, and on/off design operations are all evaluated based on the component and system output parameters.

Chapter 4

50 PAX Regional Aircraft Fuel Cell Propulsion

4.1 Introduction

In this chapter a study of fuel cell electric propulsion (EP) system for a 50 PAX regional ATR42 like aircraft is conducted. A multi-objective, multi-fidelity dynamic simulation framework is developed for EP for system sizing, subsystem integration and matching, key component on and off design evaluation for holistic flight mission. The modular nature of subsystem can be beneficial for rapid reproducible studies for different system configurations and mission cases. Also, with multi-fidelity characteristics the accuracy of model simulation can be enhanced while saving calculation time.

In this chapter, off-design performance of FC system is also considered. Both air mass flow rate $\dot{m}_{\text{air}}$ and air pressure p_{air} can significantly affect the FC performance. Variations of them will cause off-design and even malfunction for FC system. These two parameters are also sensitive to ambient environment change of aircraft application along the mission. Therefore, a sensitivity study of $\dot{m}_{\text{air}}$ and p_{air} is conducted for the FC system in aircraft application. It is found that there is a trade-off between system reliability and efficiency. Therefore, a data-based control strategy over $\dot{m}_{\text{air}}$ and p_{air} is then proposed to avoid system

malfunction, enhance the reliability and improve efficiency.

Due to limited power in single FC stacks, the propulsion system is normally formed of multiple number of them to for high power requirement. However, the FC stacks are also suffered from degradation or poor design. This would result in voltage/current/power (VIP) reduction. Consequently, different FC stack VIP states can cause imbalance performance within FC system. In this chapter, a quantitative analysis is conducted to capture this imbalance performance and its effects on the whole energy storage system. Also, upon exploring different FC stack configurations, it is found that FC stacks connection arrangements can mitigate the impacts brought by stack imbalance performance. The findings in Section 4.6.1 are published in [39].

The fact that FC configurations can affect the system performance enlightened the final section in this chapter. Nine different multi-stack FC configurations are proposed in this chapter. These configurations are assessed and compared based on their FC stacks and system efficiencies as well as the electrical component efficiencies, power losses due to failure, voltage and current variation due to degradation, and their total weight. Moreover, with a proposed DC/DC converter design process, the challenges of handling high voltage and current in aircraft application are demonstrated. A potential FC configuration amongst these competitors are recommended based on the quantitative simulation results. The findings in Section 4.7 are published in [20].

This chapter is arranged as follows: The selected 300 nms mission profiles and simulation framework for propulsion system is presented in Section 4.2. The results and analysis for on-design system performance simulation for the 300 nms mission are presented in Section 4.4. The off-design performance results of FC stack due to $\dot{m}_{\text{air}}$ and p_{air} variation, and the data-based control strategies are discussed in Section 4.5. The FC stack imbalance performance impact is evaluated in Section 4.6. The mitigation measures using different configurations are also presented. Finally, the nine potential multi-stack FC configurations are assessed in Section 4.7.

4.2 Proposed mission and power profile

In this study, a fuel cell retrofit aircraft model, based on ATR42 is used here. Firstly, MIT's Qmil/Qprop tool is used for the design and performance analysis of aircraft propellers. The generated propeller performance maps are input to Cranfield in-house aviation and gas turbine model: Hermes and Turbomatch. These are flight path analysis and gas turbine performance analysis and modelling-simulation advanced methods and tools. The flight mission specifications are included in Table 4.1 and the flight data are shown in Fig. 4.1. They will be used for future system analysis.

Table 4.1: Flight mission specifications used by Cranfield in-house toolkit.

Range	300 nmi	OEW	10900 kg
Total Engine Weight	2×480 kg	Max Fuel Weight	4500 kg
Calibrated Climb Speed	160 kts	Cruise Mach	0.46
Take-off Weight	17913 kg	Cruise Altitude	19000 ft

*kts: knot, OEW: Operational Empty Weight, ft: foot.

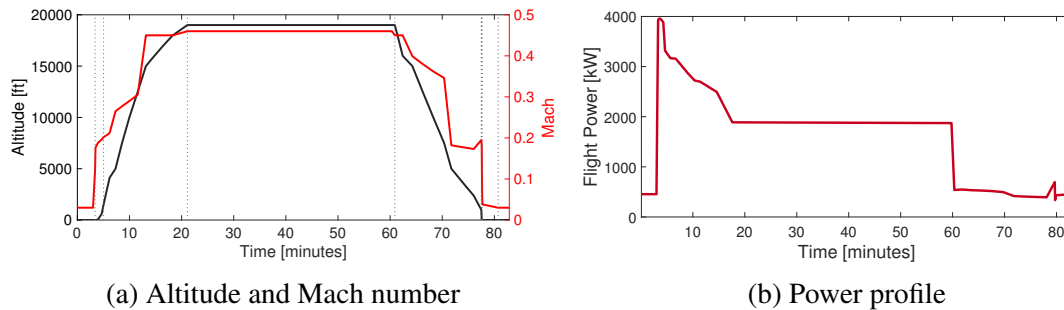


Figure 4.1: Flight mission specifications obtained by Cranfield in-house toolkit.

4.3 Fuel cell propulsion system: components, sizing, operation and modelling

A fully electrified aircraft propulsion system is considered. It is modelled to demonstrate the interactions between the FC stacks and the electrical configurations (Fig. 4.2). In this system, two 2000 V_{dc} buses are connected with bus ties. This voltage is selected

as a reference for bus voltage based on the acquired optimum motor efficiencies at this voltage [144]. 2.4 MW of power is required from each “side” of the propulsion system. A more detailed subsystem level introduction is presented in the following sections.

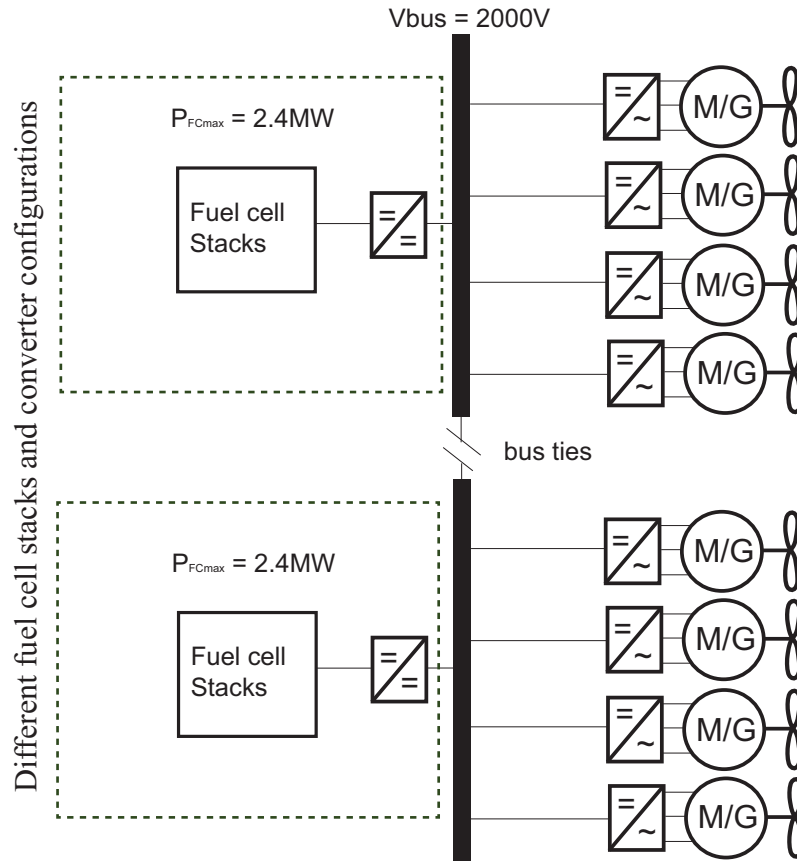


Figure 4.2: An example of a propulsion system with FC stacks configured for different voltage and current outputs. Different DC/DC converter configurations are assessed to maintain the bus voltage at 2000 V. These configurations are shown in Fig. 4.21. Eight permanent magnet synchronous machines were designed for 500 kW power at rotational speed of 2000 RPM.

4.3.1 Fuel cell and its air breathing system operation during mission

Fuel cell air breathing system introduction

The fuel cell modelling is addressed in detailed in Chapter 3. A brief review is here and the methodology flow diagram is presented in Fig. 4.3. Air needs to be supplied to fuel cell systems so that oxygen can be moved to cathode for reaction. A typical schematic diagram of this air breathing system is shown in Fig. 4.4. It can be seen that compressor

is the key component. The compressor is modelled based on thermodynamics equations, which are detailed in Chapter 3.

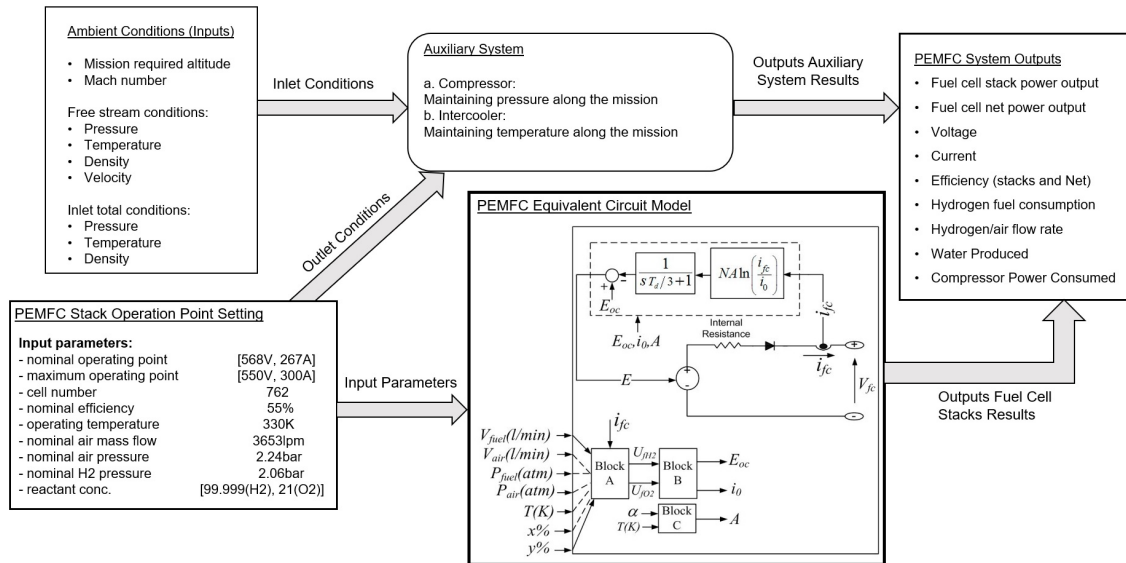


Figure 4.3: The inputs and outputs to the FC system model. The FC model is adopted from an existing MATLAB model published in [7].

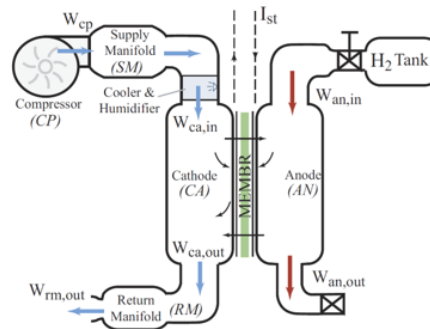


Figure 4.4: The schematic diagram of a fuel cell and its air breathing system. The diagram is adopted from [22].

Air breathing system power calculation

A ram-air intake is used, so that the inlet air condition is determined by the dynamics air conditions seen by the aircraft. The calculation flow chart is shown in Fig. 4.5. Firstly, the predetermined mission profile, including speed and altitude are input to the ISA table. By using lookup table module in Matlab and the data of ISA Table [158], the static and total pressure, temperature and air density along the mission can be obtained.

Secondly, the predetermined flight power is used to calculate the required air mass flow rate for compressor and fuel cell system, which will be discussed in detailed later. The time-varying compressor power is then obtained via compressor thermodynamics equations using these values.

And finally, it is assumed that the compressor power is provided by the fuel cell system. In the simulation framework, these power is subtracted from the fuel cell power. Therefore, the performance of fuel cell air breathing system is determined by: flight mission characteristics (altitude, speed and flight power), as well as local ambient air conditions (pressure, temperature and density). Due to this reason, there will be two efficiencies describing the fuel cell system performance: one is the fuel cell stack efficiency, which only considers the fuel cell stack itself; another one is fuel cell system efficiency, which includes the power consumption of air breathing system.

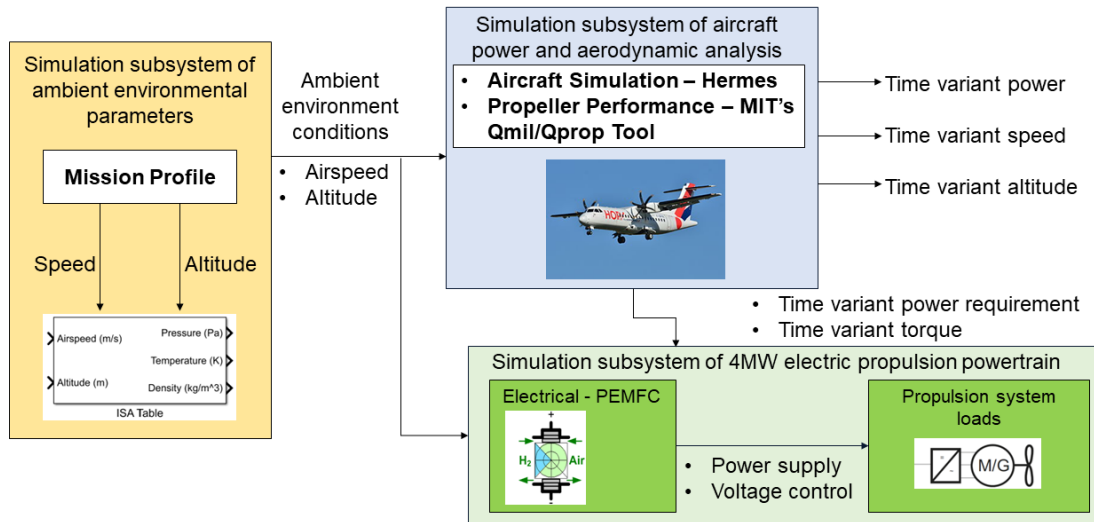


Figure 4.5: The integration flow chart of ISA table, power profile and FC system model.

4.3.2 DC/DC converter system

The voltage of fuel cell system varies and fluctuates under different loads, which would greatly affect the safety and reliable operation of the propulsion system. Therefore, it is

important to maintain the bus voltage to a desired value to stabilise the PMSM and the rest of system. A controlled DC/DC converter system needs to be used. There are three main types of converters: boost converter to step up the voltage; buck converter to step down the voltage and buck/boost converter to do both.

The detailed converter system modelling is addressed in Chapter 3. As discussed previously, there are two levels of fidelity models presented for power electronics and motor systems: a low fidelity, mathematical based or fixed value model and a high fidelity, physics based model. Different research aims or focuses require distinct model fidelity. Both converter models have the ability to maintain the bus voltage of the system, which is the prior function in the system. The only difference is that:

- The low fidelity converter model uses a first-ordered mathematical relation to express the its efficiency by eqn (3.29). The proposed equation reflects that: the converter efficiency approaches unity when voltage ratio is close to one, and decreases otherwise. The converter efficiency along flight missions can be calculated mathematically. A closed loop PI control strategy is adapted to maintain the bus voltage at desired value over different power requirement.
- The high fidelity model emulates real switching on/off process inside the converter. Important characteristics such as conduction and switching losses of IGBTs, ohmic losses of resistors during switching operation are captured. Electric and logic circuits are used in Simulink, accompanying with off-shelf IGBTs, resistors, capacitors and inductors specifications, so that a detailed, physical based converter model is created. The pulse width modulation (PWM) technique, implemented in a cascade PI control system, is used to maintain bus voltage at desired values. In this way, high fidelity converter performance can be captured, at the same time, voltage control purpose can be achieved. Moreover, a more detailed sizing methodology and weight analysis based on the off-shelf component specifications is discussed.

In this study, both model groups will be considered. Their results and research contri-

butions will be introduced later.

4.3.3 DC/AC inverter - motor drive system

Three-phase bridge inverter is a device that inverts single-phase DC power input to three-phase AC power output. They are often seen in AC motor drives applications. Inverter system is often coupled with field orient control (FOC) technique to control PMSM. It provides good capability of motor control over a full torque and rotational speed range. The PWM signals generated by the FOC algorithm are fed to inverter to control the switches (IGBTs) inside. With these controlled switching operations, the upstream DC power can be inverted to desired three-phase AC power waveforms. The downstream motor receives these power and generate desired torque and rotational speed. To sum up, the main function of this device is to invert DC to AC power, and to control the motor torque and rotational speed.

The detailed inverter principle and modelling is explained in Chapter 3. Similar to converter system, there are two fidelity levels for inverter:

- With low fidelity model, a fixed inverter efficiency of 98% is assumed. The motor control function is achieved by PI controllers and ' $I_d = 0$ ' control strategy.
- The high fidelity model simulate the real switching process inside the inverter. The component characteristics are captured, with off-shelf IGBTs. High fidelity inverter performance can be presented. Different operation parameters like input DC voltage, motor torque and rotational speed can affect the performance of inverter. In later sections, the inverter efficiency contours as functions of input voltage, motor torque and speed would be presented later. A more detailed sizing and weight analysis based on off-shelf specifications is discussed later.

4.3.4 Motor system

Eight permanent magnet electric machines (PMSMs) are used in the complete propulsion system in this study. The electric motor chosen decision is discussed previously, the key consideration is of its high specific power and non-slip property. The detailed model principles and simulation is discussed previously in Chapter 3. Again, multiple fidelity level models have been considered:

- A relatively low fidelity, dq mathematical model has been used to simulate electric and mechanical performance of PMSM. With the assumptions of no iron core saturation, no induced eddy current loss or magnet hysteresis loss, symmetrical three-phase current, and constant dq-axis inductance L_d and L_q . This model enables fast motor simulation in a system level with relatively high accuracy. It has good capability of control strategies implementation, especially for dq-axis decoupling strategies. But the assumptions limit its capability to simulate the motor performance in terms of losses simulation, field-weakening operations and so on.
- For high fidelity finite element model (FEM), more accurate electromagnetic and electrical performance are simulated in Ansys MotorCAD. This model provides more detailed and accurate power losses prediction for the motor as above-mentioned assumptions are relaxed. Moreover, the coupling effects of thermal and electromagnetic can also be captured.

4.3.5 The complete electric power-train

How these subsystems are connected to form a complete propulsion system is demonstrated previously in Chapter 3 Section 3.3. The holistic system performance can be demonstrated via Fig. 4.6. Since this is a serial connected system, the product of different subsystem component efficiencies is the total system efficiency. In the right hand side output data sink, all simulation results are collected. These data are important basis for system assessment, architecture studies, decision makings, risk identifications, propul-

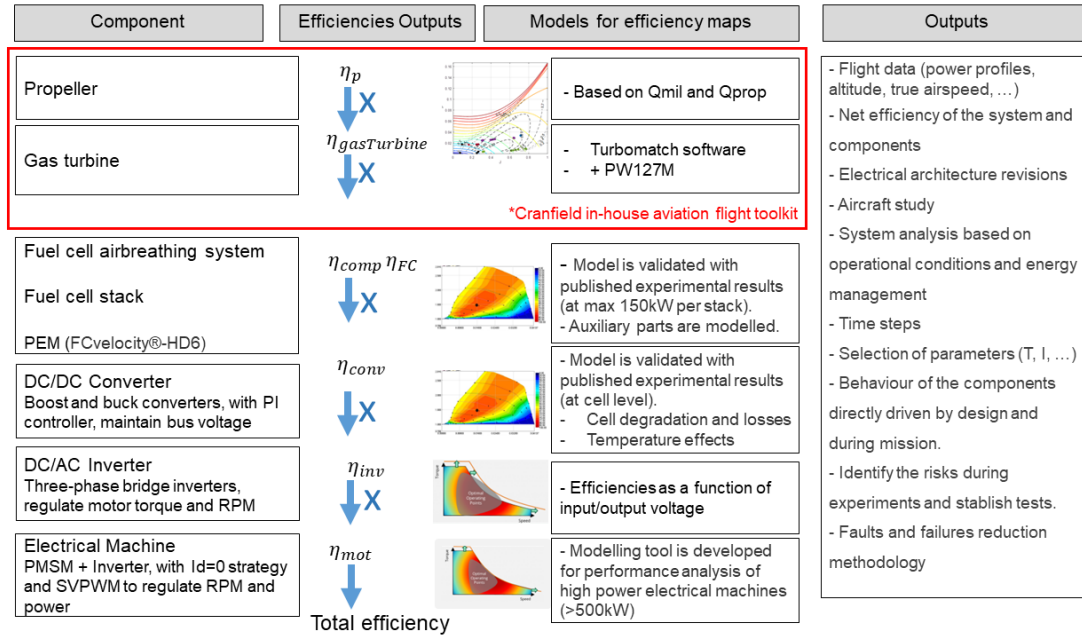


Figure 4.6: The connection of electric components and data flow of propulsion system performance assessment.

sion system topology comparisons. With models of appropriate fidelity, the simulation framework enables fast studies for key characteristics of the system, and capture subsystem interaction while satisfying holistic mission analysis. Finally, due to the generic and scalable features, the proposed components are easily integrated to various propulsion architectures, for example, the pure fuel cell system in this chapter and hybrid system in Chapter 5. System performance subsystem interactions can be captured for different missions and operation strategies.

4.4 On-design electric system performance assessment

This section focuses on an on-design performance analysis of the propulsion system. Due to symmetrical features, only one “side” of system is considered. The specifications for on-design component are listed in Table 4.2 and Table 4.3. There are 16 fuel cell stacks per side, two configurations of fuel cell stack connections are proposed and shown in Fig. 4.7. Under on-design performance with individual fuel cell stack operating at nominal points, there is no difference between them due to configuration symmetry, so in this section, the

“Parallel-Series configuration” is selected. The impact of FC multi-stack configuration on propulsion system design and performance will be addressed in later sections.

Table 4.2: PEMFC system nominal specifications.

Symbol	Description	Value
T	Fuel cell operating temperature	330 K
N	Fuel cell stack number	762
z	Moving electron number	2
τ	Fuel cell dynamic time constant	0.1 s
η_c	Compressor adiabatic efficiency	85% [159]

Table 4.3: Bus line, converter, inverter, and PMSM specifications.

Symbol	Description	Value
V_{bus}	Bus voltage	2000 V
η_{conv}	Converter efficiency	$1 - 0.9 \left \log_{10} \left(\frac{V_{\text{fc}}}{V_{\text{bus}}} \right) \right $
η_{inv}	Inverter efficiency	98%
L_d	D-axis inductance	$12e^{-5}$ H
L_q	Q-axis inductance	$12e^{-5}$ H
R_c	Motor armature resistance	0.02 Ω
p	Motor pole pair	16
λ	Magnetic flux linkage	0.1 Wb

* V_{fc} : fuel cell output voltage, V_{bus} : bus voltage.

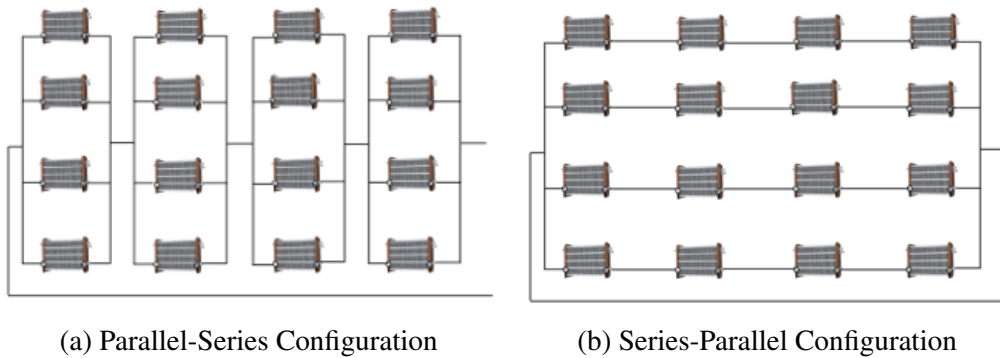


Figure 4.7: Two proposed configurations: Parallel-Series and Series-Parallel configurations of FC multi-stack system.

The characteristics of a single fuel cell stack are shown based on $V - I$ and $P - I$ curves in Fig 4.8a. The holistic system simulation results are shown as following, including: efficiencies of fuel cell stack, fuel cell system, and other components in Fig 4.8b; power

generated by fuel cell stacks and net power delivered from fuel cell systems in Fig 4.8c; voltage and current across fuel cell systems, bus voltage and current in Fig 4.8d; torque and rotational speed of motors in Fig 4.8e. Moreover, Fig 4.9 shows the air mass flow and consumption rate, fuel flow and consumption rate and water generation rate.

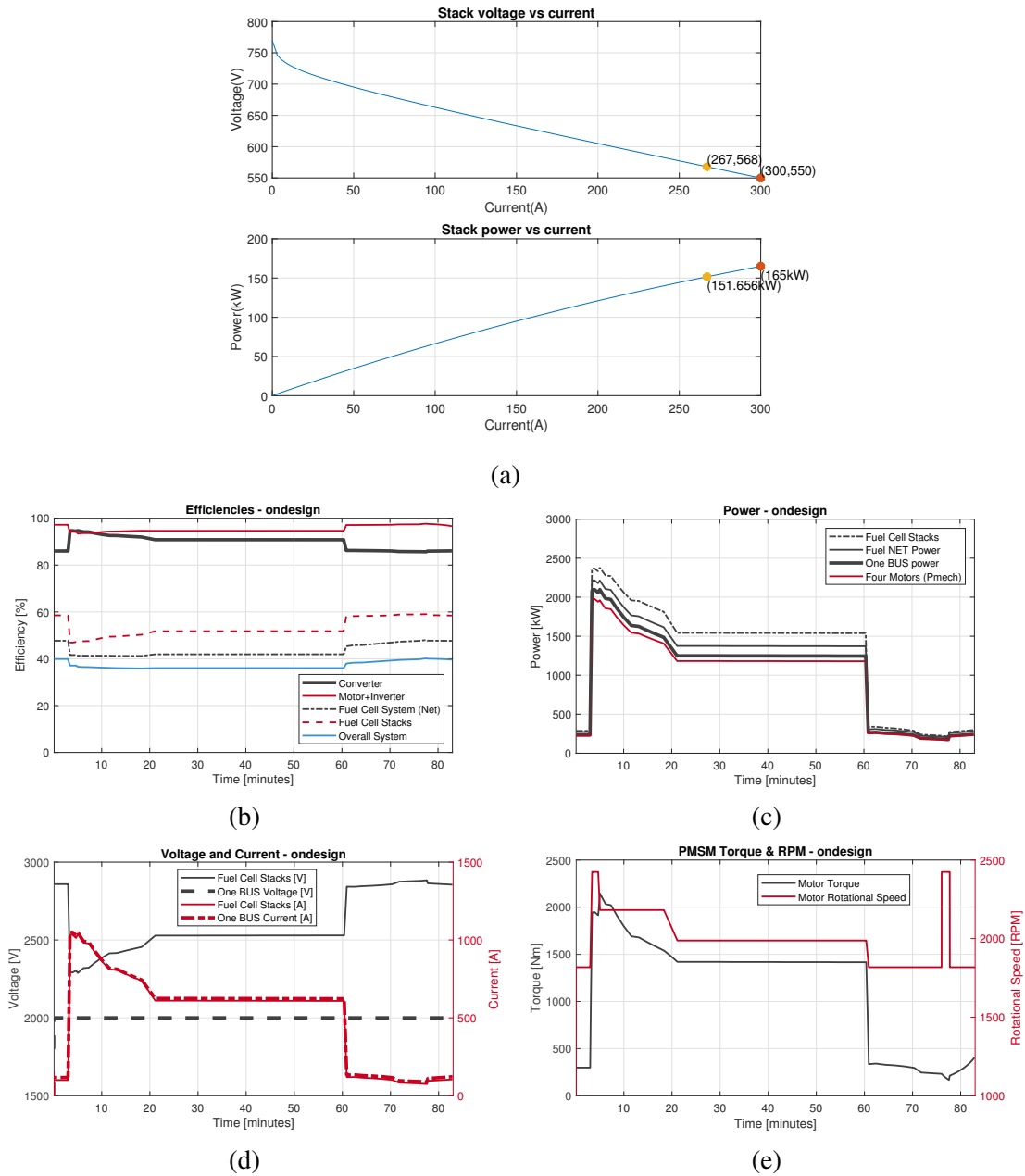


Figure 4.8: (a) Polarisation curves for FC stack model adopted from [7,23], (b) Efficiency for components and system, (c) Power for FC, bus line and PMSM, (d) Voltage and current of FC and bus line, and (e) PMSM torque and rotational speed.

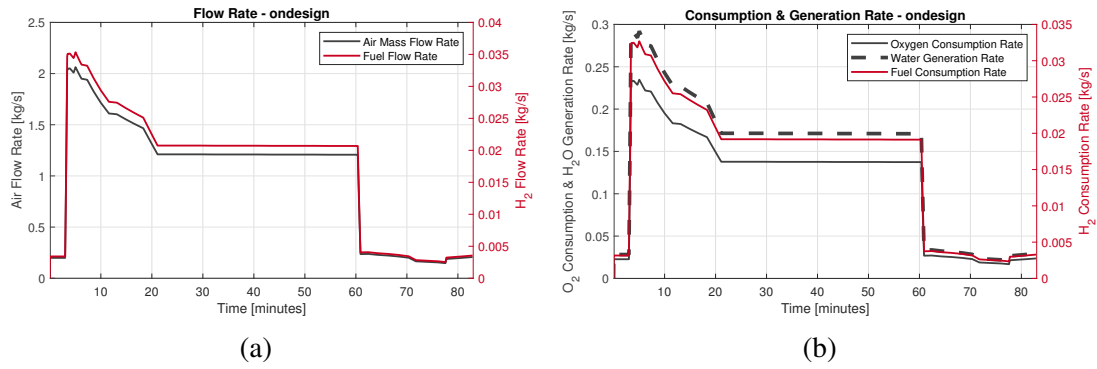


Figure 4.9: (a) Air mass and fuel flow rate and (b) O₂, H₂ consumption and H₂O generation rate.

These results are useful in terms of preliminary propulsion system design and assessment. Both different power requirements and ambient conditions along the mission affect the system performance. As demonstrated in Fig. 4.8c, the flight power requirement reaches its maximum (2 MW) at “Take-off” stage and gradually decrease to 1.2 MW cruising power through “Climbing”. Fig. 4.8a and Fig. 4.8b show that: the FC system exhibits high efficiency and voltage at low power; while at high power settings the efficiency and voltage are lower. The buck converter exhibits higher efficiency when input and output voltages are closer, therefore, its efficiency reaches maximum at “Takeoff” phases and reduces at low power “Taxiing” and “Descent” phases.

As shown in Fig. 4.9, all flow and consumption rates for oxygen and fuel share similar patterns as power curves (Fig. 4.8c). These trends reflect the reactant amounts for electrochemical reaction depend on power requirement. Moreover, the air mass flow rate is a key performance curve for FC air-breathing system design and control. Another key data is the H₂ consumption rate, as it provides the total amounts of fuel required for a mission. The integration of H₂ consumption rate provides an initial estimation of total hydrogen weight onboard, in this case, 78.6 kg. The state-of-art gravimetric hydrogen storage capacity is 5.7% (wt) [160] and a theoretical prediction can reach 18.5% (wt) for Borohydrides materials [161]. The hydrogen tank would be at least 1378.9 kg and 424.9 kg based on the fuel weight. Consequently, the required hydrogen mass needs to be considered as they will limit the payload when designing the aircraft.

In this section, the proposed subsystems, sub-models, simulation control mechanisms and the integration of them are tested and function properly in 4 MW pure fuel cell propulsion system level. With this simulation framework, the on-design performance of FC system for aircraft holistic mission is studied. Important data are collected and summarised, including: component and bus voltage, current and power against time; component and system efficiencies, reactant flow, consumption and generation rates. All these data are useful for system design, sizing and development for a pure FC regional aircraft propulsion system. In next section, FC off-design performance and their impacts on propulsion system are considered.

4.5 Off-design PEMFC system performance assessment

The performance of PEMFC is affected by a series operation parameters: the cathode air mass flow rate $\dot{m}_{\text{air}}$, the cathode air pressure p_{air} , the fuel cell operation temperature T_{fc} , and the concentrations of hydrogen $x\%$ and oxygen $y\%$.

4.5.1 Impacts of air mass flow rate and supply pressure on PEMFC performance

In this study, the temperature T_{fc} , hydrogen fuel and oxygen concentration and humidity across fuel cell are maintained at appropriate level at any load. The dynamic and performance of the fuel cell system is governed mainly by air supply system, where two operation parameters, $\dot{m}_{\text{air}}$ and p_{air} , are considered. Both $\dot{m}_{\text{air}}$ and p_{air} have significant impacts on the fuel cell stack performance, such as stack power P_{stack} and stack efficiency η_{stack} . This phenomenon has been studied and testified by peer reviewed studies [136, 162, 163]. Their impacts are discussed accordingly in below:

Impact of air mass flow rate $\dot{m}_{air}$

With the aid of fuel cell equations [30], the impacts of air mass flow rate are explained. According to Faraday's law, the minimum oxygen molar flow rate (i.e. oxygen used rate) is given by (4.1):

$$\dot{n}_{O_2,react} = \frac{N_{cell}i_{fc}}{4F} \quad (4.1)$$

The oxygen air mass flow rate is the product of $\dot{n}_{O_2}$ and M_{O_2} (4.2):

$$\dot{m}_{O_2,react} = \dot{n}_{O_2,react} \times M_{O_2} = \frac{N_{cell}i_{fc}M_{O_2}}{4F} \quad (4.2)$$

Inside the fuel cell stack, the oxygen concentration is gradually decreased along the air mass flow direction. The oxygen might be completely depleted around cathode outlet, this depletion phenomenon is called "Oxygen Starvation". In order to avoid this phenomenon and supply adequate oxidants from the beginning, excess amount of oxygen is supplied, with the new inlet oxygen mass flow rate as (4.3):

$$\dot{m}_{O_2,inlet} = \lambda_{O_2} \frac{N_{cell}i_{fc}M_{O_2}}{4F} \quad (4.3)$$

To convert oxygen mass flow rate to air mass flow rate (4.4):

$$\dot{m}_{air,inlet} = \lambda_{O_2} \frac{N_{cell}i_{fc}M_{air}}{x\%4F} \quad (4.4)$$

Where, λ_{O_2} is the "oxygen excess ratio", expressed as (4.5):

$$\lambda_{O_2} = \frac{\dot{m}_{O_2,inlet}}{\dot{m}_{O_2,react}} \quad (4.5)$$

The "oxygen excess ratio" λ_{O_2} is the ratio of inlet oxygen mass flow rate to the actual oxygen consumption rate. As explained earlier, this value needs to be greater than one to avoid "Oxygen Starvation". The shortage of oxygen would cause a series of degradation problems to the performance of fuel cell and shorten the stack life. Another impact is that

the fuel cell stack is unable to output adequate current i_{fc} (i.e. power) for required flight mission, the risk of system malfunction is increased. Therefore, high λ_{O_2} can improve the performance of fuel cell stack in terms of system reliability, stack power P_{stack} and stack efficiency η_{stack} .

However, an exceedingly high value of λ_{O_2} can also cause other issues, namely “Oxygen Saturation”. On one hand, higher λ_{O_2} and thus higher $\dot{m}_{air,inlet}$ would blow away the water adsorbed in the proton exchange membrane. The decrease of water concentration at the membrane surfaces would cause fuel cell dehydration and failures as well. Moreover, after reaching an optimum λ_{O_2} , the fuel cell stack would reach its maximum power and efficiency performance. Further increase of λ_{O_2} would not improve the stack performance, on the contrary, the compressor power is increased, and hence the overall fuel cell system performance is deteriorated.

The optimal value of λ_{O_2} also depends on power requirements and compressor operation conditions. Therefore, it is necessary to run different simulations or conduct experiment to obtain the optimal λ_{O_2} , hence optimal $\dot{m}_{air,inlet}$ for different fuel cell system operation scenarios during different flight phases.

Impact of air supply pressure p_{air}

To explain how air supply pressure affects the fuel cell performance, it is necessary to understand the electrochemical performance of PEMFC. The performance is governed by following equations:

$$V_{fc} = E_{oc} - V_{ohmic} - V_{act} \quad (4.6)$$

where V_{fc} is the fuel cell voltage, E_{oc} is the fuel cell open-circuit voltage, V_{ohmic} and V_{act} are the ohmic and activation over-potential.

The open-circuit voltage is expressed as:

$$E_{oc} = K_c \left[1.229 + (T - 298) \frac{-44.43}{zF} + \frac{RT}{zF} \ln \left(p_{H_2} p_{O_2}^{\frac{1}{2}} \right) \right] \quad (4.7)$$

where K_c is the voltage constant at nominal condition, T is the fuel cell operating temperature, z is the moving electron number, F is the Faraday constant, R is the universal gas constant, p_{H_2} and p_{O_2} are the hydrogen and oxygen partial pressures.

The ohmic and activation over-potentials are expressed as:

$$V_{act} = \frac{1}{\tau_s + 1} N_{cell} A \ln \left(\frac{i_{fc}}{i_0} \right) \quad (4.8)$$

$$V_{ohmic} = R_{ohmic} i_{fc} \quad (4.9)$$

where τ is the fuel cell dynamic time constant, N_{cell} is the cell number, R_{ohmic} is the stack inner resistance, and i_{fc} is the fuel cell current. The Tafel slope A and exchange current i_0 are expressed as follows:

$$i_0 = \frac{z F k (p_{H_2} + p_{O_2})}{R h} e^{(-\Delta G / RT)} \quad (4.10)$$

$$A = \frac{RT}{z \alpha F} \quad (4.11)$$

where k is the Boltzmann's constant, h is the Planck's constant, and ΔG is the activation energy barrier.

$$\eta_{FC,stack} = \frac{P_{stack,tot}}{\dot{m}_{H_2} \Delta h_{HHV,H_2}} \quad (4.12)$$

$$\eta_{FC,system} = \frac{P_{stack,tot} - P_{BoP}}{\dot{m}_{H_2} \Delta h_{HHV,H_2}} \quad (4.13)$$

where $\eta_{FC,stack}$ and $\eta_{FC,system}$ are fuel cell stack and system efficiency, $P_{stack,tot}$ and P_{BoP} are stack and balance of plant power, $\dot{m}_{H_2}$ is the supplied hydrogen fuel flow rate, and h_{HHV,H_2} is the hydrogen higher heating value (HHV).

It can be observed that, the voltage is linearly proportion to the logarithm of gas par-

tial pressure p_{H_2} and p_{O_2} . As p_{O_2} increases, the terms E_{oc} and $-V_{act}$ increase, which causes fuel cell voltage V_{fc} rises. Since the stack power $P_{stack,tot}$ is the product of V_{fc} and i_{fc} . For a fixed stack power, the fuel cell current i_{fc} reduces. The oxygen mass flow rate $\dot{m}_{O_2,inlet}$ and hydrogen consumption rate $\dot{m}_{H_2}$ thus decrease. Therefore, the stack efficiency $\eta_{FC,stack}$ increases along with the rise in oxygen partial pressure p_{O_2} . This phenomenon is also supported by other studies shown in Fig. 4.10.

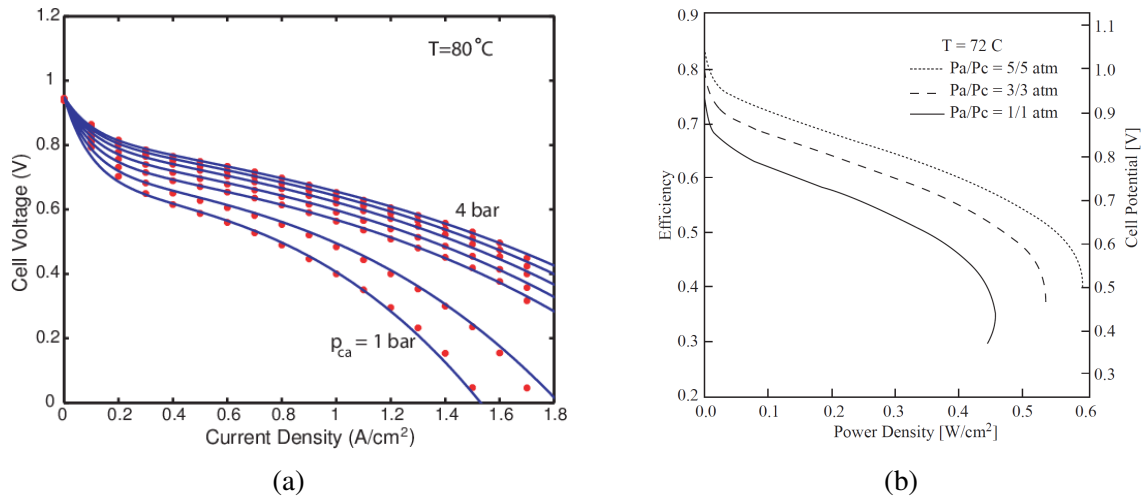


Figure 4.10: (a) FC Polarisation curve fitting results at cathode pressure of [1, 1.5, 2, 2.5, 3, 3.5, 4] bar adopted from [22], (b) Relationship between FC stack efficiency and power output for various reactant pressures from [24].

However, similar to air mass flow rate, further increase in p_{air} would consume more compressor power. Therefore, a system level trade-off study is required to determine the best operation and control strategies to handle these two control parameters for different mission phases and requirements. The detailed system simulation modelling and results will be introduced in the following section.

4.5.2 Off-design operation calculation and results discussion

In order to investigate the off-design operation of the PEMFC along different flight phases, six representative points are selected in the 300 nms mission. The selected phase points are: taxiing, take-off, climb, cruise, descent and landing. They are demonstrated in Fig. 4.11 along with the flight power profile.

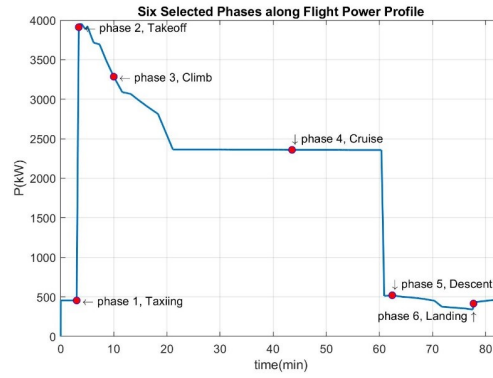


Figure 4.11: Six selected points for [taxiing, take-off, climb, cruise, descent and landing].

Because this study focuses on PEMFC system performance, the inverter and motor systems downstream of bus is omitted. Instead, the corresponding bus power value obtained in Section 4.4 is used to represent the power load for these chosen phases. A low fidelity converter model is adopted (5.8) to control the bus voltage and emulate converter power losses. Moreover, the altitude, ambient temperature and pressure, and flight Mach number for these phases are used in the fuel cell system.

Similar to on-design calculation (Fig. 4.5), the off-design operation calculation methodology is demonstrated in the following figure 4.12.

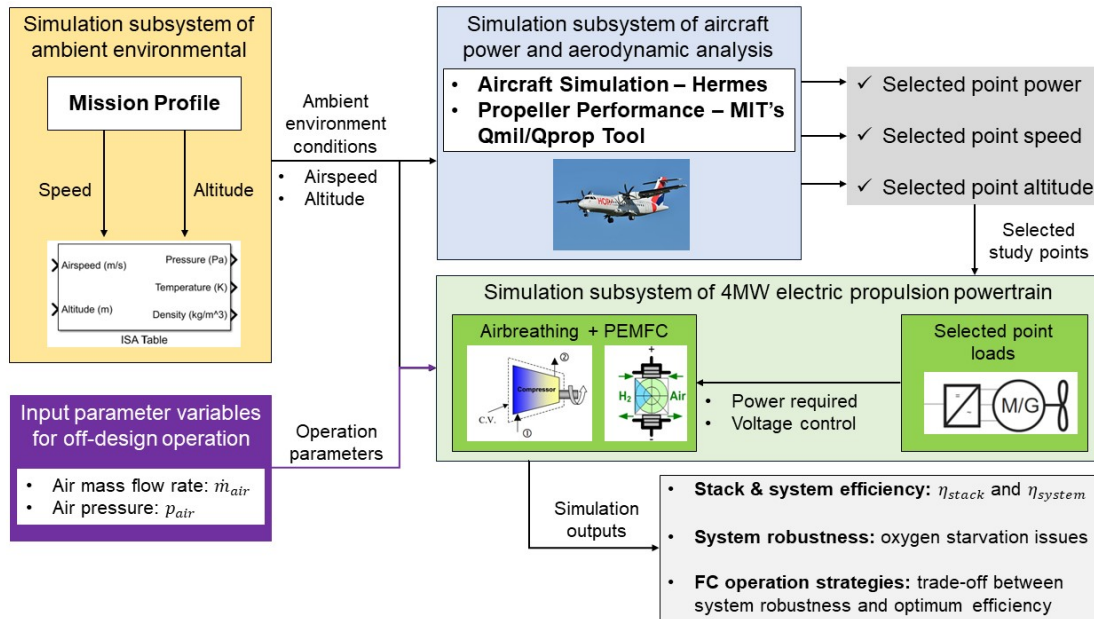


Figure 4.12: The integration flow chart for off-design case study.

There are two main differences between them. Firstly, the fuel cell is set to operate at different inlet $\dot{m}_{\text{air}}$ and p_{air} conditions. Arrays of $\dot{m}_{\text{air}}$ and p_{air} operation variables are input to the fuel cell system, coupled with the afore-mentioned input parameters, the fuel cell stack and system efficiencies are obtained and analysed. Secondly, the power, speed, and altitude are point parameters for six mission phases, instead of the time-variant parameters. This way, the sensitivity studies on operation variables $\dot{m}_{\text{air}}$ and p_{air} can be conducted.

The sensitivity study results of $\dot{m}_{\text{air}}$ variation only, and both $\dot{m}_{\text{air}}$ and p_{air} variations are demonstrated as follows:

Air mass flow rate $\dot{m}_{\text{air}}$ impact only

With fixed nominal air pressure p_{air} set as 2.06 bar, the air mass flow rate $\dot{m}_{\text{air}}$ is varied accordingly at different phases. Fig. 4.13 shows the variation of stack and system efficiencies of PEMFC ($\eta_{\text{FC,stack}}$ and $\eta_{\text{FC,system}}$) against $\dot{m}_{\text{air}}$ for each fuel cell stack. The assumption is that, identical off-design operations are applied to the fuel cell system, so that same variations of air mass flow $\Delta\dot{m}_{\text{air}}$ are applied to 16 stacks. The total air mass flow rate $\dot{m}_{\text{air, total}}$ is therefore 16 times the single one for this propulsion architecture.

It can be seen that for each phase, the stack efficiency $\eta_{\text{FC,stack}}$ is not sensitive to $\dot{m}_{\text{air}}$ variation but the system efficiency $\eta_{\text{FC,system}}$ decreases significantly as $\dot{m}_{\text{air}}$ increases. The huge $\dot{m}_{\text{air}}$ reduction occurs because compressor needs to consume necessary compression power for FC system to function. With higher air flow, more power needs to be used to deliver the air to fuel cell cathode channel. Moreover, the optimal $\eta_{\text{FC,stack}}$ is different from that of $\eta_{\text{FC,system}}$.

Another observation shows that there is a corresponding minimum $\dot{m}_{\text{air}}$ for each phase. The minimum $\dot{m}_{\text{air}}$ varies with phases. For example, the value is 0.02 kg/s and 0.09 kg/s at “Taxiing” and “Takeoff” respectively. These minimum $\dot{m}_{\text{air}}$ set the lower operation boundaries for each stack. Once lower than this value, the PEMFCs will malfunction, output zero power and the efficiencies ($\eta_{\text{FC,stack}}$ and $\eta_{\text{FC,system}}$) plunge to zero. This is

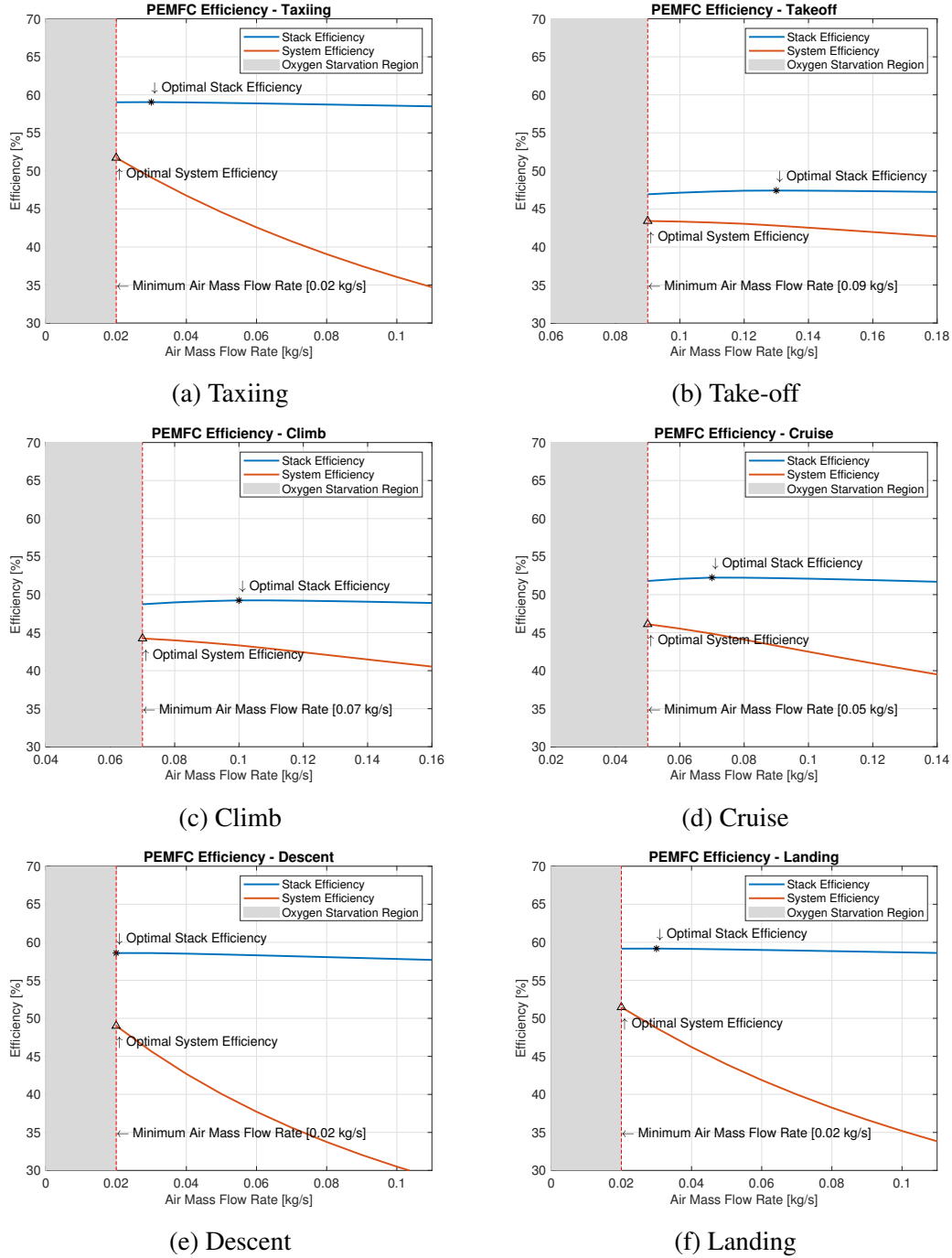


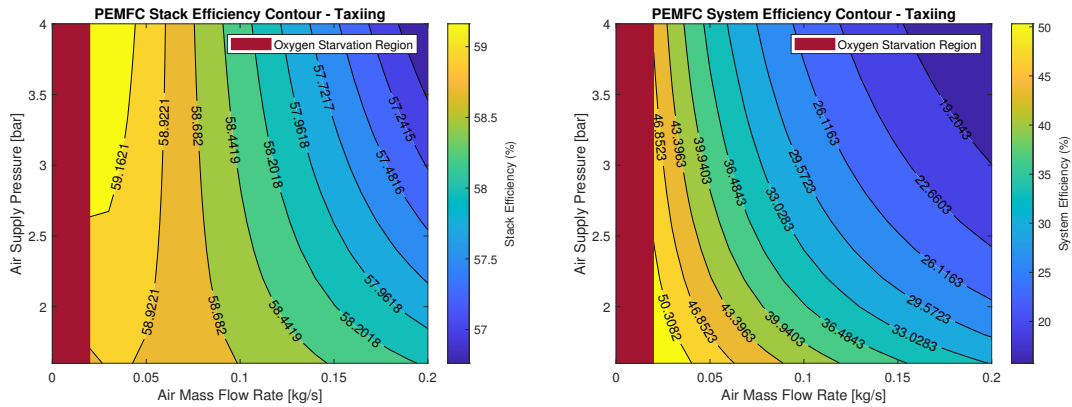
Figure 4.13: PEMFC $\eta_{FC,stack}$ and $\eta_{FC,system}$ against $\dot{m}_{air}$ for six selected flight phases [taxiing, take-off, climb, cruise, descent and landing], at p_{air} of 2.06 bar.

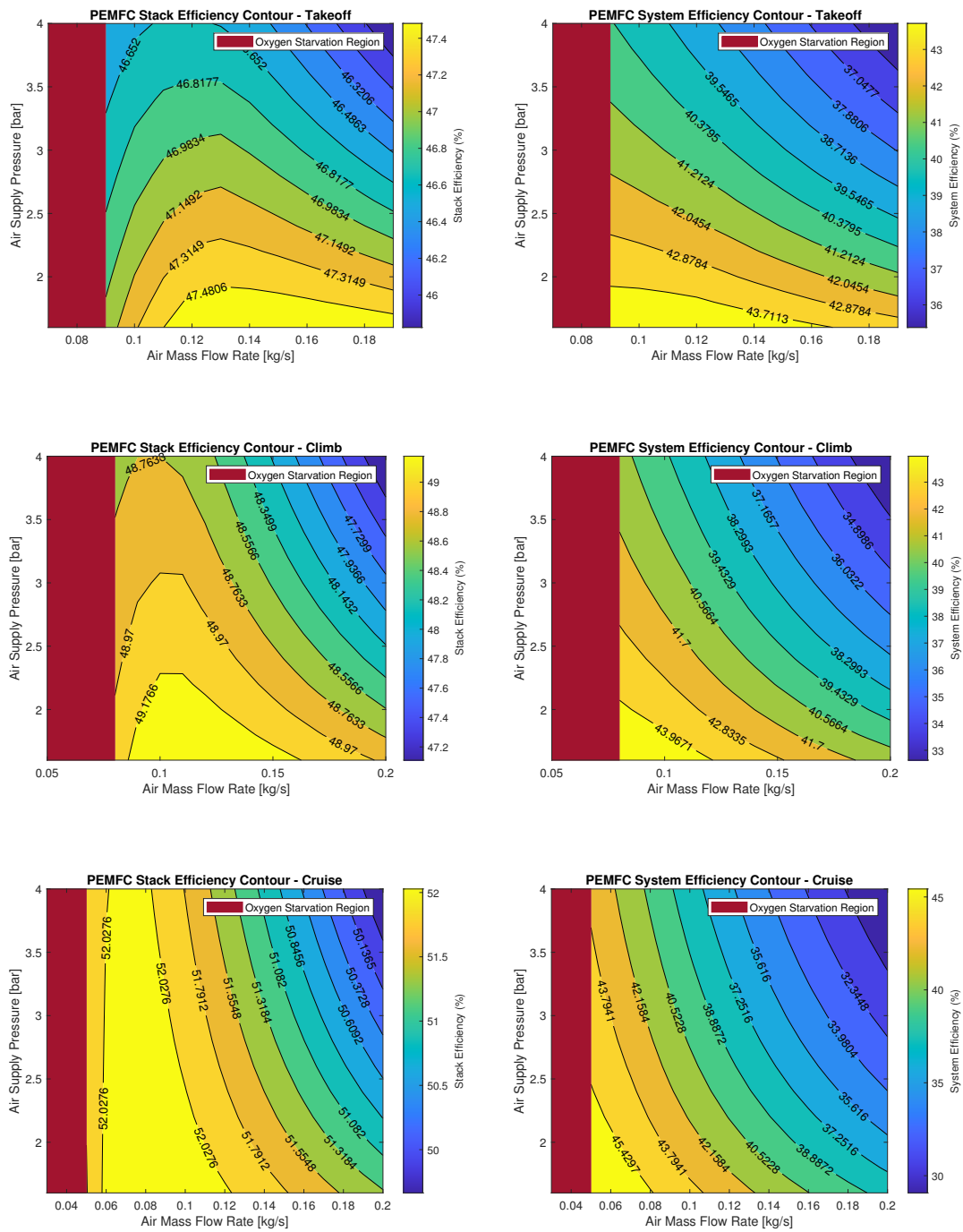
where “Oxygen Starvation” occurs. The dangers and risks of “Oxygen Starvation” are introduced previously. The fuel cell system is strictly required to avoid operating in this region. The value of $\dot{m}_{\text{air}}$ depends on power requirement, with greater “Takeoff” power, higher flow rate is required. This means that the air-breathing system needs to adjust its operation modes accordingly, by controlling pressure ratio and rotational speed.

Contradictorily, the optimal $\eta_{\text{FC,system}}$ always occurs at minimum allowable $\dot{m}_{\text{air}}$. Because at minimum air mass flow rate, lowest power is consumed at compressor so that the FC system is most efficient. However, it is dangerous because a slight perturbation of supplying $\dot{m}_{\text{air}}$ could cause “Oxygen Starvation”. Therefore, operating at optimal $\eta_{\text{FC,system}}$ is considered as “unstable equilibrium”. Other safer operation strategies would be proposed later, including p_{air} as a control parameter as well.

Both air mass flow rate $\dot{m}_{\text{air}}$ and air supply pressure p_{air} impacts

In this case, the fixed air pressure p_{air} condition is relaxed. Both $\dot{m}_{\text{air}}$ and p_{air} impacts are considered at the same time. Fig. 4.14 shows the stack and system efficiency contours in $\dot{m}_{\text{air}} - p_{\text{air}}$ plane for selected phases. Note, the left figures of Fig. 4.14 shows the stack efficiency and right one shows the system efficiency.





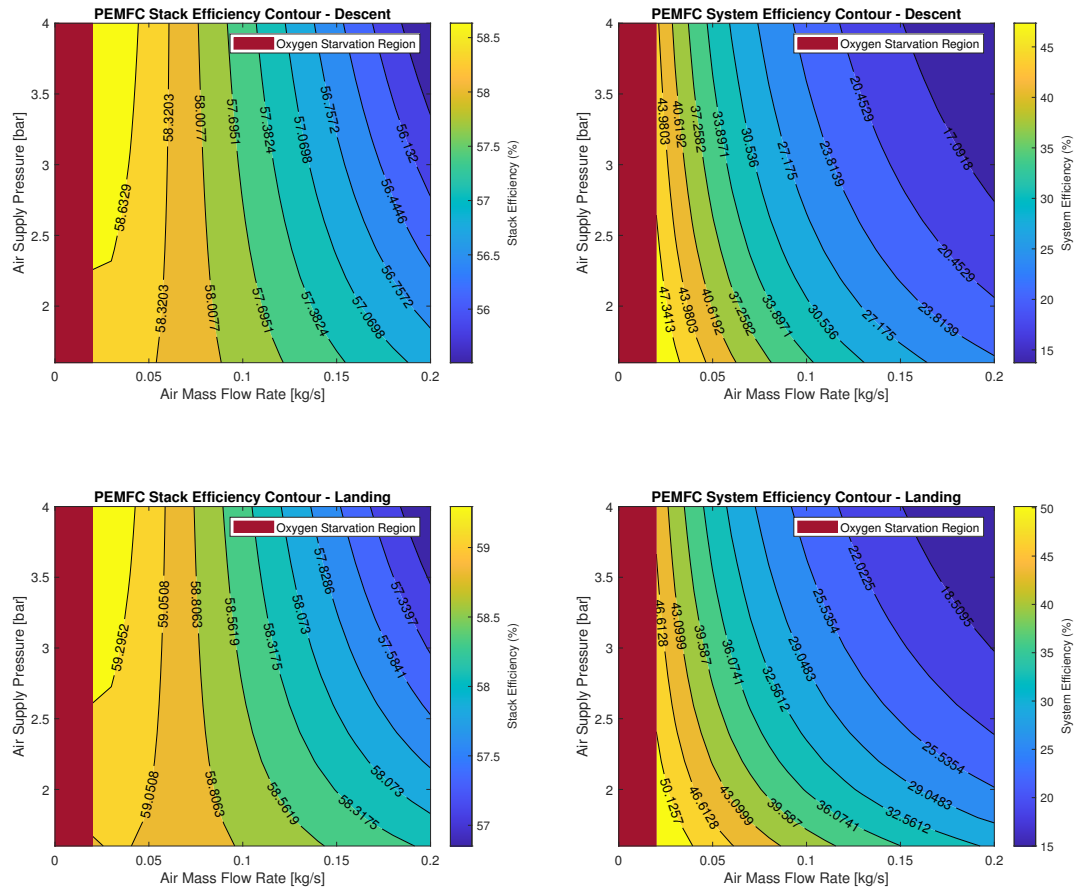


Figure 4.14: Stack efficiency, system efficiency contours and oxygen starvation regions for different flight phases [taxiing, take-off, climb, cruise, descent and landing].

According to the results, FC efficiency can be controlled by inlet air pressure p_{air} . As shown in Fig. 4.14, the yellow region represents higher efficiency while blue region means lower efficiency. All system efficiency contours exhibit higher system efficiency at lower p_{air} . Although some stack efficiencies $\eta_{\text{FC,stack}}$ are improved with higher air pressure, the extra compression power would compensate this improvement. Therefore, it is desirable to reduce the inlet pressure for better system performance.

4.5.3 Data-based air mass flow rate and supply air pressure control strategies

Based on the simulation results, data based strategies scheme of air mass flow rate $\dot{m}_{\text{air}}$ and supply air pressure p_{air} can be formulated, for the purpose of avoiding “Oxygen Starvation” and improving system efficiency.

Three control strategies are proposed and their FC system efficiency performance are shown in Fig. 4.15 by black, blue and red asterisk lines. The numbers in both figures indicate different flight phases, from ‘1’ to ‘6’: taxiing, take-off, climb, cruise, descent, and landing. Moreover, @bar indicates the value of p_{air} , for example: 1@1.6 bar means at taxiing phase, high efficiency occurs when air supply pressure p_{air} is 1.6 bar.

For Fig. 4.15a, only air mass flow rate $\dot{m}_{\text{air}}$ is handled, and p_{air} is fixed at 2.06 bar. The black line indicates the radical “Maximum efficiency but unstable” strategy, where FC performs most efficiently at each phase but the system is on the brink of “Oxygen Starvation”. The blue line represents a more conservative “Lower efficiency but stable” strategy, where $\dot{m}_{\text{air}}$ is doubled as the radical cases for each flight phase. Twice air mass flow rate can ensure that the system perform much reliably in this strategy, as the doubled $\dot{m}_{\text{air}}$ can drive the system away from “Oxygen Starvation” regions for each phase. For Fig. 4.15b both air mass flow rate $\dot{m}_{\text{air}}$ and supply air pressure p_{air} are controlled, with red line showing an improved strategy “High efficiency and stable”.

From Fig. 4.15a, it can be seen that FC efficiency performance is highest when adopting black radical strategy, but a slight reduction in $\dot{m}_{\text{air}}$ can result in system instability and oxygen starvation. With double air mass flow rate, the danger of system malfunction can be eliminated but at the expense of efficiency loss. For example, a maximum 12.9% efficiency reduction can be seen in “descent” phase, and a 7.8% reduction in long duration “cruise” phase. The efficiency reduction directly results in higher fuel consumption. With controlled air supply pressure p_{air} , a new strategy is proposed as red line. The FC efficiency performance can be improved as shown in Fig. 4.15b. All phases can benefit from this control strategy. For instance, 6.6% and 4.0% efficiency improvements are achieved

at “descent” and “cruise” phases. Although this strategy is not as efficient as the “Maximum efficiency but unstable” one, it provides more stable and reliable operation modes for the propulsion system. Another observation is that, although FC stack performance can be improved by higher p_{air} , the benefits are compensated by air compressor power consumption. This feature is prominent for aircraft applications. High air compression power is required as the ambient pressure is generally low. Therefore, it is recommended to operate FC system efficiency with lower air supply pressure (i.e. 1.6 bar).

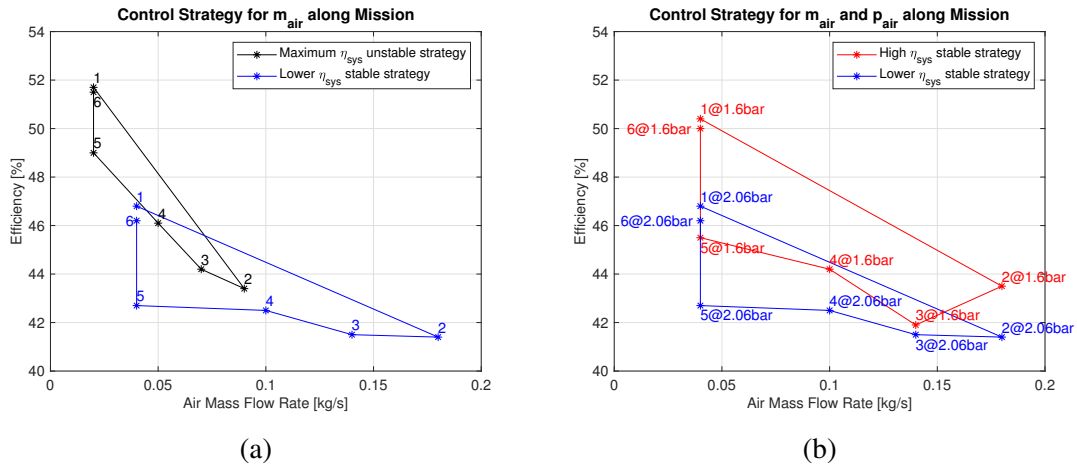


Figure 4.15: (a) Two control strategies for m_{air} only with p_{air} fixed at 2.06 bar. (b) Two control strategies for both m_{air} and p_{air} .

In this section the impacts of m_{air} and p_{air} on FC system performance are investigated. The potential danger of “Oxygen Starvation” is demonstrated. Based on the system performance analysis, three control strategies over m_{air} and p_{air} are proposed for six selected phase points along the mission. A data-based control strategy is recommended to balance system reliability and efficiency. In the next section, the stack imbalance performance, the multi-stack configuration design and their impacts on system performance are investigated.

4.6 Fuel cell stack degradation and its effect on stack configuration design

Currently, most commercial PEMFC stacks have limited maximum power. As previously stated, the Ballard FCvelocity®-HD6 FC stack is used, with 150 kW and 165 kW as nominal and maximum power. To achieve higher power, voltage and current as well as redundancies for aircraft propulsion, 16 stacks are connected in series and parallel to form “half side” of power-train. The wiring configuration of individual fuel cell stack can affect the propulsion system performance which needs to be captured.

In this section, “Parallel-series” and “Series-parallel” are used and their schematic diagrams are shown previously in Fig.4.7. The performance of these two configurations are identical if all fuel cell stacks are operating at their nominal conditions. However, long-term degradation, changes in fuel cell’s individual auxiliary parts, or faults in component connections can lead to difference of the voltage and current performance ($V-I$ polarisation curve deviates from intact condition) for each individual stack. These stack variations can cause imbalance performance among fuel cell array. The imbalance performance impacts due to voltage and current drop are explored for two selected configurations. This section focuses on fuel cell stack performance and the rests of the system are identical for these two configurations. Therefore, the lower fidelity level models for the rest of electrical components (converter, inverter, and PMSM) are utilised.

4.6.1 Stack degradation analysis and simulation

To simulate the degradation performance in one stack, the voltage and current of cell are set by 10% decrease in comparison to a normal intact stack. The polarisation curves of a healthy and degraded stack are shown in Fig.4.16, based on “Voltage-Current” and “Power-Current” curves. It can be seen that, for degraded stack, the overall $V-I$ and $P-I$ curves are shrunk compared to healthy ones. The operation power, voltage for each current is lowered. The boundary of available current is also decreased. This is similar to

the degraded FC polarisation curves presented in different literatures [164, 165].

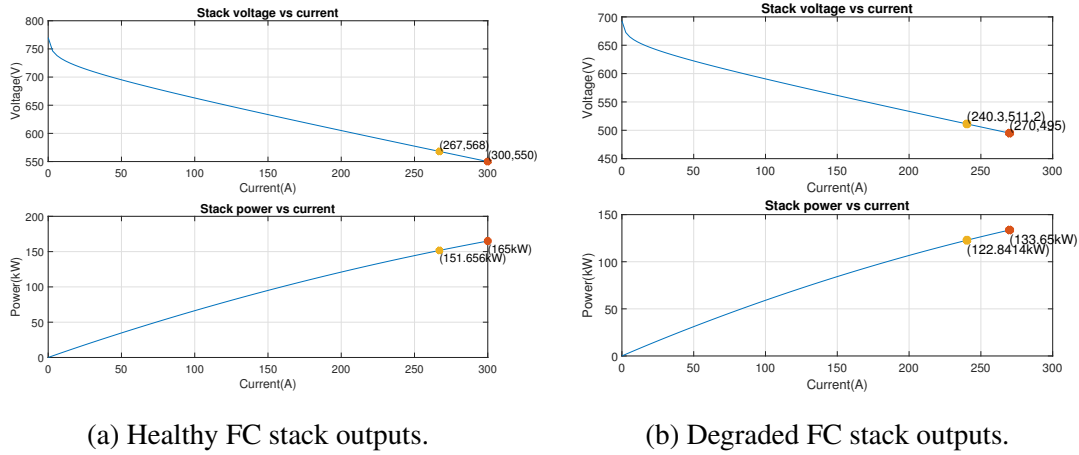


Figure 4.16: Simulated Voltage-Current and Power-Current polarisation curves for healthy and degraded FC stack.

4.6.2 Fuel cell system imbalance performance due to stack degradation

In Fig. 4.17, the 10% voltage and current degradation condition is applied to one of the stacks in the “Parallel-series” and “Series-parallel” configuration. Due to the electric circuit characteristics, the voltage level for stacks in parallel must be identical, while the current level for stacks in series should be the same. The fuel cell stacks are designed to be a voltage source, therefore, the voltage of each stack can be increased before it reaches its maximum value to adapt to voltage variations due to stack imbalance performance. In “Parallel-series” case, in order to compensate for voltage reduction in degraded FC, the rest FCs in the same parallel branch would reduce their voltages correspondingly. The reduction in voltage corresponds to increase in current and power output according to fuel cell characteristics curve, therefore, these FCs are denoted as “overworked”. Similar principles apply to “Series-parallel” configuration, but this time the current level is maintained. Due to degradation in electric current, the rest FCs in the serial branch undergo “underworked” conditions (lower output power) according to polarization curves, and the rest of the FC array would “overwork” to compensate the power reduction.

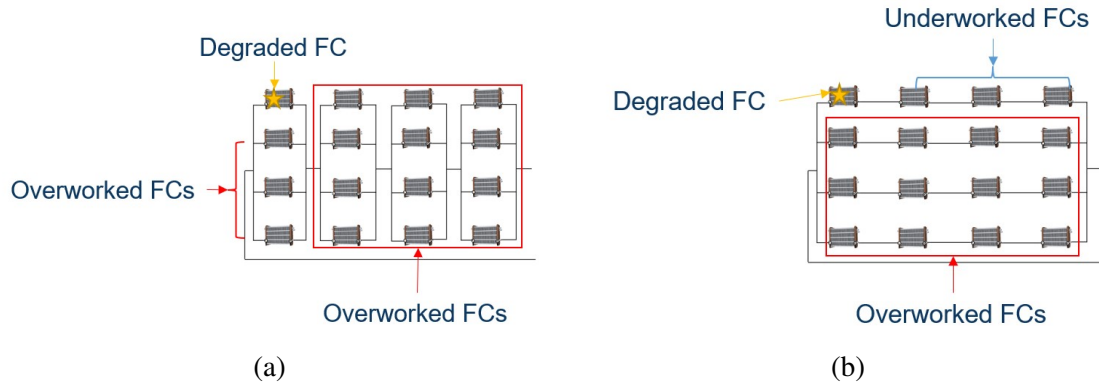


Figure 4.17: (a) Parallel-Series case (b) Series-Parallel case, with normal, degraded, overworked and underworked FC stacks.

The imbalance performance characteristics can be demonstrated and investigated via individual stack power, efficiency, voltage and current assessment:

Individual stack output power and efficiency

In Fig.4.18, individual stack power along mission for two proposed configurations are shown. Note that, normal FC refers to a healthy stack that is not in the same branch as the degraded FC stack. Normal FC connected to the degraded FC stack refers to the normal stack that is connected in series or parallel to the degraded stack. One degraded FC refers to the preset degraded stack. FC for on-design operation refers to the normal FC operating on-design condition in Section 4.4.

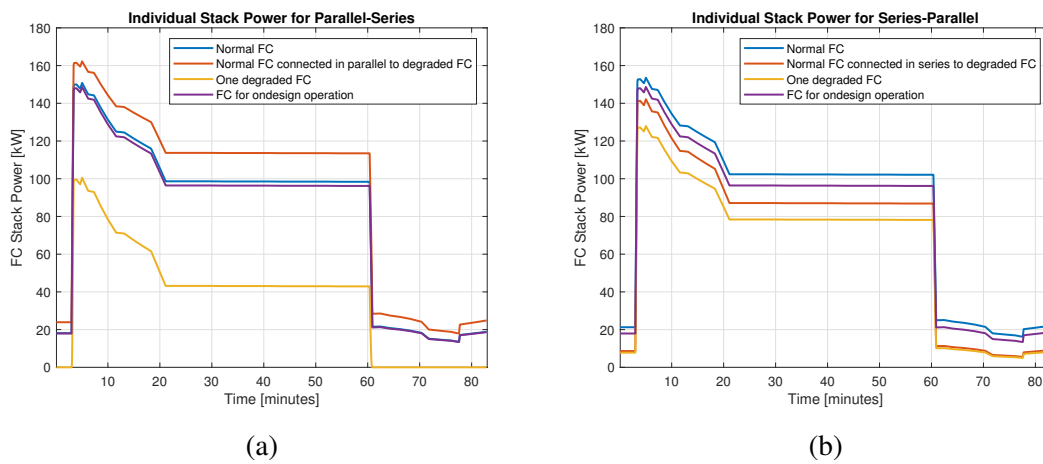


Figure 4.18: Individual FC stack power output along mission for (a) Parallel-Series configuration and (b) Series-Parallel configuration.

The purple line is the baseline on-design stack power calculated from Section 4.4. The power output for each FC stack matches the working state demonstrated in Fig. 4.17, with “overworked” FCs outputting higher power and “underworked” ones providing lower power in comparison to on-design case. It can also be noted that in “Parallel-series” configuration, the degraded fuel cell stack provides “0 power” for some flight durations. These periods correspond to low power requirements flight phases, which are “Taxiing-out”, “Descent”, “Approach & Landing”, and “Taxiing-in”.

Similar to power variation, the stack efficiencies for these two proposed cases are shown in Fig. 4.19. “Zero efficiency” occurs for the degraded FC in “Parallel-Series” configuration at low power phases. While in “Series-Parallel” all FCs can function and provide power throughout the mission.

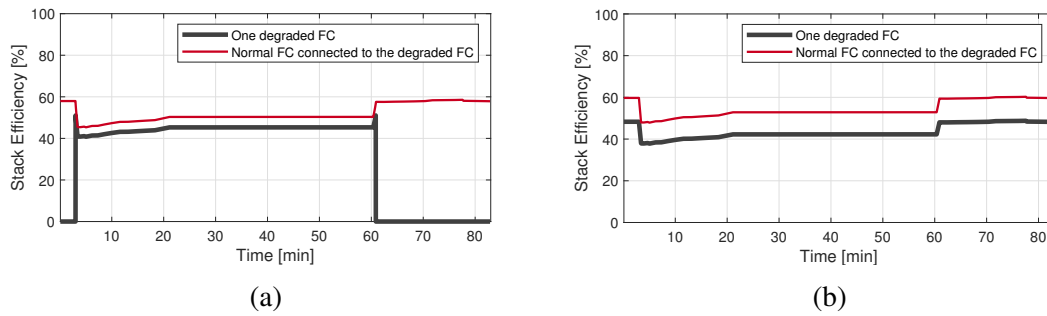


Figure 4.19: Individual FC stack efficiency along mission for (a) Parallel-Series configuration and (b) Series-Parallel configuration.

The reason for this phenomenon and its potential impact on the system will be explained in the following stack voltage and current assessment subsection .

Stack voltage and current assessment

To explain why the one degraded FC outputs zero power, it should note that: a FC has higher output voltage for lower power. This is shown in Fig. 4.16. However, due to degradation, the maximum voltage of degraded FC stack is lower than the high voltage required at low power, which causes it malfunction during these periods. This phenomenon is captured in Fig. 4.20a. For Parallel-Series configuration, it can be found that the degraded

FC has lower voltage than others in the same parallel branch during low power phases.

Consequently, there is voltage difference between FC stacks and current would be drawn between FC stacks. This could potentially damage the power system and needs to be avoided. On the other hand, for “Series-parallel” configuration, the malfunction scenario is not seen as there is no voltage matching requirement. Therefore, the potentially damage due to voltage imbalance between stacks does not exist in this configuration.

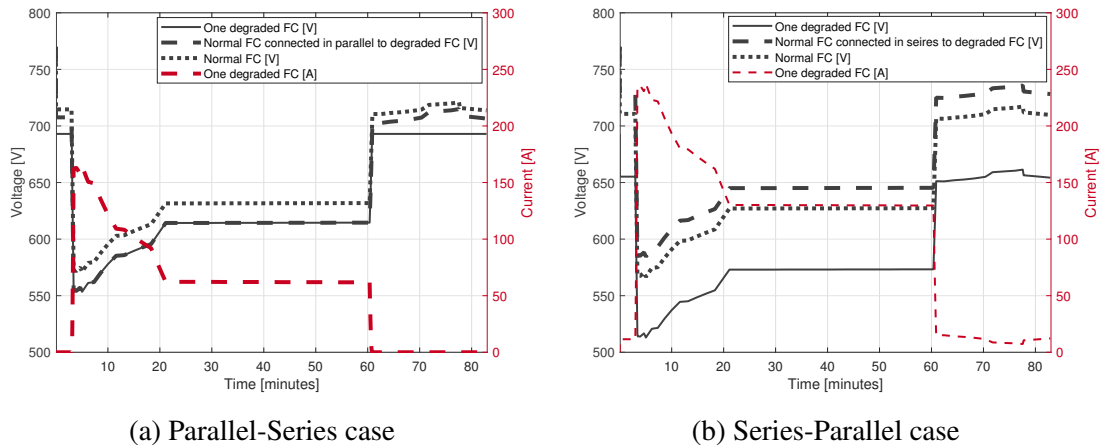


Figure 4.20: Individual FC stack voltage and current outputs along mission for (a) Parallel-Series configuration and (b) Series-Parallel configuration.

In this section, the voltage and current drop due to stack degradation and the impact on FC system is explored. Upon setting one FC degraded in two proposed configurations, it is found that the arrangements of FC stacks connections could help in reducing the impact of voltage and current variations due to degradation in each stacks. A potential malfunction scenario is identified for the degraded FC in “Parallel-Series” configuration. This malfunction and voltage mismatching within parallel branch can cause current flowing between stacks, which will potential damage the stacks. On the other hand, this potential risk can be eliminated by choosing “Series-Parallel” configuration. Therefore, the “Series-parallel” configuration is recommended, as it is less affected by one FC stack degradation.

4.7 The impact of multi-stack fuel cell configuration on the propulsion system

Apart from the two configurations discussed previously, there are more potential fuel cell configurations to be investigated. There is a need to assess their suitability to the special requirements of aviation application, including but not limited to: high altitude application, system weight sensitivity, system reliability and robustness, power loss mitigation measures and high system performance efficiencies.

In this section, nine fuel cell configurations and their DC/DC converter arrangements are proposed. Their advantages and disadvantages for the regional aircraft propulsion system are investigated by assessing fuel cell stack and system efficiencies, electrical component efficiencies, system performance and system weight. Moreover, the system reliability and robustness are analysed qualitatively.

High fidelity level models are used for converter, inverter and PMSM in this study to cover all necessary parameters for system sizing, converter topology, and system level efficiency comparison between these configurations.

4.7.1 Proposed fuel cell system and DC/DC converter configuration

Fig. 4.21 shows the proposed fuel cell stack configurations and different DC/DC converters arrangements. The qualitative analysis of their characteristics, advantages and disadvantages, potential risks and mitigation measures are discussed in Table 4.4.

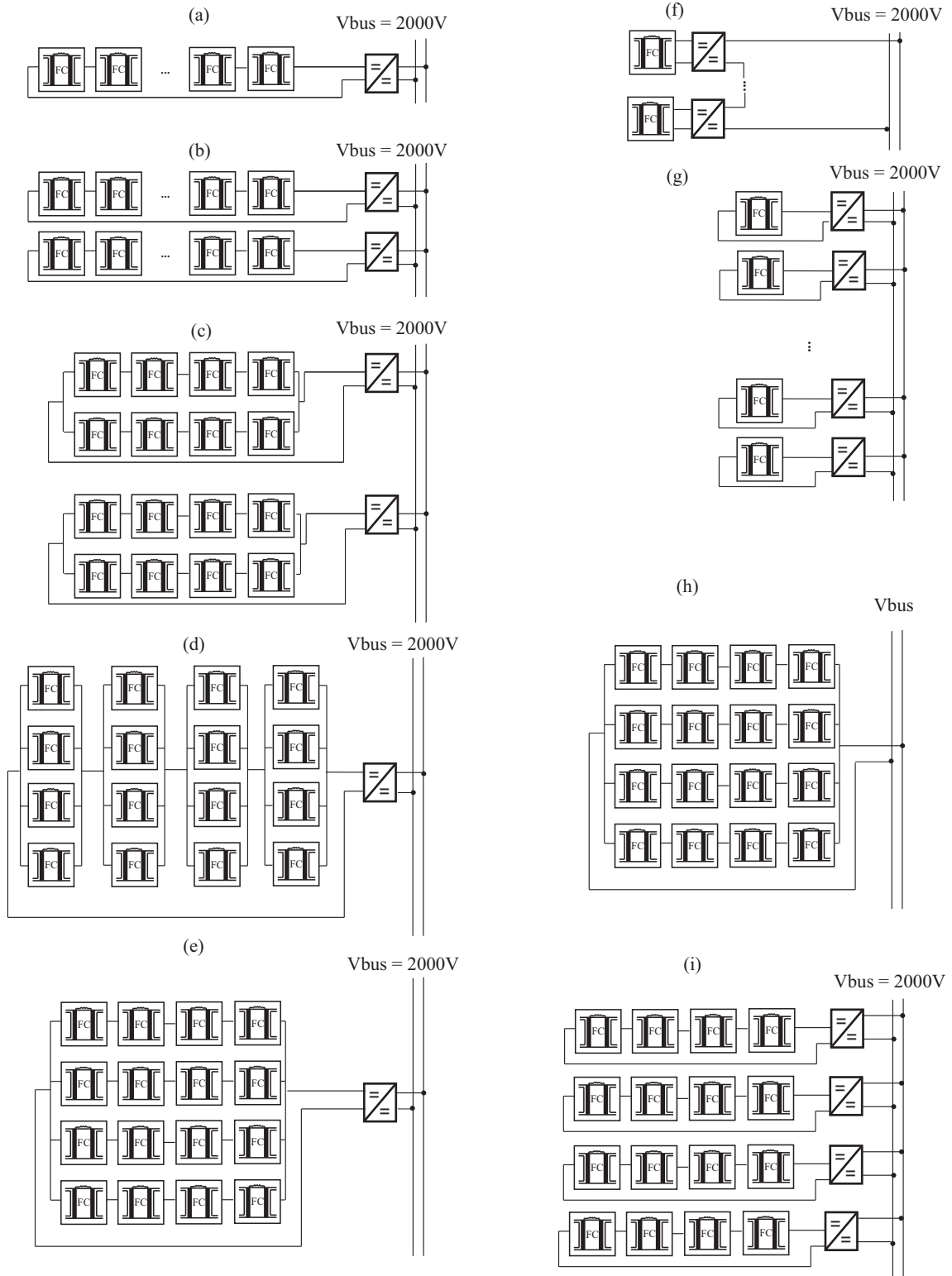


Figure 4.21: Proposed electrical configurations for the FC stacks and DC/DC converters.

Configs	Description	Comparisons
(a - a)	Highest voltage achieved by adding 16 stacks in series. High voltage conversion to V_{bus} .	Independent control of stack voltage is no longer achieved by one DC/DC converter. This system has lowest reliability if some of the FCs degrade or in the case of faults. This configuration at high voltage (>3000 V [166]) is not recommended due to lack of protections and insulation designed for partial discharges at high altitude (at 40 kft above sea level) that can be used without high weight penalties.
(b - b)	8 stacks can be connected in series.	Efficiency optimization with only few power electronics converters. This configuration at high voltage (>3000 V [166]) is not recommended due to partial discharges at high altitude. However, if the design of cable insulation changes to provide higher power density, higher voltages can be recommended. This configuration is also more vulnerable to faults at high altitude, so it is not recommended because limiting the altitude capability of the aircraft will result in cruising at lower altitudes where the drag is higher and the fuel consumption will be higher.
(c - c)	8 stacks can be connected in series and 2 branches of them in parallel.	Efficiency optimization with only few power electronics converters. This configuration allows higher efficiency for the DC/DC converter due to smaller converter gain.

Configs	Description	Comparisons
(d - d)	4 stacks connected in parallel and then in series.	This configuration provide higher current and has 1 converter for voltage control which can be a single failure point if the converter fails and half of the total power from the FCs is lost. This configuration is more reliable than configuration (e) when one FC degrades [39]
(e - e)	4 stacks connected in series and then in parallel.	Converter for this configurations could be designed but also the rest of the system could be designed without a converter like case (h).
(f - f)	16 stacks with individual DC/DC converters connected in series then to the bus	For this configuration, all converter currents must be identical due to series connection, so that the currents cannot be decoupled. Consequently, the voltage cannot be controlled. Therefore this configuration is not recommended.
(g - g)	16 stacks with individual DC/DC converters with controllers are connected to the bus	Several degrees of freedom for energy management, control of power drop as as result of degradation with individual converters, and faulty mode operation are possible. Voltage conversion rate is the highest if $V_{bus} > V_{st}$, efficiency of the converter and its power density is the lowest. Configuration (g-g) is heavier so the maximum payload will be reduced and the energy consumption will be higher when performing the same mission, but it offers better operability in degraded and faulty mode. Degradation tolerance of this configuration may prolong time-on-wing.

Configs	Description	Comparisons
(h - h)	4 stacks connected in series and then in parallel.	This configuration provide lower current to the bus than case (g) and does not have a converter for voltage control. The electric machine and the inverter have to be designed to support the voltage range and consequently the power requirement during each phase of the mission.
(i - i)	4 stacks connected in series.	This configuration is the most reliable system with higher efficiency for the converter in comparison to case (d) and (e) due to reduction in current. But four converters add higher weight compare to case (h), but instead provide constant voltage for the bus.
(g - i)	Two different configurations for each buses.	Since two buses are connected for power sharing in the case of failure a mixture of more efficient or highly reliable but heavier configurations can be joint together. For example configuration (g) is the most reliable but the heaviest and configuration (i) is the most efficient

Table 4.4: Assessment of electrical configurations for the FC stacks and DC/DC converters. Where configurations are connected, for example a-a, means the two 2000 V bus are connected with a bus ties for power sharing.

4.7.2 DC/DC converter sizing

The capacitor and inductor within the buck converter play significant roles in smoothing the voltage/current from square on/off waveform. They are also key components to store and release electric energy for boost converters. For different configurations proposed, the voltage and current across the converter (also the capacitor and inductor inside) are varying. Therefore, the sizing of inductors and capacitors of converters must be deter-

mined individually to satisfy safe operation under various voltage and current. In this study, the off-shelf high power inductor [148] and capacitor [147] are selected for the converter design. Also, the high power IGBTs components [16] are selected based on off-shelf product.

The schematic diagrams of buck and boost converter are shown in Fig. 4.22. The inductor and capacitor numbers are determined by the maximum voltage and current across them, as well as the component peak allowable voltage and current. The sizing equations utilised are shown in Chapter 3 Section 3.6.5. Table 4.5 shows the different topologies of DC/DC converter for different FC stack configurations.

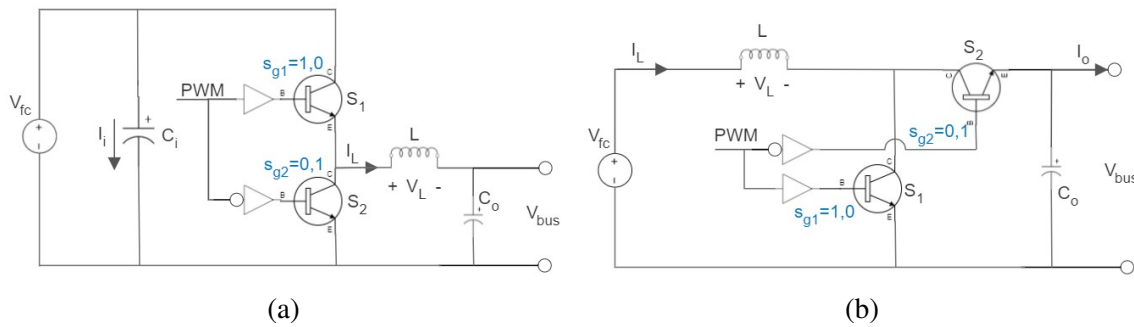


Figure 4.22: Schematic diagrams of (a) buck converter and (b) boost converter.

Configurations	Max. Voltage [V]	Max. Current [A]	Component Topology
<i>Config (a)</i>			
Capacitor C_i	12320	300	7R3C
Capacitor C_o	2000	1400	2R11C
Inductor L	10320	1400	7R18C
<i>Config (b)</i>			
Capacitor C_i	6160	300	4R3C
Capacitor C_o	2000	700	2R6C
Inductor L	4160	700	4R7C

Configurations	Max. Voltage [V]	Max. Current [A]	Component Topology
<u>Config (c)</u>			
Capacitor C_i	3080	600	2R5C
Capacitor C_o	2000	700	2R6C
Inductor L	2000	700	4R4C
<u>Config (d)</u>			
Capacitor C_i	3080	1200	2R9C
Capacitor C_o	2000	1400	2R11C
Inductor L	2000	1400	7R4C
<u>Config (e)</u>			
Capacitor C_i	3080	1200	2R9C
Capacitor C_o	2000	1400	2R11C
Inductor L	2000	1400	7R4C
<u>Config (f)</u>			
This is ruled out	-	-	-
<u>Config (g)</u>			
Capacitor C_o	2000	300	2R3C
Inductor L	1230	300	2R3C
<u>Config (h)</u>			
No converter	-	-	-
<u>Config (i)</u>			
Capacitor C_i	3080	300	2R3C
Capacitor C_o	2000	350	2R3C
Inductor L	2000	300	2R4C

Table 4.5: Maximum voltage and current across the capacitors and inductors within DC/DC converter, and their sizing topologies of different converters for the FC multi-stack configurations listed in Fig. 4.21.

Note, the component topology in Table 4.5 means the number of rows and columns for indicated components shown in Fig. 4.22. For example: in configuration (c), buck converter has 2R5C-capacitors C_i and 4R4C-inductors L . Their respective topologies are shown in following Fig. 4.23.

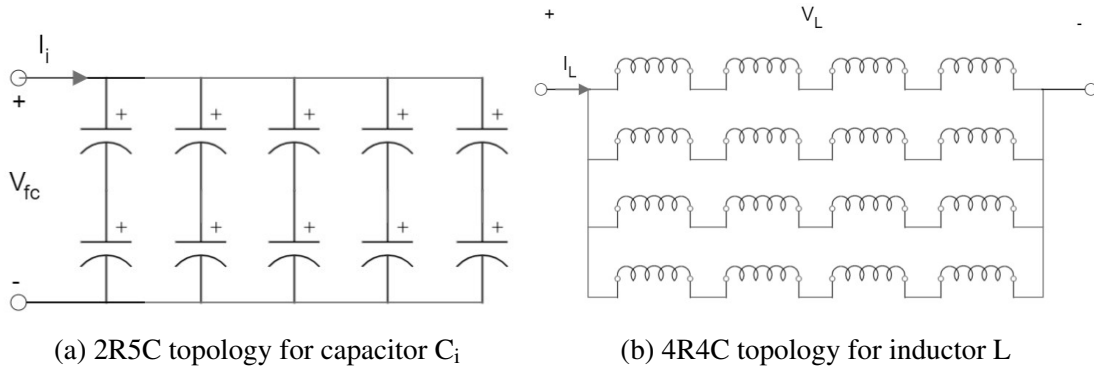


Figure 4.23: Schematic diagrams of exemplary capacitor and inductor topologies for FC configuration (c).

The converter sizing results are demonstrated for proposed configurations. With different capacitive, inductive and FC multi-stack configurations, the system performance are different. In the next section, the simulation framework will be set up individually to simulate the system performance of these configurations. With converter All sizing results from Table 4.5 and configurations setting from Fig. 4.21 are used.

4.7.3 Converter efficiency contours

By utilising the methods detailed in Chapter 3 Section 3.6.2, the converter efficiency maps of candidate configurations are shown in Fig. 4.24. With output power P_o and converter input voltage V_i as the $x-y$ plane, and a fixed output converter voltage $V_o = 2000V$. Note that configuration (f) is not considered due to its infeasibility, as analysed in Table 4.4. And there is no converter maps for configuration (h) as there is no converter equipped.

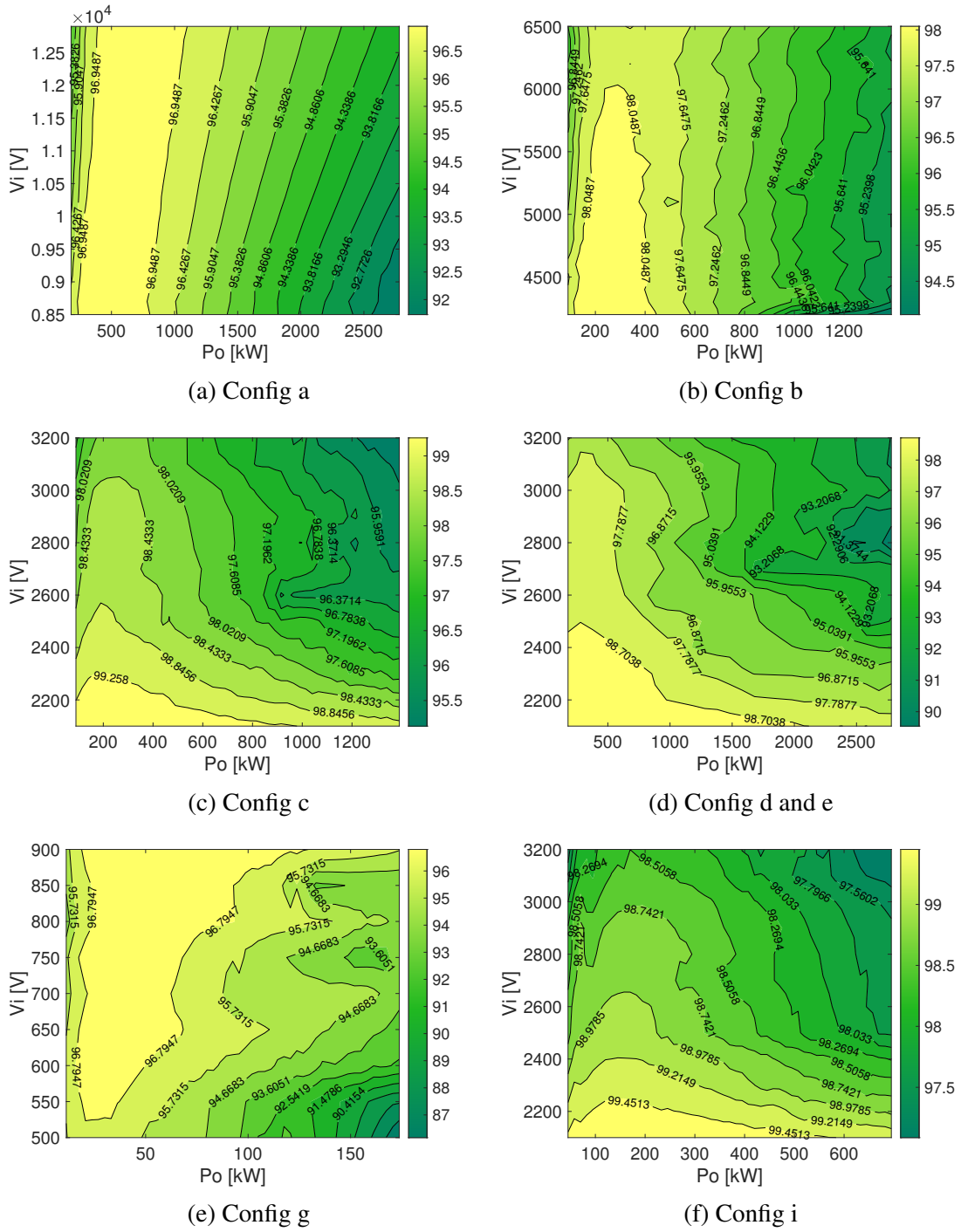


Figure 4.24: Converter efficiency contours over ' $P_o - V_i$ ' plane for configuration (a), (b), (c), (d), (e), (g), and (i).

It can be seen that each designed converter exhibits high efficiencies, normally above 90%. The converters exhibit low efficiency at high output power P_o range. The efficiencies also tend to reduce as the difference between input and output voltage increases.

Firstly, for configuration (g) efficiency is generally lower than others. This is because boost converters are used in this case. The boost converters generally exhibit lower efficiency than their bucking counterparts. The fundamental reason is that the inductor current flows directly to ground during the on-time, instead of to the loads.

For configurations (a), (d) and (e), only one buck converter is equipped to step down the input fuel cell voltage. Their efficiencies over ' $P_o - V_i$ ' plane are relatively low because the single converter needs to operate at either extremely high voltage at 12320 V (the highest system voltage for case a) or both high voltage and current (3080 V and 1200 A) conditions for case d and e. Notice that, the converter maps of d and e are identical due to FC configuration symmetry.

For configuration (b) and (c), two buck converters are equipped. The efficiencies are improved as voltage and current across the converter are lowered down. Especially the lower current level, which significantly reduces the ohmic losses over the components inside.

Finally for configuration (i), four buck converters are used. This significantly reduces the voltage and current across them. The efficiency contours over ' $P_o - V_i$ ' plane are generally higher than others. Therefore, using more medium-sized converters can improve their efficiencies than applying single full-sized one.

A 2-D lookup table is used in Matlab/Simulink environment to extrapolate the converter efficiency against input voltage and output power for mission performance analysis.

4.7.4 Proposed inverter model and its efficiency contours

High fidelity H-bridge DC/AC inverter model is chosen and its modelling method is detailed in Chapter 3 Section 3.8.3. The inverter efficiency maps for the variation of motor torque and rotational speed are shown in Fig. 4.25.

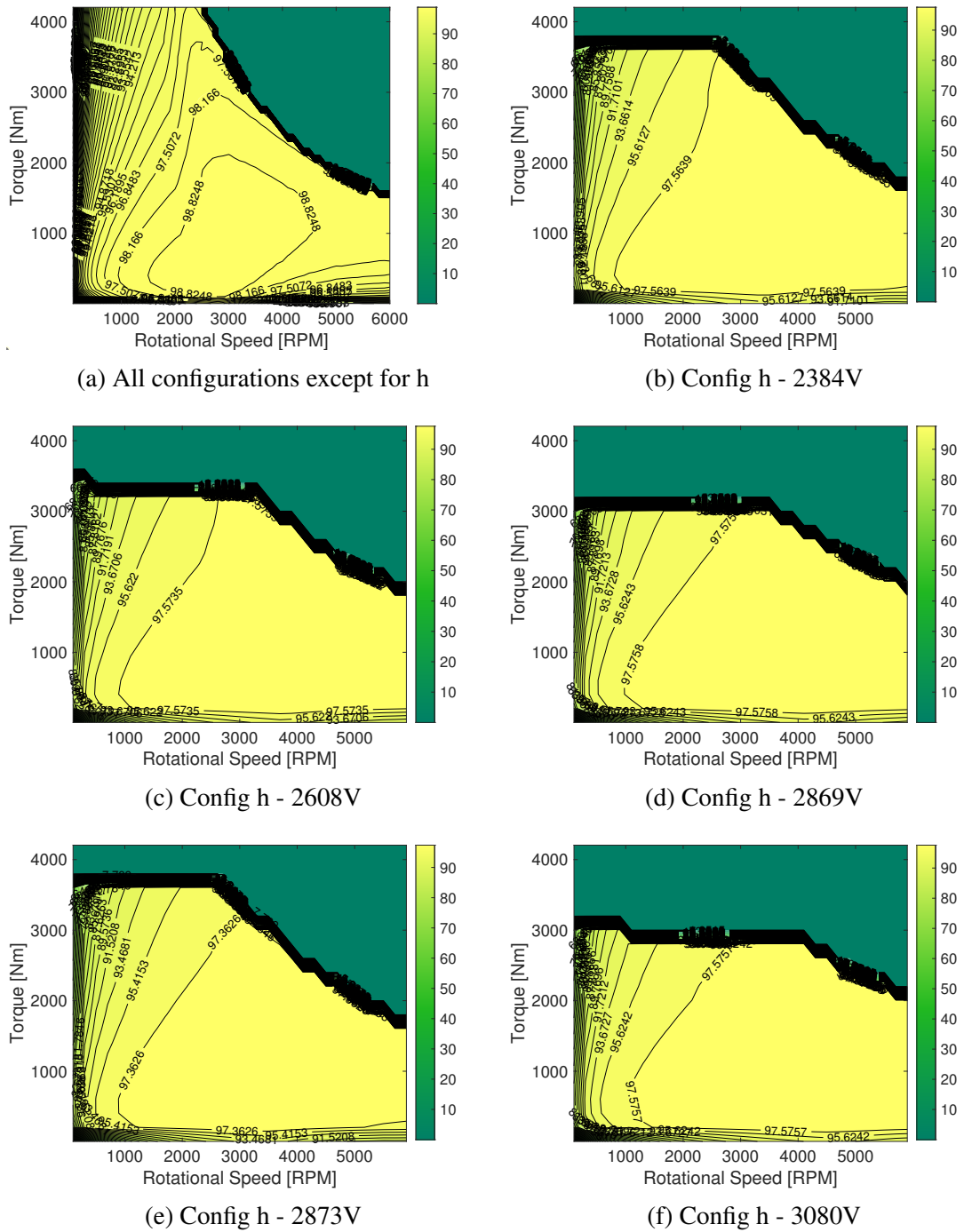


Figure 4.25: Inverter efficiency maps for all configurations with fixed DC bus voltages at 2000V, and configuration h with five bus voltages: 2384V, 2608V, 2869V, 2873V, and 3080V.

The input/output conditions of inverters are the same for all configurations apart from (h), for which the input voltage varies. Therefore, only one efficiency map (Fig. 4.25a) is enough to summarise all configurations besides (h). For (h) five input DC voltage levels

(2384V, 2608V, 2869V, 2873V, and 3080V) are selected and their respective efficiency maps are shown in Fig. 4.25b to Fig. 4.25f.

A 2-D lookup table is used against motor torque and rotational speed for all configurations with 2000V_{dc} bus voltage, whereas a 3-D one is applied for configuration h, with input voltage as the third reference element. Their values is integrated in the system model for mission performance analysis.

4.7.5 High-fidelity PMSM and its efficiency contours

Interior Permanent Magnet Synchronous Motor (PMSM) is designed in ANSYS Motor-CAD with parameters provided in Table 4.6 and the efficiency maps are shown in Fig. 4.26.

Table 4.6: Electric machine design parameters.

Parameters	Values
Rotor diameter	317.5 [mm]
Stator diameter	450 [mm]
Number of poles	16
Airgap	1.25 [mm]
Stack length	370 [mm]
Number of slots	48

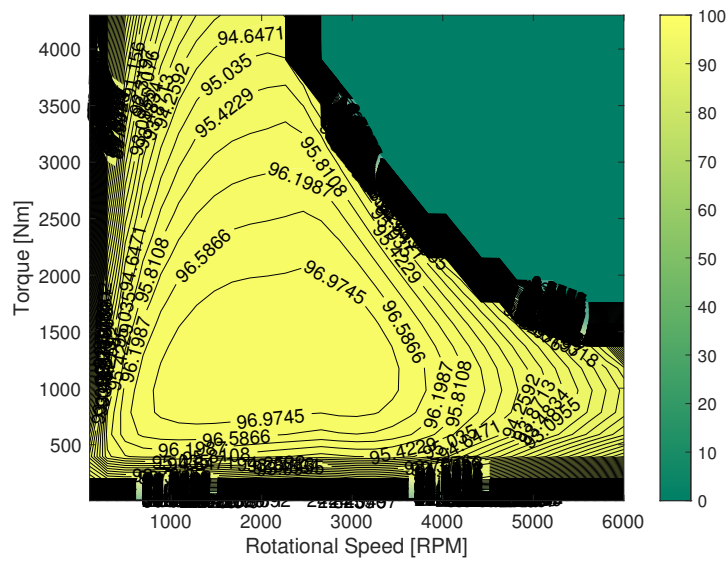


Figure 4.26: Electric motor efficiency map. This is for the case where bus voltage was constant at 2000 V.

Similarly, a 2-D lookup table is used to interpolate the efficiency against motor torque and rotational speed for mission analysis.

4.7.6 Comparison between different configurations

Using the IGBTs [16] and LC components [148] [147] data, and topology from Table 4.5, the weights of these configurations are calculated. The converter weights of all configurations are normalised against that of (g) (Fig. 4.27a), and their respective weights are shown in the caption. Note that (h) has zero value since the converter is not equipped. The overall propulsion system efficiencies for each case are shown in Fig. 4.27b.

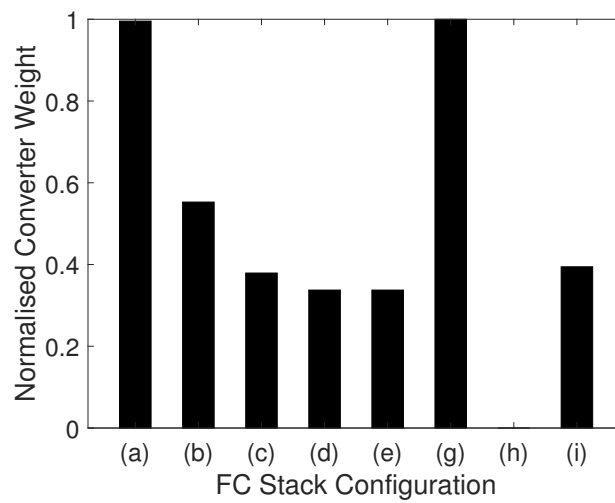
Configuration (a) and (g) are significantly heavier than others. Case (a) has the highest fuel cell output voltage, a large number of inductors are required to distribute the potential difference across them. The high voltage problem also increase the capacitor numbers significantly. Whereas for (g), each of 16 FC stack is equipped with individual converter. Although the LC component numbers for each converter is relatively low, 16 of them become extremely heavy. Moreover, their overall system efficiencies are lower than others. The main reason behind the poor efficiency performance for (a) is because higher ohmic losses occur for larger amount of LC components equipped. The second reason is the conversion efficiency drop along with larger source and load voltage discrepancy. As for (g), the low overall efficiency is mainly due to the utilisation of the boost converters, which exhibit lower efficiencies than its buck counterparts. Therefore, these two configurations are not ideal for regional aircraft applications.

For (d) and (e), they are the lightest apart from (h). Their converters handle moderate voltage and current levels so that less total LC components are needed. But again, they do not have good system reliability since a single converter failure can result in half system power loss. Moreover their efficiency performances are mediocre amongst. Therefore, they are not recommended for this application.

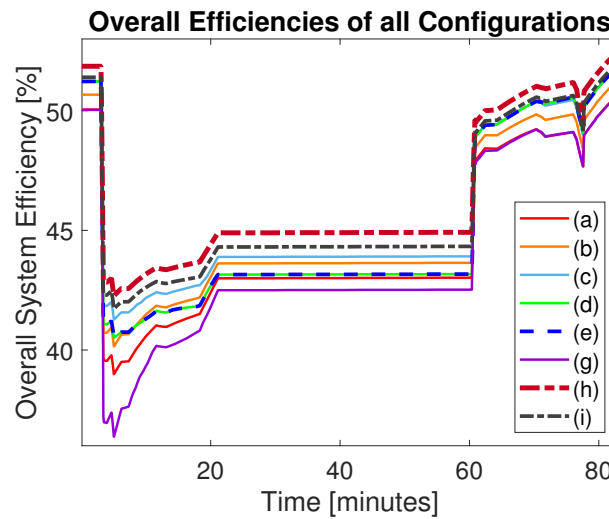
For (b) and (c), their weight are relatively low among the all candidates, but again, their efficiency performance are not the highest. They are more reliable than (a), (d) and

(e). But still in case of converter failure, a one-fourth of total power loss occurs to the aircraft propulsion system.

Finally, (h) has zero converter weight as it is removed. (i) also has relatively low converter weight among these options. Moreover, the reliability of (i) is the second highest. A converter malfunction only causes one-eighth of total power loss. Furthermore, both of them exhibit higher overall efficiencies than others. Therefore, these two configurations are recommended for the propulsion system.



(a)



(b)

Figure 4.27: (a) Normalised converter weight against case g for all configurations. The weights of configuration a, b, c, d, e, g, h, and i are 3153.7, 1751.2, 1201.2, 1069.2, 1069.2, 3168, 0, and 1249.6 kg respectively. (b) Overall propulsion system efficiency of all configurations for 300 nms mission.

4.7.7 A detailed investigation on configuration (h) and (i)

The system and component performance of configuration (h) and (i) are shown in Fig. 4.28, Fig. 4.29, and Fig. 4.30. It can be seen that removing the converter increases the system efficiency by a small percentage (Fig. 4.28). This is an additional benefit on removing the converter from propulsion system apart from weight saving.

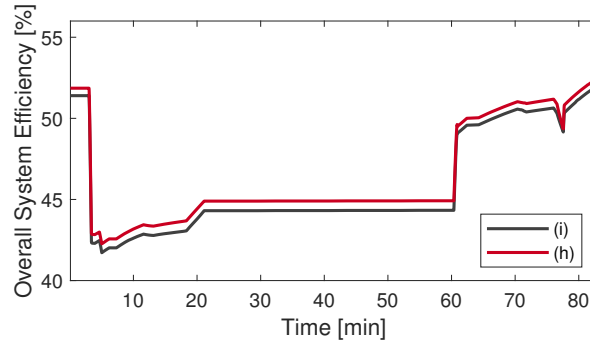


Figure 4.28: Overall system efficiency for cases i and h.

The FC stacks and system efficiencies are almost the same for configuration (h) and (i) (Fig. 4.29a), regardless the bus voltage variation (Fig. 4.30d). This is because, for nominal operation conditions, the efficiency of FC is solely dependent on its output power. With the same propulsive power (Fig. 4.30a) and similar overall system efficiency, their FC efficiencies have a slight difference. There is a small drop of inverter efficiency for (h) due to the IGBTs characteristics at higher inverter input voltage (Fig. 4.29c). And finally, motor performance is similar for both case (Fig. 4.29b) due to careful selection of motor design parameters to enable a wide range of voltage requirements.

It can be seen that, the system without a converter and with variable bus voltage (configuration h) provides highest overall system efficiency and accounts for lowest system weights. However, the power converter can be used as a measure of protecting against electrical faults and a complete power loss. The system safety redundancy design can be achieved by including these converters. Additionally, more critical cable insulation designs at 3080 V (the highest bus voltage for h) and arcing protection measures need to be considered.

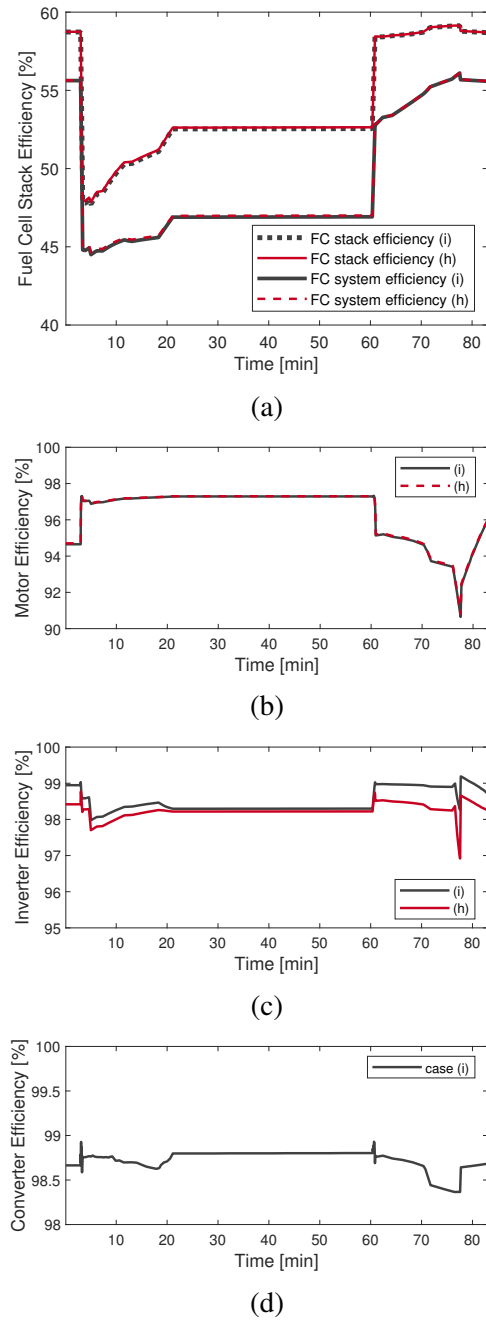


Figure 4.29: Efficiencies of the proposed propulsion system components for the duration of the flight.

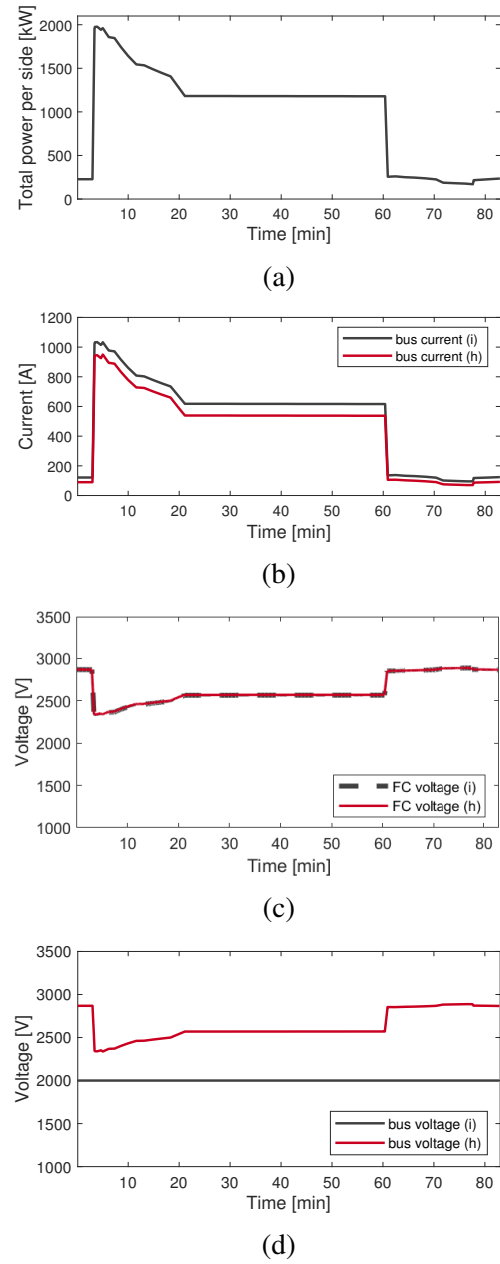


Figure 4.30: Total power, voltage, and current required for the duration of the mission per bus side.

4.8 Concluding remarks

The pure fuel cell propulsion architecture for a typical 50 PAX (4 MW level) regional aircraft is designed and investigated in this chapter. Firstly, an on-design mission-level performance evaluation is conducted for a 300 nms flight. The capability of proposed simulation framework is testified. The key finding is that the system exhibits higher efficiency at low power level. Therefore, a slight over-sized system can improve the efficiency performance.

Secondly, a series of off-design performance evaluations on fuel cell supply air mass flow rate and pressure are conducted for main mission phases (taxiing in/out, takeoff, climb, cruise, descent, and landing). It is found that the system efficiency is higher at low air mass flow rate and supply pressure level. However, for low flow rate level, the risks of instability and system malfunction are identified due to oxygen starvation. There is a trade-off between system efficiency and stability. Based on the simulation results, a ‘high efficiency - stable control strategy’ is proposed for the mission.

Thirdly, the imbalance performance impacts on the complete multi-stack system due to degradation of single fuel cell are investigated. This study is conducted on two multi-stack configurations: “Parallel-series” and “Series-parallel”. It is found that a 10% voltage and current degradation can the stack malfunction during at low power phases (taxiing, descent, and landing) for “Parallel-series” configuration. This is detrimental for the system as great electric potential difference can occur between stacks. “Series-parallel” configuration can avoid this scenario.

Fourthly, nine different multi-stack fuel cell configurations are proposed and assessed qualitatively and quantitatively using high-fidelity models. Their efficiencies, component failure modes, converter design challenges, and sizing considerations are all explained. It is found that two variants of “Series-parallel”, namely configuration (h) and (i), exhibit the highest efficiencies compared to others. Although the weight of configuration (i) is not the lightest, its converter failure impact is less than others. For configuration (h), it has the least weight size and no converter failure concerns, but a more sophisticated motor

control system is required for varying bus voltage. In conclusion, these two configurations are most suitable for the propulsion system.

Finally, in consideration of current technology level, the PEMFC-EP architecture is still too heavy to be implemented. For instance the single stack weights 404 kg so that the whole 16 FC stack arrays weight 6464 kg; The consumed hydrogen fuel is around 80 kg; The available 70 MPa gaseous hydrogen tank has 5.7% wt gravimetric density so that the tank weights around 1406 kg; A single PMSM used is around 400 kg so that eight of them weight 3200 kg. Even if using configuration (h) for power electronics (i.e. no converter). The weight of above listed components already reach 11150 kg. It can be seen that FC stacks contribute most weight of the electrical system. The total engine and maximum fuel weights are 5460 kg combined according to Table 4.1, This means at least 5690 kg will be compromised from aircraft payload. A typical ATR42-300 has around 4640 kg, this means the weight penalty is higher than the maximum payload. However, as introduced in Chapter 2, FC system S.P. is predicted to reach to 2.5 kW/kg in year 2030, the FC system then weights around 1920 kg for maximum 4.8 MW in this application. This means the weight penalty will drop to 1146 kg. It can be concluded that, more research and development should be conducted to improve the S.P. technology level for FC systems, as the heavy stacks are the main barriers for realising the PEMFC-EP architecture.

Chapter 5

50 PAX Regional Aircraft Hybrid Propulsion

5.1 Introduction

In this chapter a study of hybrid electric propulsion (HEP) system for a typical 50 PAX (4 MW power level) regional aircraft is carried out. A simulation framework is developed for HEP system to perform sizing, subsystem integration and matching investigation, and holistic system mission performance evaluation.

Three competitive propulsion architectures are proposed and built within the simulation framework, they are: hybrid-battery, hybrid-fuel cell and hybrid-battery/fuel cell. Various component and system parameters are captured and simulated for these three architectures.

With this simulation framework, the mission and energy management strategy (EMS) features such as, power requirements, mission length, hybridisation level and power split between battery and FC are investigated. It is found that they all have significant impacts on the system performance, sizing, and weight consideration.

As the key component, lithium battery irrevocably suffered from capacity degradation over use. This phenomenon is called “cycle ageing” [167]. The consequent is detrimental

for HEP system along usage time. Therefore, the cycling degradation impact on system performance, maximum range and system sizing are studied.

And finally, a sizing and weight comparison investigation is conducted for three proposed architectures with different dimensions: EMS, mission length, battery degradation degree, and predicted technology level (*S.P.* and *S.E.*). Based on the results, a more intelligent EMS method is proposed for hybrid battery/fuel cell architecture. It is found that this architecture is potentially the lightest amongst the three. Consequently, it can save most payloads for the aircraft.

This chapter is arranged as follows: The selected mission profiles and simulation framework for propulsion system is presented in Section 5.2. A real time flight specification, with constant 700 kW power profile is utilised from Section 5.2 to Section 5.4.3 to exam the simulation capability for “hybrid-battery” and “hybrid-fuel cell” architectures. Weight analysis and comparison between them are demonstrated based on mission lengths, battery cycling number, technology level. In Section 5.5, flight specification is obtained by in-house toolkit. Different energy management strategies replace the constant power profile along the mission and their impacts on system performance, sizing and weight are investigated. A potential lightest architecture is also found in this section, enabling highest effective payloads for the aircraft.

5.2 Proposed mission, power profile, hybridisation level and electric power demand

In this study, both ATR42 regional aircraft real flights and hybrid electric retrofit model are considered. The real flight results were adopted from [25]. Where a real time Toulouse to Rennes flight is considered and selected from Flightradar24 [168]. A series of flight mechanical equations [169] and ATR42-300 aircraft geometry and aerodynamic data are used to obtain the power profiles. And this power profile is used as the initial power profile in this chapter. With the flight mission specifications summarised in Table 5.1 and

illustrated in Fig. 5.1.

Table 5.1: Flight mission specifications adopted from [25].

Range	300 nmi	Payload	3500 kg
Calibrated Climb Speed	160 kts	Cruise Mach	0.333
Take-off Weight	17913 kg	Cruise Altitude	18097 ft

*kts: knot, ft: foot.

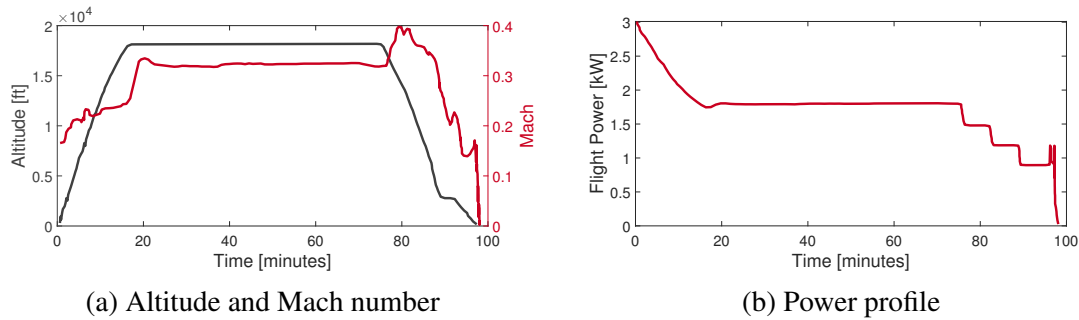


Figure 5.1: Flight mission specifications adopted from [25].

The second set of power profiles are obtained based on the in-house aircraft performance and flight path analysis platform in the Centre for Propulsion Engineering at Cranfield University. With the propeller performance modelled using MIT's Qmil/Qprop tool [129]. With the flight mission specification included in Table 5.2, Fig. 5.2. The reason for having two flight profile is because, the electric propulsion simulation part was first proposed in this study and by that time the author did not use profile obtained by Cranfield in house toolkit yet. Therefore the author directly adopted the flight profile from available literature [25]. Again, as illustrated in Chapter 4, the author did not contribute to Hermes or Turbomatch development or validation. The profile was also adopted, since this study was part of a larger Cranfield research project, and the author focused on developing the electrical system part.

Table 5.2: Flight mission specifications used by Cranfield in-house toolkit.

Range	300 nmi	OEW	10900 kg
Total Engine Weight	2×480 kg	Max Fuel Weight	4500 kg
Calibrated Climb Speed	160 kts	Cruise Mach	0.46
Take-off Weight	17913 kg	Cruise Altitude	19000 ft

*kts: knot, OEW: Operational Empty Weight, ft: foot.

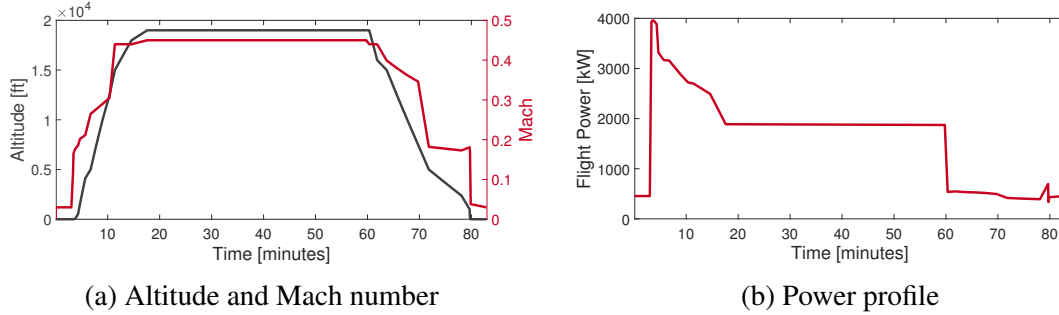


Figure 5.2: Flight mission specifications obtained by Cranfield in-house toolkit.

As discussed in Chapter 3, the parallel propulsion architecture is selected in this study. The hybridisation level is defined by eqn (5.1), where DoH is the hybridisation level in terms of power, $P_{\text{mot, mech}}$ is the output mechanical power from the electric motor, and P_{tot} is the total power required from the propeller to satisfy the flight power. Hybridisation level indicates the power supplied from electric system. This value can be fixed or varying along the mission.

$$DoH = \frac{P_{\text{mot, mech}}}{P_{\text{tot}}} \quad (5.1)$$

For dual electric storage system “hybrid-battery/FC” architecture, the EMS is further defined by power distribution between battery and FC in eqn (5.2). Where Φ_{split} is the power ratio between battery and whole electric storage system, P_{battery} is the battery output power, and P_{ESS} is the power output of battery/FC energy storage system.

$$\Phi_{\text{split}} = \frac{P_{\text{battery}}}{P_{\text{ESS}}} \quad (5.2)$$

With the ability to adjust DoH and Φ_{split} , the impacts of EMS on the system sizing

and performance can be investigated.

5.3 Three proposed HEP architectures in this study

5.3.1 Hybrid battery

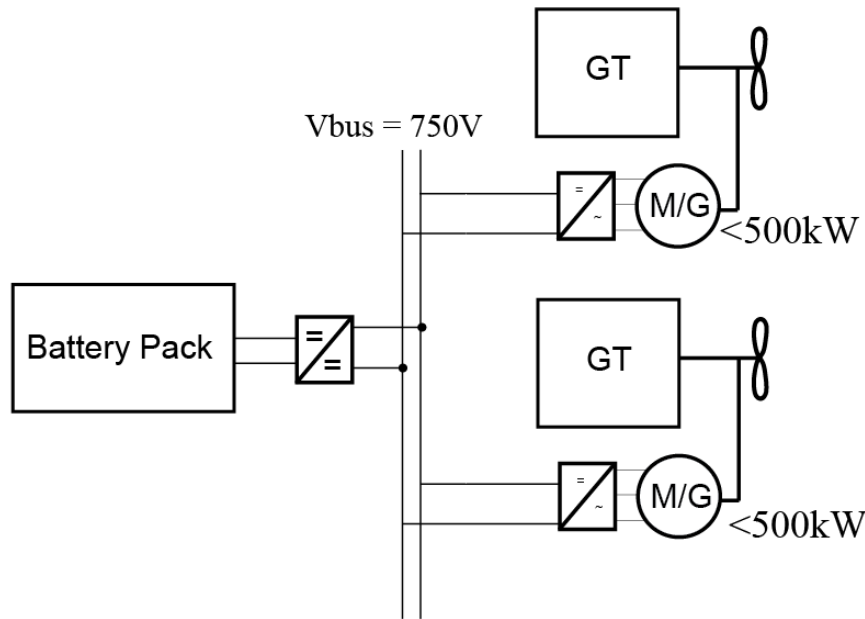


Figure 5.3: Schematic diagram of hybrid battery propulsion architecture.

Fig. 5.3 shows the schematic diagram of hybrid battery architecture. The electric power is provided by battery and transmitted to two motors via power electronics and bus. The electric power is converted to mechanical power by motors. The motors and gas turbines are coupled via a gearbox and provide propulsion power to propellers. The value of hybridization level is adjustable by an electric power management system. The bus voltage is maintained at 750 V via a controlled converter system in this case, which is considered a suitable voltage for a 500 kW level electric motor.

5.3.2 Hybrid fuel cell

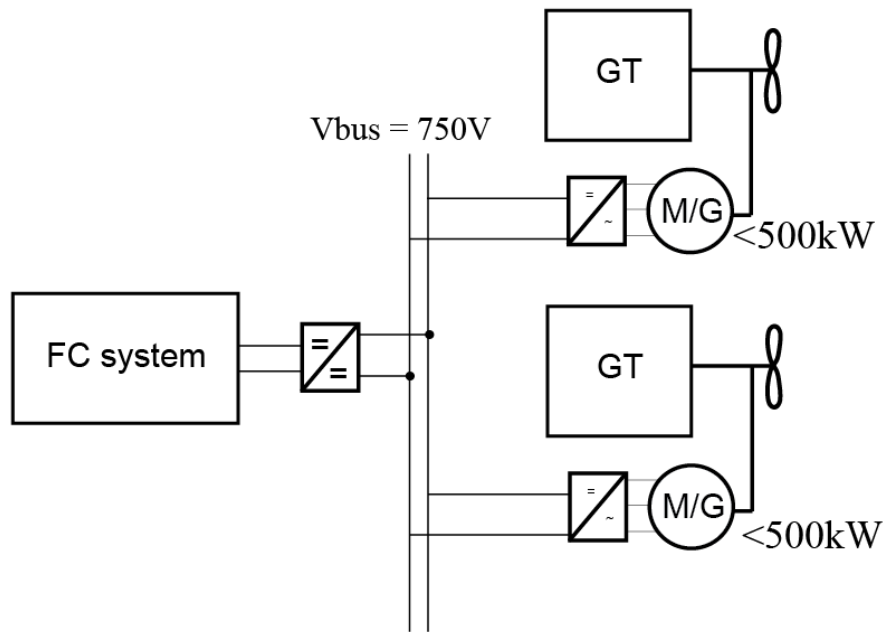


Figure 5.4: Schematic diagram of hybrid fuel cell propulsion architecture.

Fig. 5.4 shows the schematic diagram of hybrid fuel cell architecture. The main difference from hybrid battery is that, proton membrane exchanged fuel cell (PEMFC) is used. For FC system, other key components are also included: compressor system, hydrogen tank, water management and heat management system. In this study, the balance of plant (BoP) power consumption only includes the compressor system, the other subsystems only account for sizing considerations.

5.3.3 Hybrid battery/fuel cell

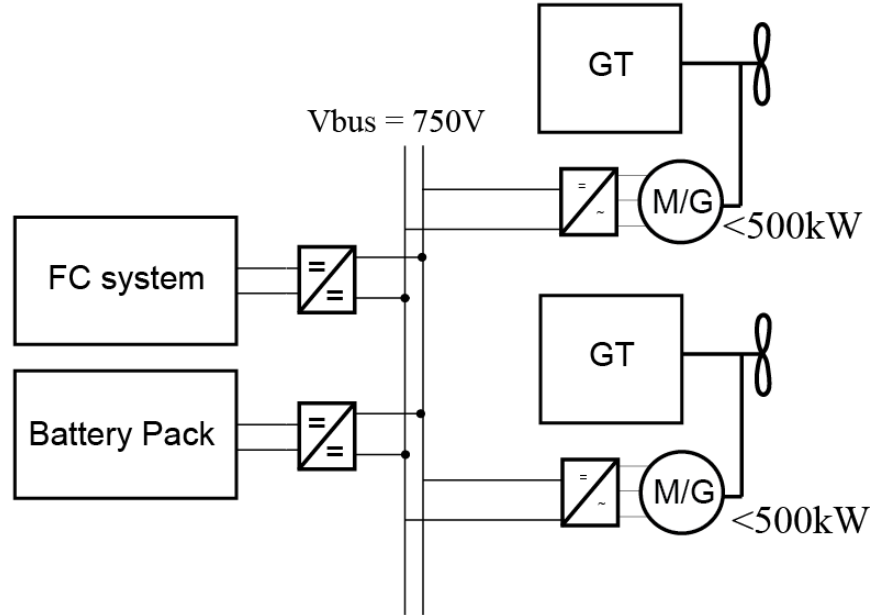


Figure 5.5: Schematic diagram of hybrid fuel cell propulsion architecture.

Fig. 5.5 shows the schematic diagram of hybrid battery/fuel cell architecture. In this case, both battery and fuel cell system are utilised in electric energy storage and power systems. They are connected in parallel to the bus line, and controlled by power electronics individually. This way, better control and energy split implementation between them can be achieved.

5.3.4 Simulation models and their specifications for the three architectures

In this study, the main focus is on weight, sizing and off-design operation of battery system. The detailed performance of converters, motor control system and PMSM are not considered, therefore, low-fidelity converter model is used to maintain the bus voltage; low-fidelity motor controllers, coupled with ' $I_d = 0$ ' control strategies are used to maintain torque and rotational speed; and low-fidelity dq-model of motor is applied. The

detailed specifications of the converter, inverter, and motor are summarised in Table 5.3.

Table 5.3: Converter, inverter, and motor specifications.

Symbol	Description	Value
η_{conv}	Converter efficiency	98%
η_{inv}	Inverter efficiency	99%
L_d	D-axis inductance	12e^{-5} H
L_q	Q-axis inductance	12e^{-5} H
R_c	Motor armature resistance	0.02Ω
p	Motor pole pair	16
λ	Magnetic flux linkage	0.1 Wb

5.4 Comparison between hybrid battery and hybrid fuel cell architectures

In this section, hybrid battery and hybrid fuel cell architectures are compared. The impacts of mission length on their system weight and sizing are evaluated. Moreover, the battery capacity degrades rapidly along with usage cycle number. The impacts of cycling effects on hybrid battery system are also investigated.

Three different mission length: 200-, 300- and 600 nms are selected for the first set of studies. They are variants of the original 300 nms mission adopted in [25], only by contracting and expanding the cruising phase accordingly. Moreover, the mechanical power from the motor system is fixed 700 kW throughout the mission in this case. These power profiles are shown in Fig. 5.6.

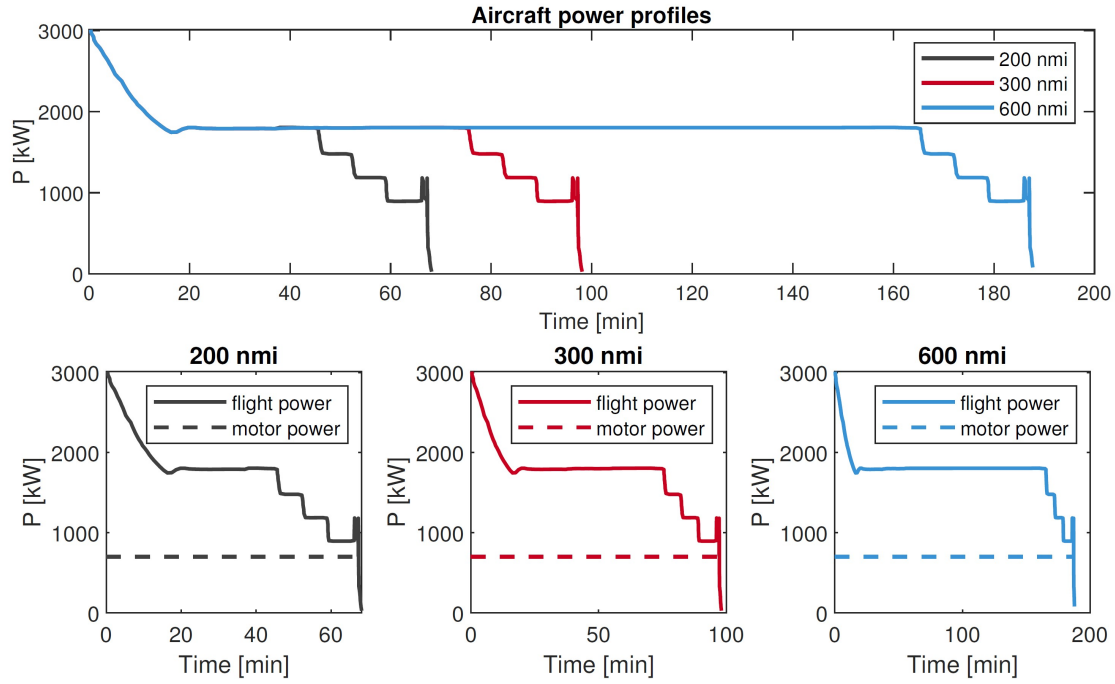


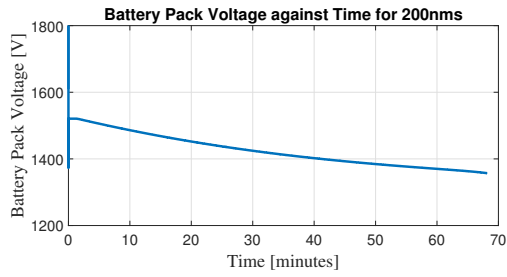
Figure 5.6: Power profiles modified from [25].

5.4.1 700kW constant power for hybrid battery

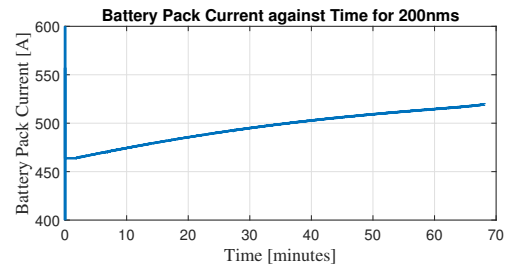
Hybrid battery propulsion system performance

Fig. 5.7, 5.8, and 5.9 show the key performance outputs of hybrid battery architecture for 200-, 300-, and 600 nms. The total motor power is 700 kW, the rest of flight power is provided by the gas turbines. For the electric distribution system (bus line), the voltage is maintained at 750 V_{dc} along the system, and the current at around 960 Amperes. The bus are distributing a constant power slightly higher than required 700 kW. This is due to the losses of motor and inverter.

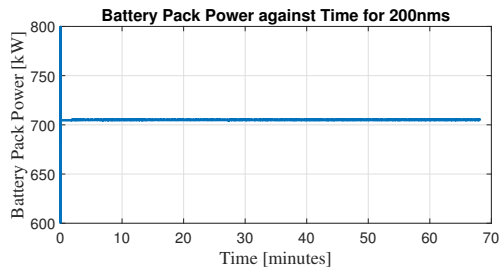
The lithium battery voltage decreases along the mission (Fig. 5.7a, 5.8a, and 5.9a). To maintain constant output motor power, an increase in output current is seen (Fig. 5.7b, 5.8b, and 5.9b). Another key parameters are the battery state of charge (*SOC*). It is recommended an above 20% residual *SOC* is a preferable for battery life and safety considerations [151]. The mission-level *SOC* variations are illustrated by Fig. 5.7g, 5.8g, and 5.9g and the end residual values are maintained above 20%.

200 nms results

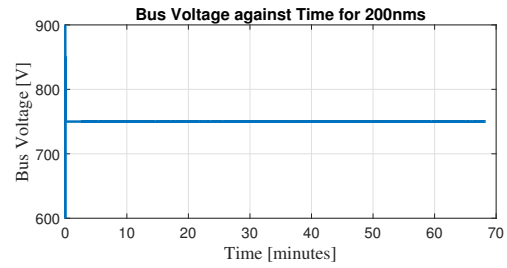
(a) Battery pack voltage



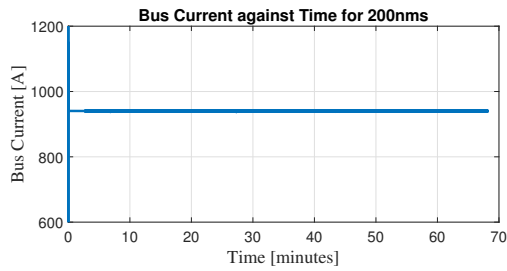
(b) Battery pack current



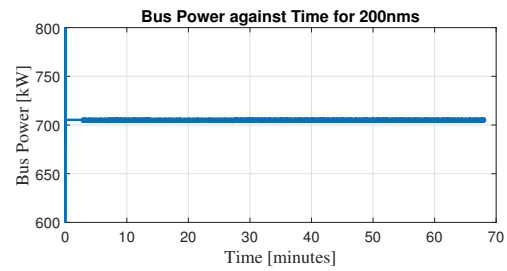
(c) Battery pack power



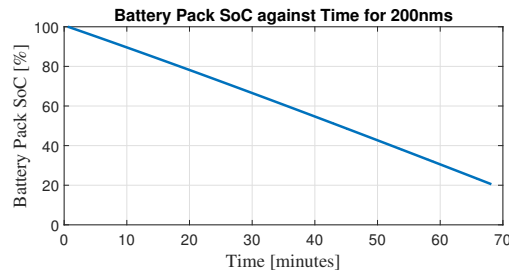
(d) Bus voltage



(e) Bus current

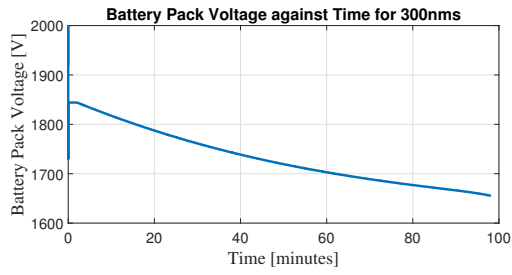


(f) Bus power

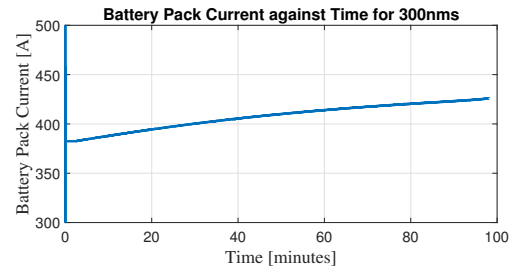


(g) SOC of battery

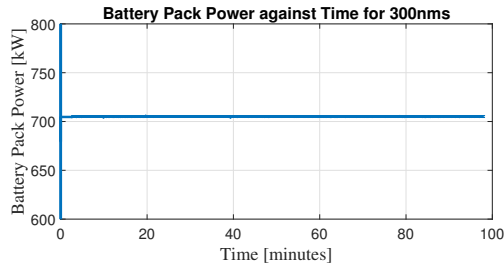
Figure 5.7: Voltage, current, power, and state-of-charge of battery system and electric power distribution bus line for 200 nms mission.

300 nms results

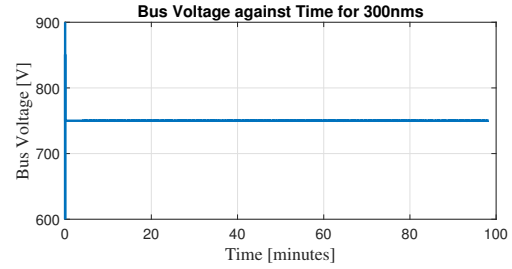
(a) Battery pack voltage



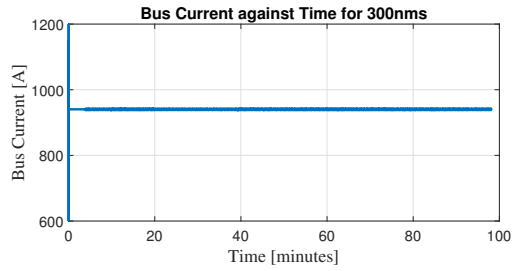
(b) Battery pack current



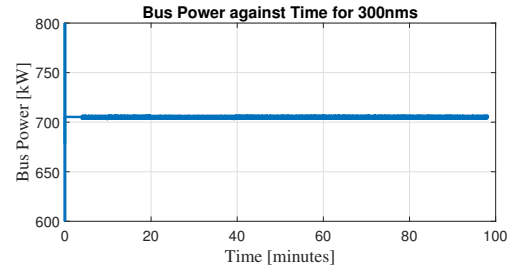
(c) Battery pack power



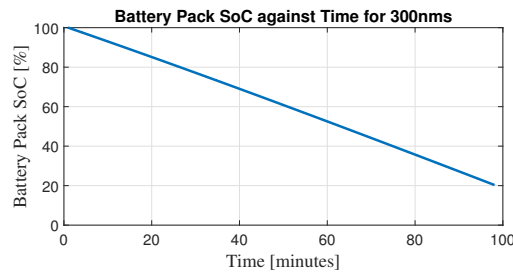
(d) Bus voltage



(e) Bus current



(f) Bus power



(g) SOC of battery

Figure 5.8: Voltage, current, power, and state-of-charge of battery system and electric power distribution bus line for 300 nms mission.

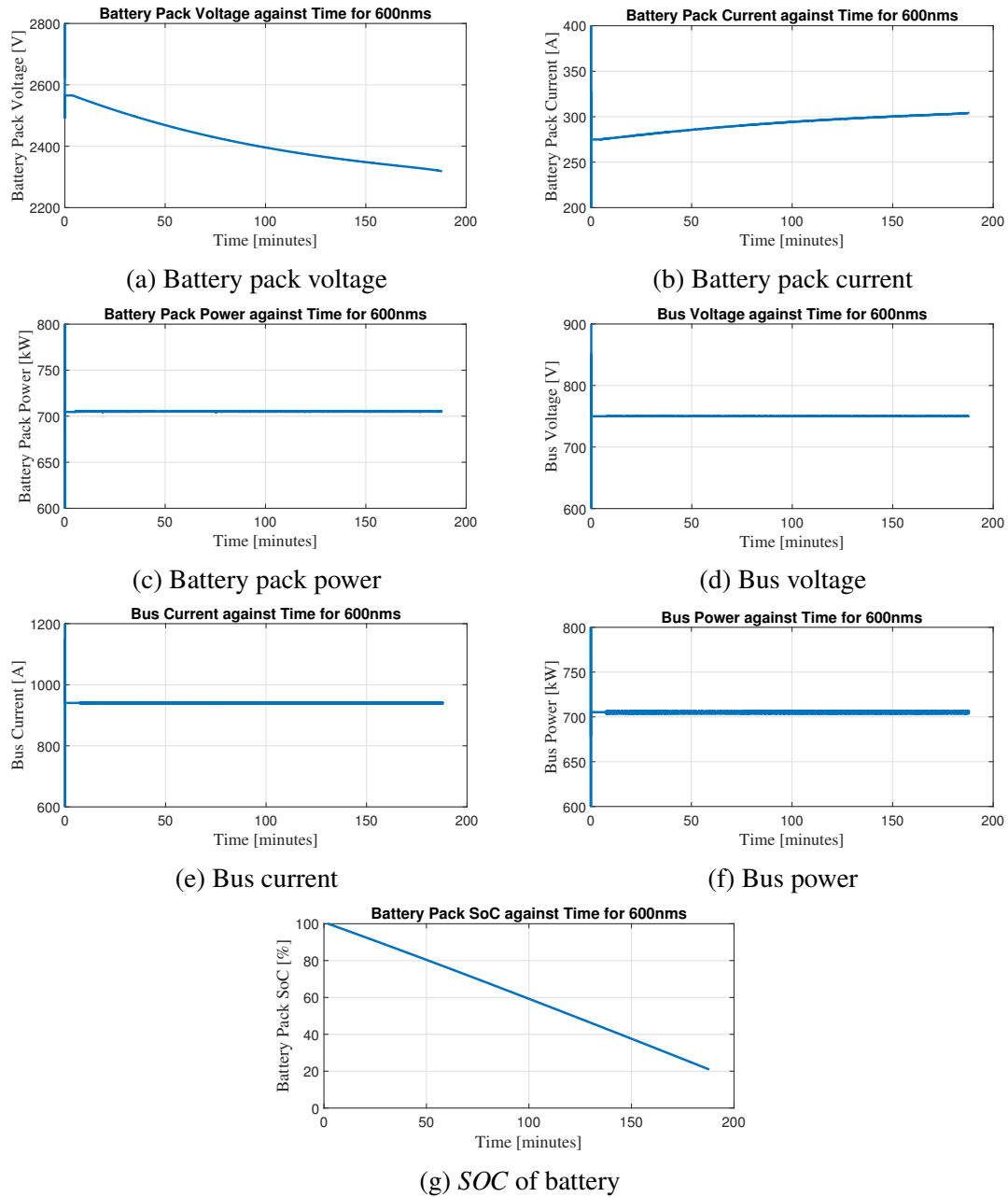
600 nms results

Figure 5.9: Voltage, current, power, and state-of-charge of battery system and electric power distribution bus line for 600 nms mission.

Energy storage system sizing

Apart from electric system performance, the battery pack sizing is another key issue, as aircraft is highly weight sensitive. Battery pack is the main contribution to the system weight. A battery sizing flow chart is shown in Fig. 5.10.

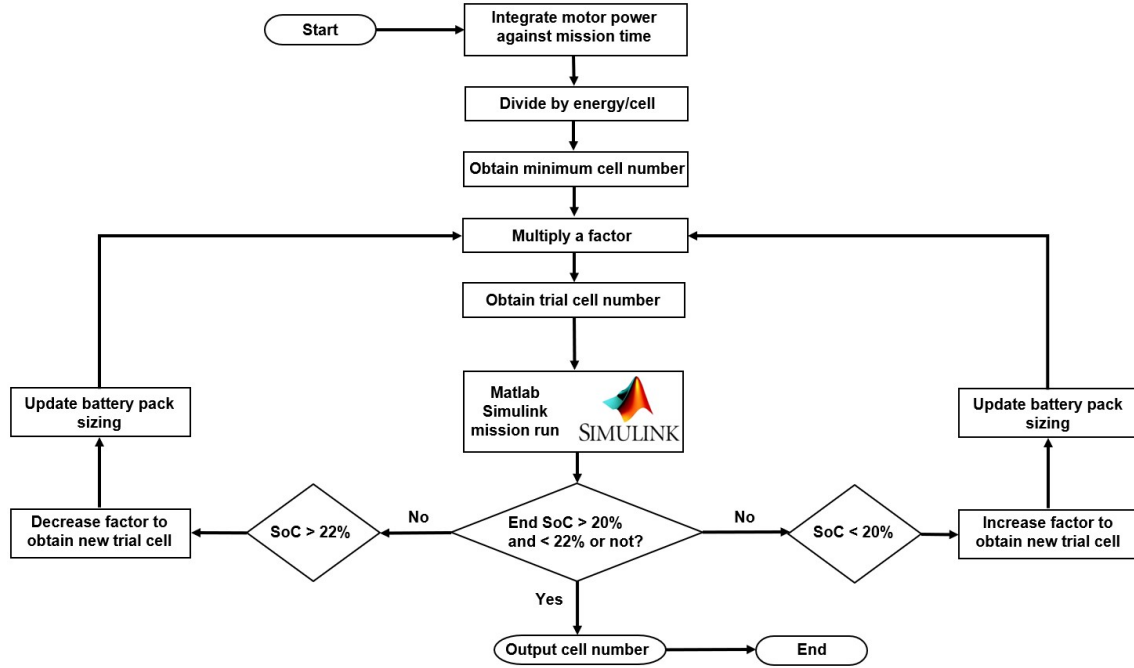


Figure 5.10: Flow chart for battery sizing.

The relevant equations used in this battery sizing flow chart is listed below:

$$E_{\text{elec,mission}} = \int_{t_{\text{ini}}}^{t_{\text{end}}} P_{\text{mot,mech}} dt \quad (5.3)$$

$$n_{\text{cell}} = \frac{E_{\text{elec,mission}}}{E_{\text{percell}}} \quad (5.4)$$

$$n_s = n_p = \sqrt{n_{\text{cell}}} \quad (5.5)$$

The end mission residual *SOC*, mission length, and the total energy consumption for battery are the main factors that influence the size of battery pack. Moreover, the battery storage capacity and performance are highly affected by cycling degradation. This impact need to be considered in sizing process. One strategy is to reduce the battery power or battery duration as cycle number rises. Another strategy is to size the battery so that the energy stored is adequate and lasts until the end of the cycle number. Table 5.4 illustrates the battery sizing outcomes for 200-, 300-, and 600 nms. Table 5.5 shows battery sizing

results allowing for adequate storage energy remaining after different cycling numbers for 200 nms mission. 20% is set as the mission-end *SOC*. The parameters n_p and n_s are defined in Chapter 3, Section 3.5.3.

Table 5.4: Battery pack sizing for 200 nms - healthy condition.

Mission Length	Total Cell Number	n_p	n_s	Battery Pack Weight
200 nms	152100	390	390	Battery pack weight is related to <i>S.E.</i> and cell number by eqn (5.6) and (5.7).
300 nms	216225	465	465	
600 nms	403225	635	635	

Table 5.5: Battery pack sizing for 200 nms - cycling degradation considered.

Cycle Number	Total Cell Number	n_p	n_s	Battery Pack Weight
0	152100	390	390	Battery pack weight is related to <i>S.E.</i> and cell number by eqn (5.6) and (5.7).
100	156025	395	395	
200	160801	401	401	
400	170569	413	413	
600	182329	427	427	

More cells are equipped for longer mission, and extra number of cells are needed for higher cycle numbers. This way, battery system can withstand more mission counts so that battery replacement and maintenance costs can reduce, but results in a less effective payload and heavier aircraft.

5.4.2 700 kW constant power for hybrid fuel cell

Hybrid fuel cell propulsion system performance

For a constant 700 kW electric power hybrid-fuel cell architecture, five 150 kW Ballard fuel cell stacks [23] are used. Fig. 5.11, Fig. 5.12, and Fig. 5.13 show the key simulation results for 200-, 300-, and 600 nms missions.

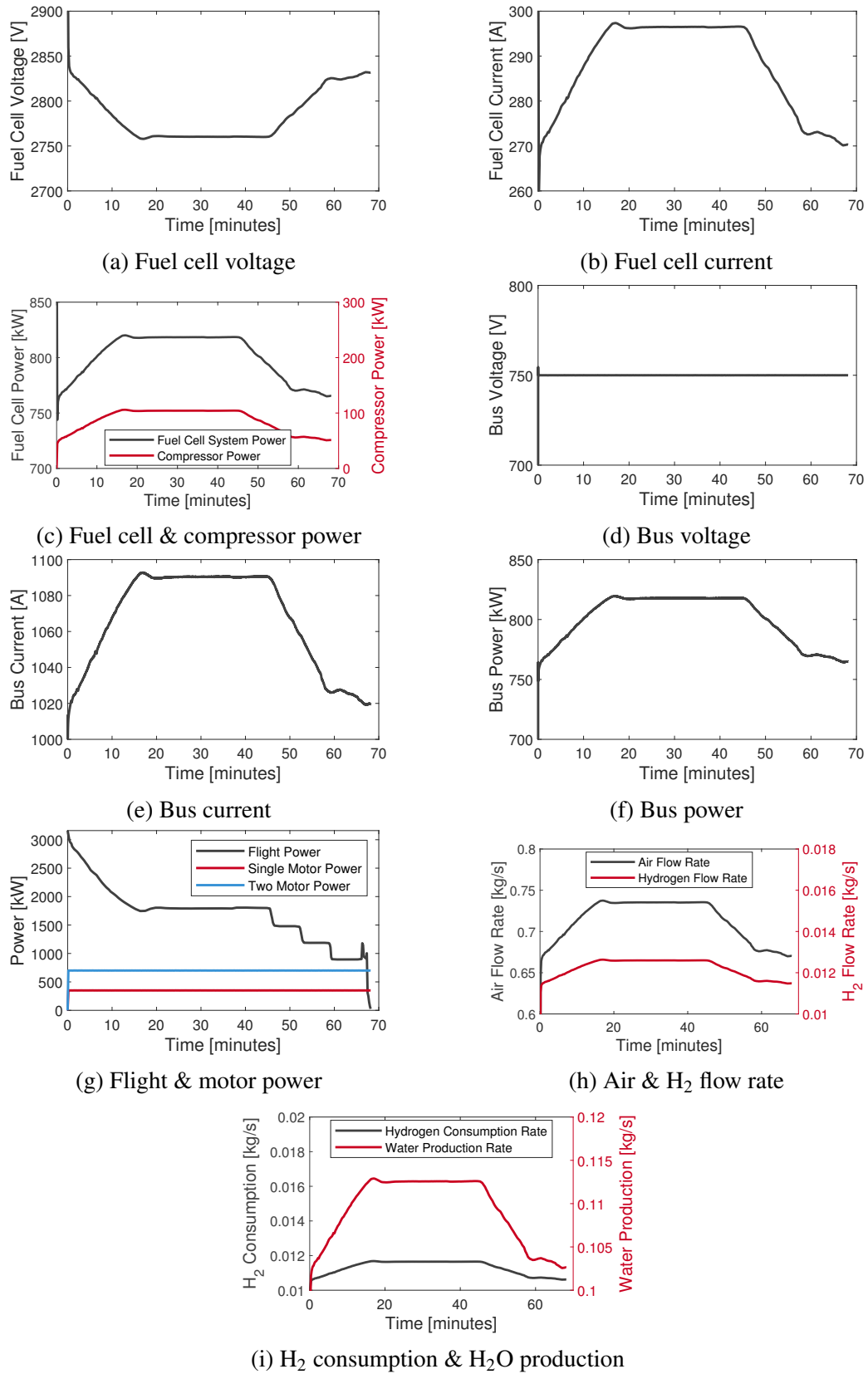
200 nms results

Figure 5.11: Simulation results of hybrid-fuel cell architecture for 200 nms.

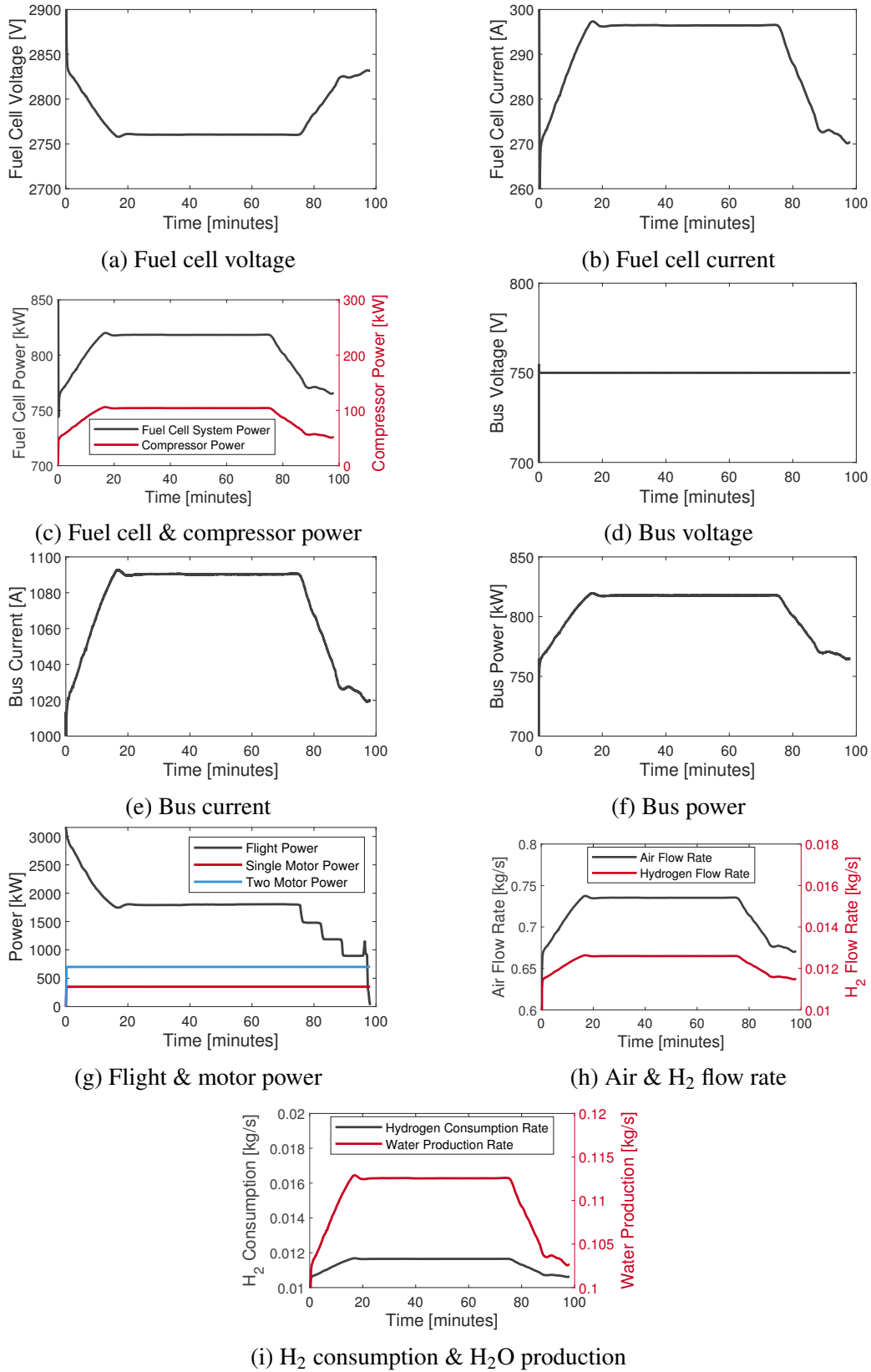
300 nms results

Figure 5.12: Simulation results of hybrid-fuel cell architecture for 300 nms.

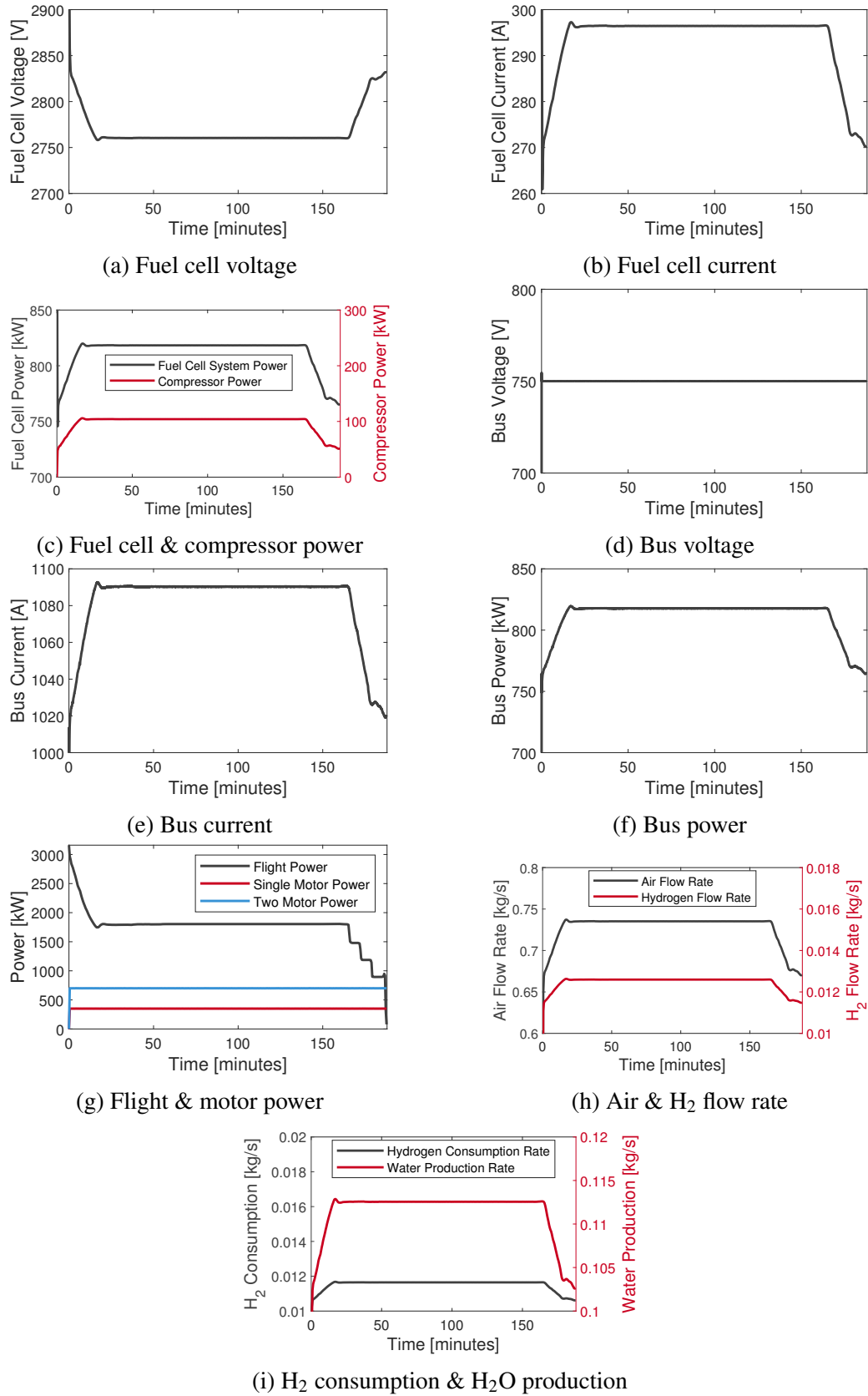
600 nms results

Figure 5.13: Simulation results of hybrid-fuel cell architecture for 600 nms.

The bus voltage (Fig. 5.11d, 5.12d, 5.13d) is maintained at 750 V_{dc} and motor power (Fig. 5.11g, 5.12g, 5.13g) at 700 kW throughout the mission. The operation altitude varies from 0 to 19,000 ft (cruise altitude) and drops back, the ambient pressure changes accordingly. This leads to an increase and a decrease in compressor power for maintaining the stack operation pressure. The peak compression power can reach at 106kW. This compression power is provided by the fuel cell so that its power variation along the mission is seen (Fig. 5.11c, 5.12c, 5.13c). Under this power variation, fuel cell voltage and current vary along the mission. According to the fuel cell polarisation curve, the output voltage drops and current rises for high power requirement; and in contrast, the voltage rises and current drops for at low power setting. The feature is shown in voltage and current mission profiles (Fig. 5.11a, 5.12a, 5.13a and Fig. 5.11b, 5.12b, 5.13b). Finally, the air and hydrogen fuel (H₂) mass flow and consumption rates, and the water generation rates are proportional to fuel cell output power. As shown in Fig. 5.11h, 5.12h, 5.13h and Fig. 5.11i, 5.12i, 5.13i, the fuel cell power and reactants flow, consumption, and production rates match with each other.

Fuel cell system sizing

Unlike battery system, of which sizing highly depends on mission length, the fuel cell size and stack number are mainly determined by the maximum power. Hence five 150 kW rated fuel cell stacks are considered adequate for the 700 kW power. With each stack providing a maximum 165 kW power, there is an 18% power margin. Moreover, the battery is more prone to capacity losses due to storage and cycling, the sizing of battery need more attention to consider these impacts.

Apart from the power sizing aspect, the flow rate and net consumption of reactants need to be considered, since they can impact the sizing and weight of the fuel and oxygen supplier and storage system. With the simulation results, system weight analysis is conducted in the following sections.

5.4.3 Weight analysis of hybrid battery and hybrid fuel cell system for on-design conditions

Weight calculation method for hybrid-battery and hybrid-fuel cell architectures

In this section, a weight calculation method is introduced and developed for the on-design hybrid battery and hybrid fuel cell energy storage system.

For the battery pack system, the lithium cell numbers are summarised in Table 5.4. The combined battery pack weight is the sum of all lithium cells. And the weight of single lithium cell is calculated by dividing the energy stored in single cell by specific energy, as shown in the following equations.

$$W_{\text{batt,pack}} = n_{\text{cell}} \times W_{\text{cell}} \quad (5.6)$$

$$W_{\text{cell}} = \frac{1}{S.E. \times 0.8} \int_{SOC=100\%}^{SOC=20\%} I_{\text{cell}} V_{\text{cell}} dt \quad (5.7)$$

where, $W_{\text{batt, pack}}$ is the battery pack weight, n_{cell} is the lithium cell number, W_{cell} is the single lithium cell weight, $S.E.$ is the cell-level specific energy, I_{cell} is the discharge current, and V_{cell} is the cell voltage. A multiplier of 0.8 is used to convert cell-level specific energy to pack-level. The state-of-art $S.E.$ is 250 Wh/kg, and this value is expected to reach 500 Wh/kg in short term future [170]. Higher specific energy indicates more storage capacity is available in unit battery mass.

For the fuel cell system, the weight estimation is mostly based on the off-shelf technology level available nowadays. The main weight contributions include: fuel cell stack, compressor/motor for oxygen supply system, hydrogen fuel, hydrogen tank and water produced. The detailed weight decomposition for these three missions are summarised in Table 5.6, Table 5.7, and Table 5.8 for 200-, 300-, and 600 nms respectively, with the component specifications follow.

200 nms fuel cell system

Table 5.6: Weight decomposition table for 200 nms.

System	Components	Weight [kg]
Power source	Fuel cell stack	2020
Auxiliary system	Compressor/motor	12.00
	Hydrogen fuel mass	42.45
	Hydrogen tank	744.74
	Water produced	355.65
Total		3174.84
Total without water		2819.19

300 nms fuel cell system

Table 5.7: Weight decomposition table for 300 nms.

System	Components	Weight [kg]
Power source	Fuel cell stack	2020
Auxiliary system	Compressor/motor	12.00
	Hydrogen fuel mass	61.10
	Hydrogen tank	1071.92
	Water produced	511.87
Total		3676.89
Total without water		3165.02

600 nms fuel cell system

Table 5.8: Weight decomposition table for 600 nms.

System	Components	Weight [kg]
Power source	Fuel cell stack	2020
Auxiliary system	Compressor/motor	12.00
	Hydrogen fuel mass	116.92
	Hydrogen tank	2051.23
	Water produced	979.51
Total		5179.66
Total without water		4200.15

The methods to obtain the data in above tables are:

- According to [23], a single fuel cell stack is 404 kg, so for 700 kW five are used, hence the weight is 2020 kg.
- According to [171], the compressor is selected based on power requirement, the max power of air compressor required is 106 kW, so the EMRAX 228 was used, as its peak power is 109 kW.
- According to [172], the SOA gaseous hydrogen storage density is 5.7 wt%, with tank pressure at 70 MPa. The hydrogen tank weight is hydrogen mass consumed divided by tank storage density.
- According to [22], the equation of water mass produced rate is:

$$\dot{m}_{v,ca,gen} = M_v \times \frac{nI_{st}}{2F} \quad (5.8)$$

Where M_v is the vapour molar mass, n is the stack number, I_{st} is the stack current and F is the Faraday number, so the water produced for the whole mission is the integral of this value with time.

On-design hybrid-battery and hybrid-fuel cell weight comparison

Given that this set of study focuses on on-design conditions, there is no cycling or calendar loss for battery, nor there is other issues causing fuel cell degradation. Fig. 5.14 shows the on-design system weight comparisons between hybrid-battery and hybrid-fuel cell architectures for 200-, 300-, and 600 nms. In these figures, the weight of battery pack is varied against cell specific energy, and the weight obtained for fuel cell system are from off-the-shelf available products. Fig. 5.15 further summarises the comparisons between them.

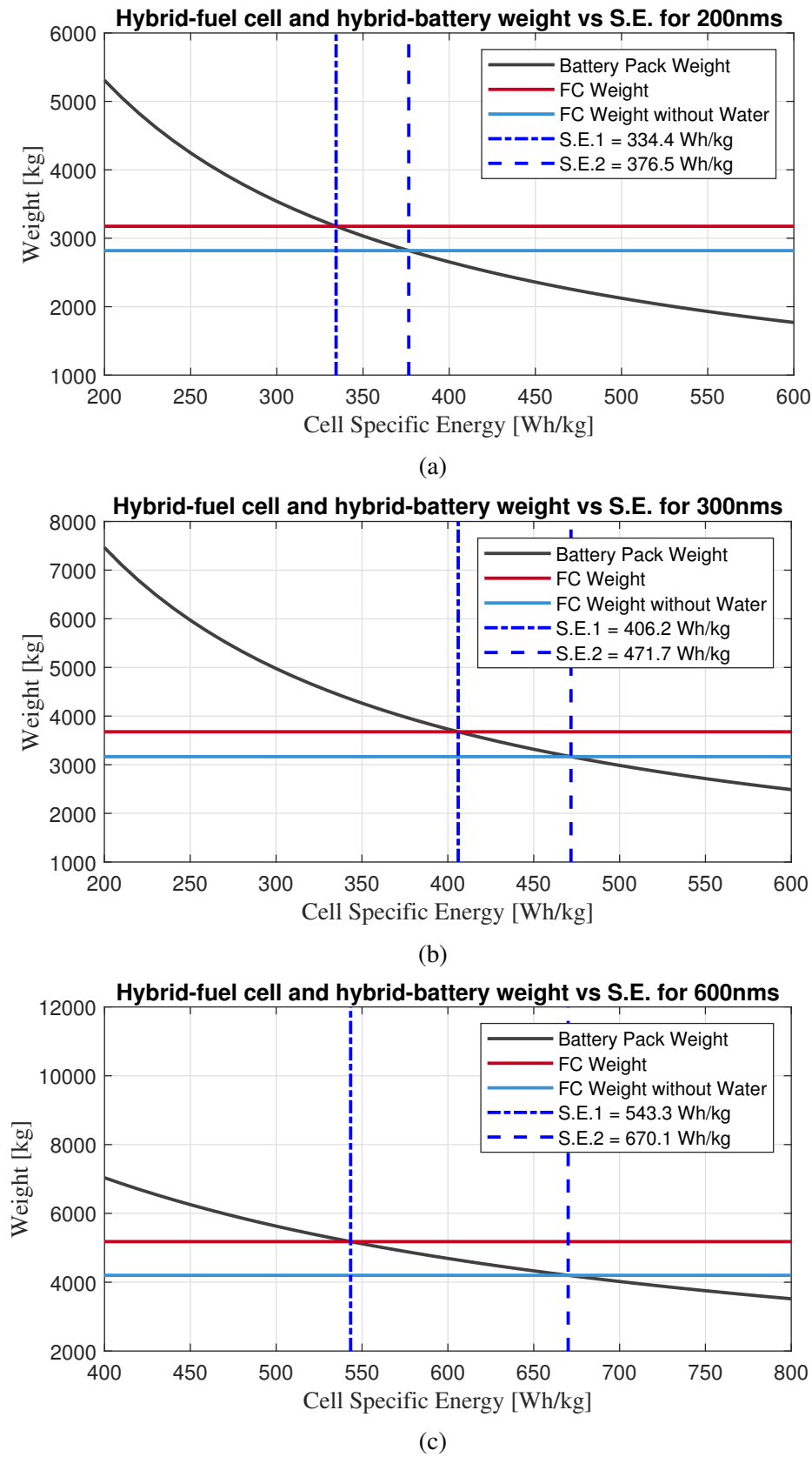


Figure 5.14: Comparisons between hybrid-fc and hybrid-battery energy storage system weights for (a) 200 nms, (b) 300 nms, and (c) 600 nms mission.

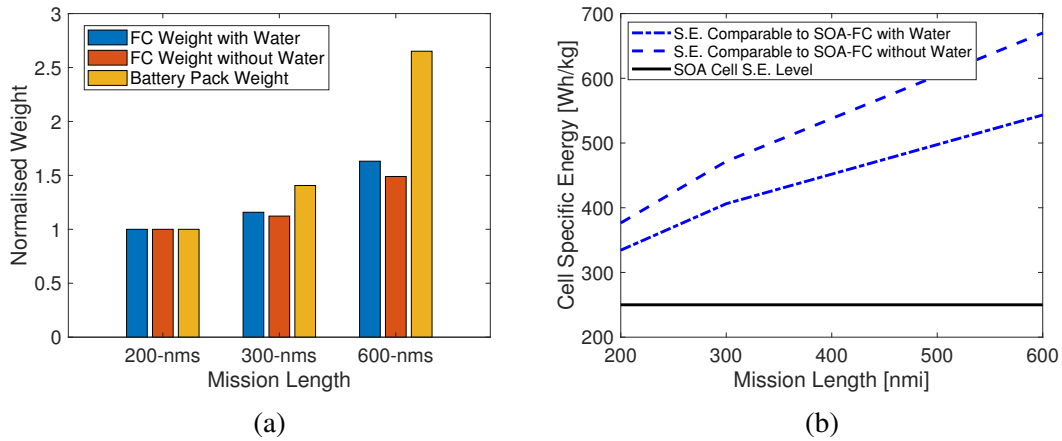


Figure 5.15: (a) Normalised weight of hybrid-fuel cell with water jettison, hybrid-fuel cell without water jettison and hybrid-battery against their 200 nms values. (b) Expectations of minimum cell specific energy for hybrid-battery to have weight advantages over hybrid-fuel cell for 200-, 300-, and 600 nms mission.

From these results, it can be seen that:

1. Both architecture weights are sensitive to mission length. Their weights increase with mission length. The weight is also affected by technology level. With higher cell specific energy ($S.E.$), the hybrid battery system becomes lighter.
2. The mission length effect on hybrid-fc is less than that on hybrid-battery. Taking 200 nms as baseline, the total hybrid fuel cell system weight, without water jettisoning, increases around 15.8% and 63.1% for 300 and 600 nms. In comparison, a rise of approximately 40.6% and 165.1% is expected for hybrid-battery architecture. This is because the specific energy of battery is much less than that of hydrogen. Unlike battery pack, of which weight is determined mostly by missions. The weight of fuel cell stack, compressor/motor, cathode and anode pipes are determined by the power requirement, the only variables that affected by mission length are hydrogen fuel mass, hydrogen tank and the water produced. However, these increments are not comparable with battery weight rise.
3. The state-of-art cell specific energy is 250 Wh/kg. Hybrid-battery architecture with this battery technology level is clearly not suitable in comparison to hybrid-fc in

weight. It can be seen from the results, the thresholds for battery specific energy are shifting towards right: 335-, 407- and 544 Wh/kg accordingly. If the water produced from fuel cell is jettisoned, the battery specific energy are required to increase even higher to compete against fuel cell system: 377-, 472- and 671 Wh/kg. These results set up expected technology level for battery to compete against fuel cell. Clearly, the state of art battery technology is inferior to fuel cell in terms of weight.

To sum up, four conclusions can be drawn from this study:

1. PEM fuel cell system can also benefit the HEP in terms of fuel savings and emission reductions like battery pack, since the products are just water.
2. PEM fuel cell system has advantages over the state of art battery pack technology in terms of weight saving.
3. For short mission ranges like 200 nms, the hybrid-battery has the possibility to take weight advantages over hybrid-fc in near future.
4. The longer the mission, the more suitable the fuel cell system is. And the higher specific energy is required for battery.

Off design and its impact on hybrid battery

In this section, the cycling degradation impact is analysed. A 200 nms mission length is selected. Battery pack with 100, 200, 400 and 600 cycle numbers are analysed and compared to baseline on-design conditions (0 cycle). The battery pack stops working when *SOC* is less than 20%. The results are shown in Fig. 5.16.

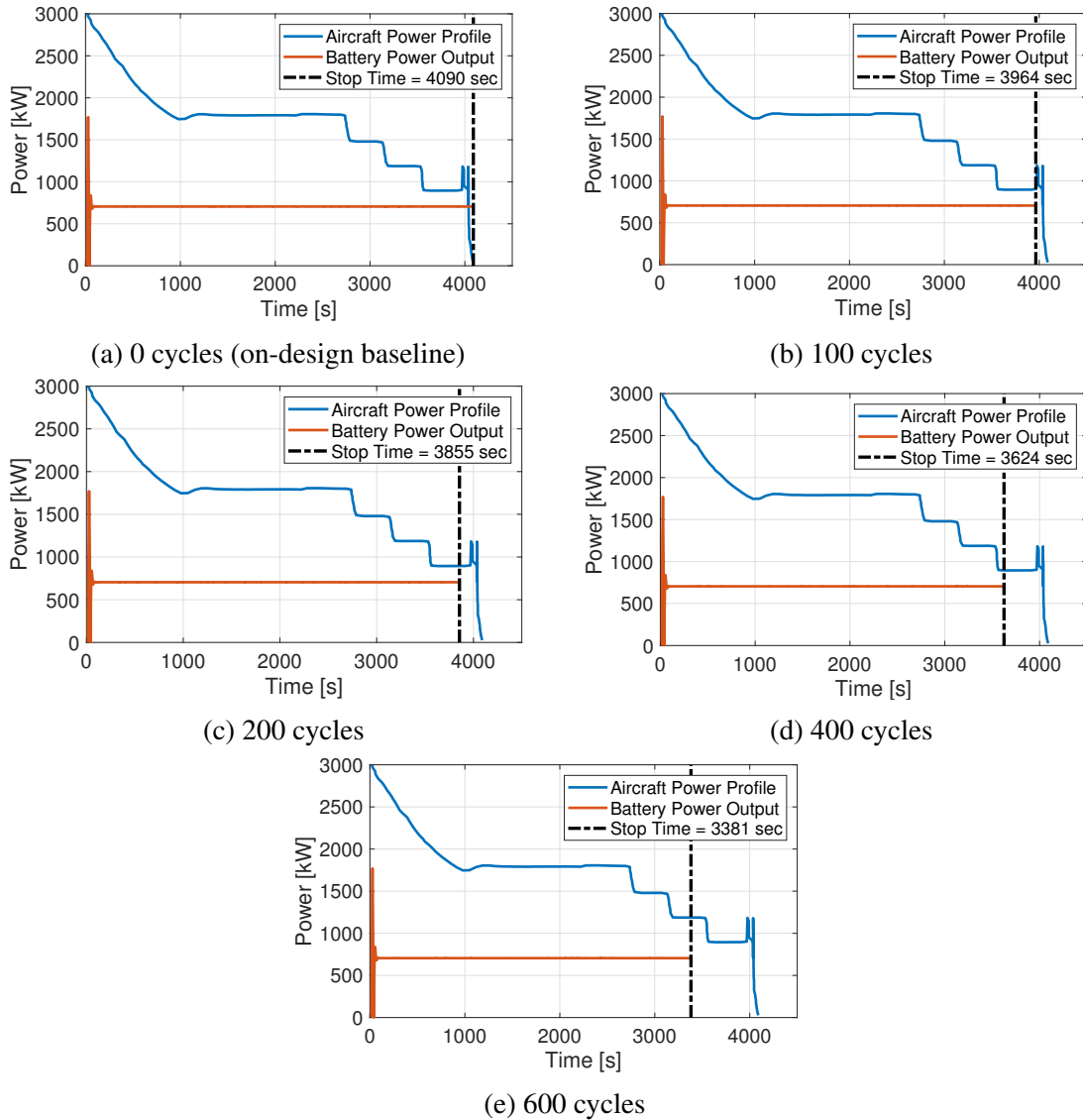


Figure 5.16: 200 nms power profile for aircraft and the maximum time battery system can operate for different cycling numbers.

From these results, it can be observed that:

1. As the cycling number increases from 0 to 600, the battery pack capacity decreases accordingly. This capacity degradation directly cuts down the operation time that battery pack can provide.
2. For on-design case, the battery is suitable to operate the complete 4090 seconds mission. However, as the battery pack degrades after 100, 200, 400 and 600 mission cycles, it can only power the system for 3964-, 3855-, 3624- and 3381 seconds.

In order to ensure complete electricity supply, there are two strategies introduced previously, either to reduce the electric power level or to oversize the batteries onboard. With oversized battery packs, additional weight would occur. These new system weights are shown in Fig. 5.17a for 200 nms range. The increase in weight for 100-, 200-, 400-, and 600 cycles are around 2.6%, 5.8%, 12.1% and 19.2% respectively.

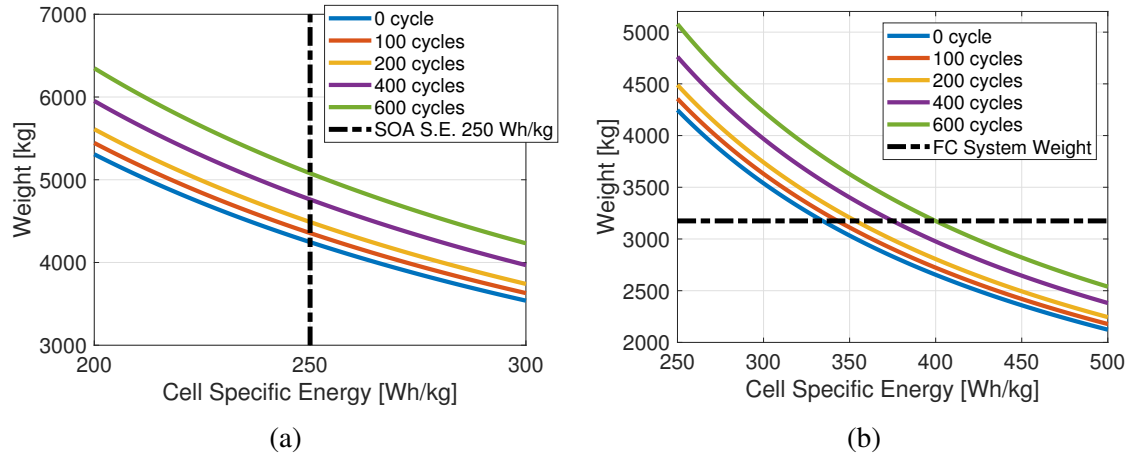


Figure 5.17: (a) Battery weights against cell specific energy for different degradation cycle numbers at 200 nms mission. (b) Comparison between hybrid-fuel cell (without water jettison) and cycling degraded hybrid-battery weight for 200 nms mission.

Finally, the weight comparison study between hybrid-fc and off-designed hybrid-battery is conducted. As shown in Fig. 5.17b, For hybrid-battery to have advantages over hybrid-fc, the required specific energy is: 343-, 353-, 375- and 400 Wh/kg. The conclusion of cycling degradation impacts study is:

1. Cycling degradation limits the designed operation time of the hybrid-battery system. The propulsion system shuts down before flight mission is completed as usage cycle increases.
2. It is necessary to oversize lithium cell for cycling. The less frequently the battery is replaced, more cells are required but in the expense of aircraft payloads.
3. The weight advantage of hybrid-fc over hybrid-battery is more prominent as the battery cycling is considered.

5.5 Hybrid battery, hybrid fuel cell and hybrid battery/-fuel cell architecture

The aim of this study is to investigate how different energy management strategies can affect the design and sizing of three proposed system architectures: hybrid battery, hybrid fuel cell and hybrid battery/fuel cell. Also to conduct a quantitative analysis on the characteristics and their advantages and disadvantages of these architectures. The power profile is based on the Cranfield in-house methodology. The aircraft platform is an ATR42 retrofit model. Three mission lengths are selected: 200-, 300-, and 600 nms. Furthermore, two hybridisation levels (10% and 20% *DoH*) are applied for the electric system. Their impacts on architecture sizing are investigated later. The flight and electric system power profiles are shown in Fig. 5.18.

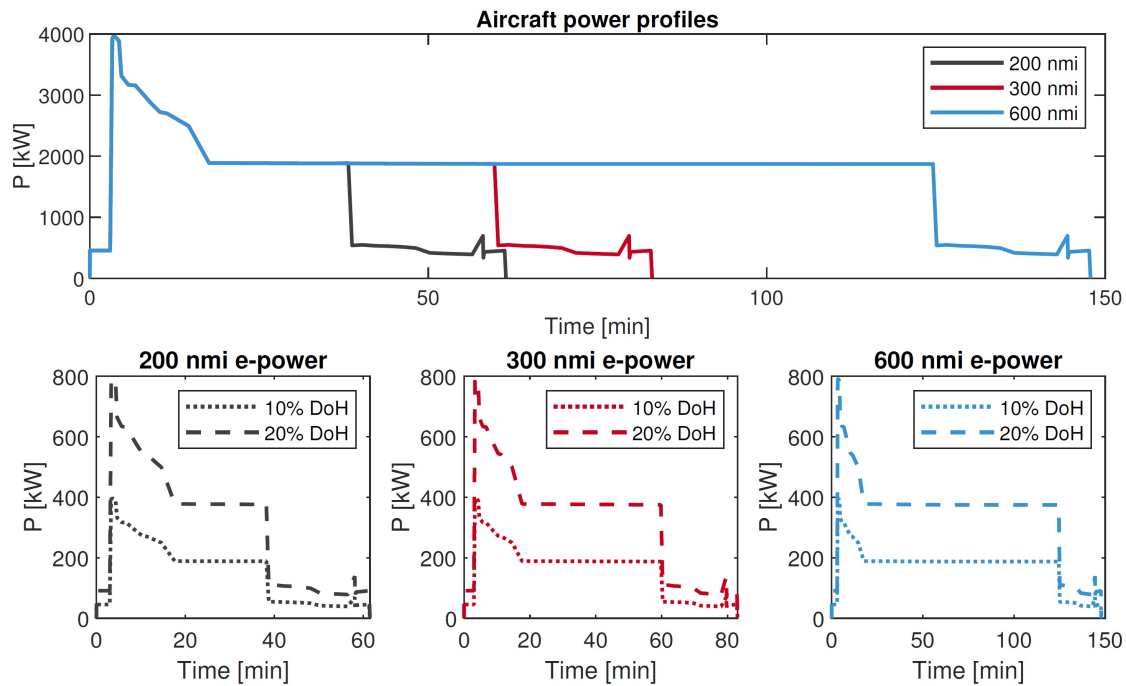


Figure 5.18: Aircraft power profiles obtained from Cranfield in-house toolkit, and electric power profiles for 10% and 20% *DoH*.

5.5.1 Sizing and weight analysis of hybrid battery, hybrid fuel cell and hybrid battery/fuel cell system

Hybrid battery

Given the power requirements, the battery is sized with methodology introduced before. The schematic diagrams of different hybrid-battery sizes are shown in Fig. 5.19. And Table 5.9 lists the sizing data of the hybrid battery system.

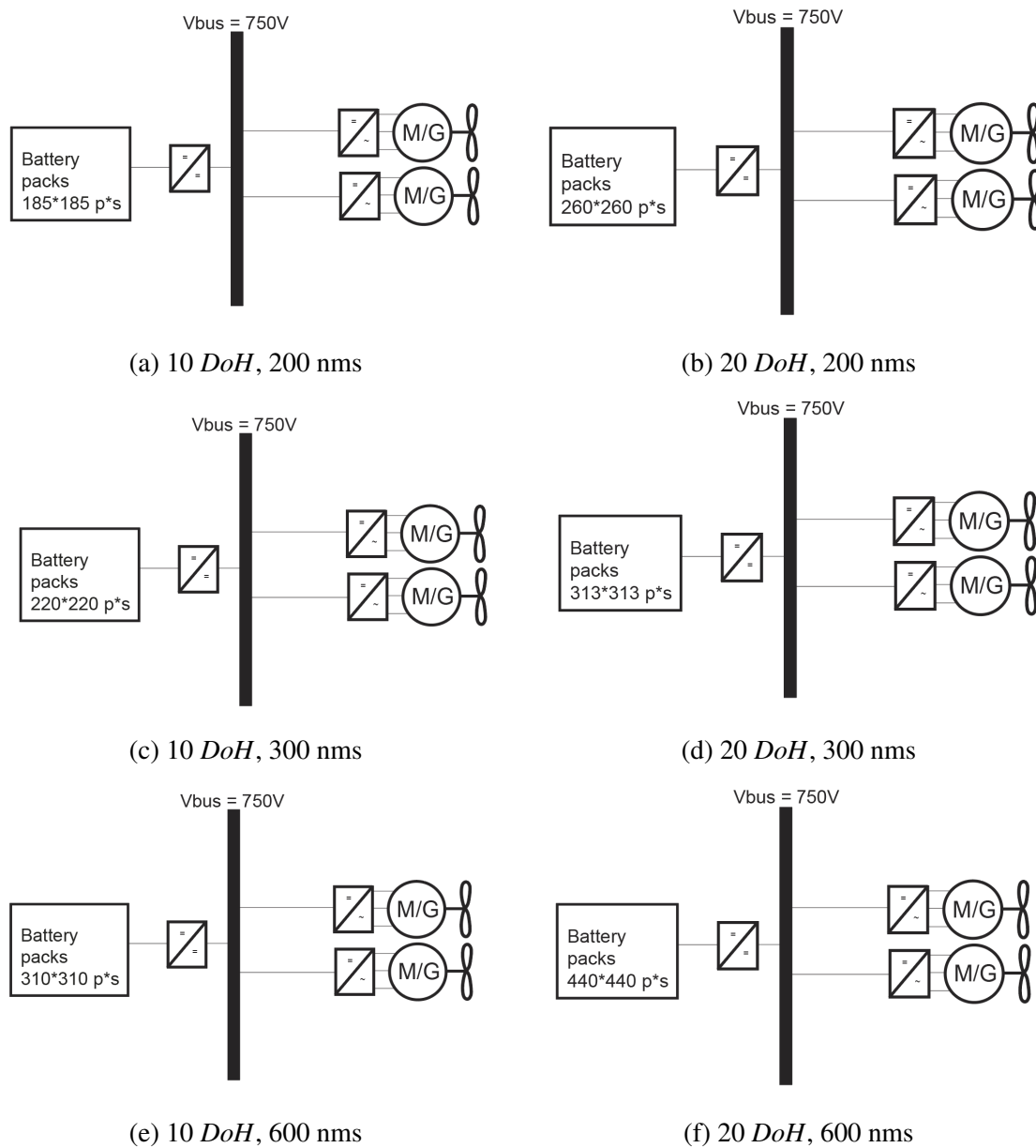


Figure 5.19: Hybrid battery architecture size for different hybridisation levels and mission lengths.

Table 5.9: Hybrid-battery architecture sizing.

Mission Length	DoH	Total Cell Number	n_p	n_s	Battery Pack Weight
200 nms	10%	34225	185	185	<i>S.E.</i> and total cell number related, from eqn (5.6) and (5.7).
200 nms	20%	67600	260	260	
300 nms	10%	48400	220	220	
300 nms	20%	97969	313	313	
600 nms	10%	96100	310	310	
600 nms	20%	193600	440	440	

Hybrid fuel cell

As fuel cell system size mainly depends on the maximum mission power, the range does not affect the number of fuel cell stacks onboard. For this reason, three and six FC stacks are implemented for 10% and 20% hybridisation level, regardless mission length.

Fig. 5.20 shows their schematic diagrams, and Table 5.10 shows the stack number.

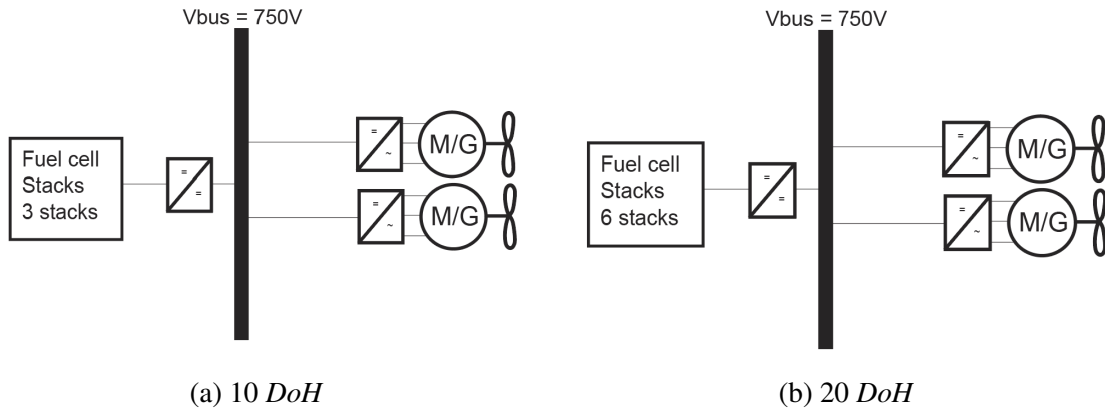


Figure 5.20: Hybrid fuel cell architectures for different energy management strategies.

Table 5.10: Hybrid-fuel cell architecture sizing.

Mission Length	DoH	FC Stack Number	FC System Weight
200 nms	10%	3	FC system weight calculation procedure is illustrated in Section 5.4.3.
200 nms	20%	6	
300 nms	10%	3	
300 nms	20%	6	
600 nms	10%	3	
600 nms	20%	6	

Hybrid battery/fuel cell

Both battery and fuel cell system are equipped in this architecture. The benefit of this combination way is, fuel cell can be sized for lower power rating (cruising). The battery can supplement during high power phases (take-off and climbing). Because these phases often account for shorter period in a mission, so that a smaller battery size is enough. With this design principle, the energy management strategy is that: battery only provides half electric power at take-off and climb phase. Fuel cell system operates at taxiing out, half take-off and climb phase, and all electric power from cruise, descent, approach, and taxiing in. The power split ratio between battery and fuel cell is defined previously (Section 5.2).

This energy management strategy is summarised in Table 5.11. With Fig. 5.21 indicating different flight phase from stage 1 to 7 (complete mission from taxiing out to taxiing in), an example of simulated power decomposition results for 20% hybridisation level, 300 nms mission is illustrated by Fig. 5.22.

Table 5.11: Energy management strategies along different flight phase.

Flight Phase	Φ_{split}	Battery State	FC State	Energy Source
1. Taxiing-out	0	off	on	GT+FC
2. Take-off	0.5	on	on	GT+battery+FC
3. Climb	0.5	on	on	GT+battery+FC
4. Cruise	0	off	on	GT+FC
5. Descent	0	off	on	GT+FC
6. Approach/Landing	0	off	on	GT+FC
7. Taxiing-in	0	off	on	GT+FC

* Φ_{split} : quantity to measure power split between battery and fuel cell, GT: gas turbine, FC: fuel cell.

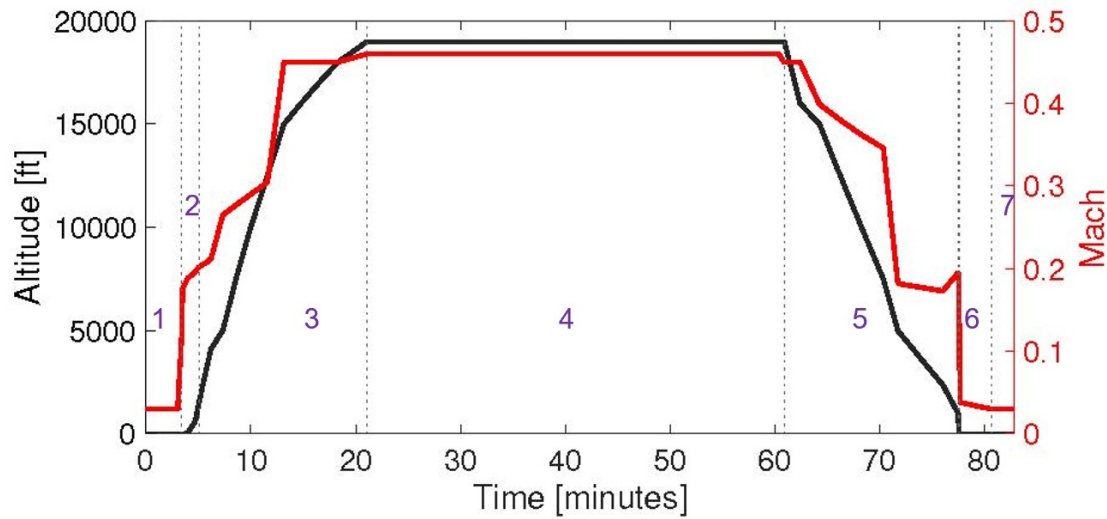
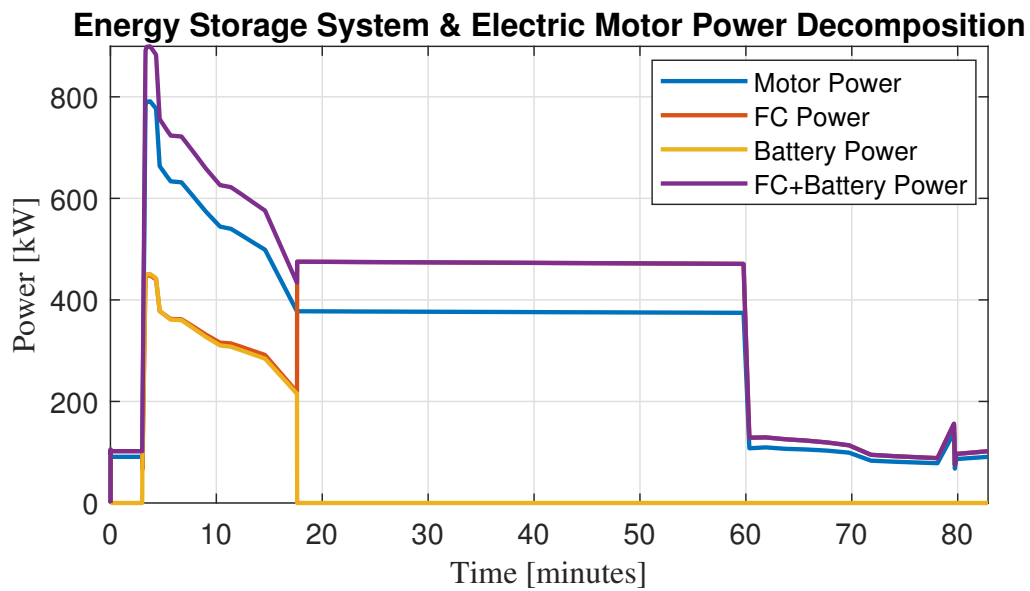


Figure 5.21: Numbers indicating flight phases.

Figure 5.22: Electric power decomposition for 20% *DoH* and 300 nms.

There are six different categories of sizing of the system, with lithium cell number and fuel cell stack number, listed in Table 5.12. The system weight calculation method is illustrated in Section 5.4.3. And their schematic diagrams are shown in Fig. 5.23.

Table 5.12: Hybrid-battery/fuel cell architecture sizing.

Mission Length	DoH	Total Cell Number	n_p	n_s	FC Stack Number
200 nms	10%	6889	83	83	2
200 nms	20%	18496	136	136	3
300 nms	10%	6889	83	83	2
300 nms	20%	18496	136	136	3
600 nms	10%	6889	83	83	2
600 nms	20%	18496	136	136	3

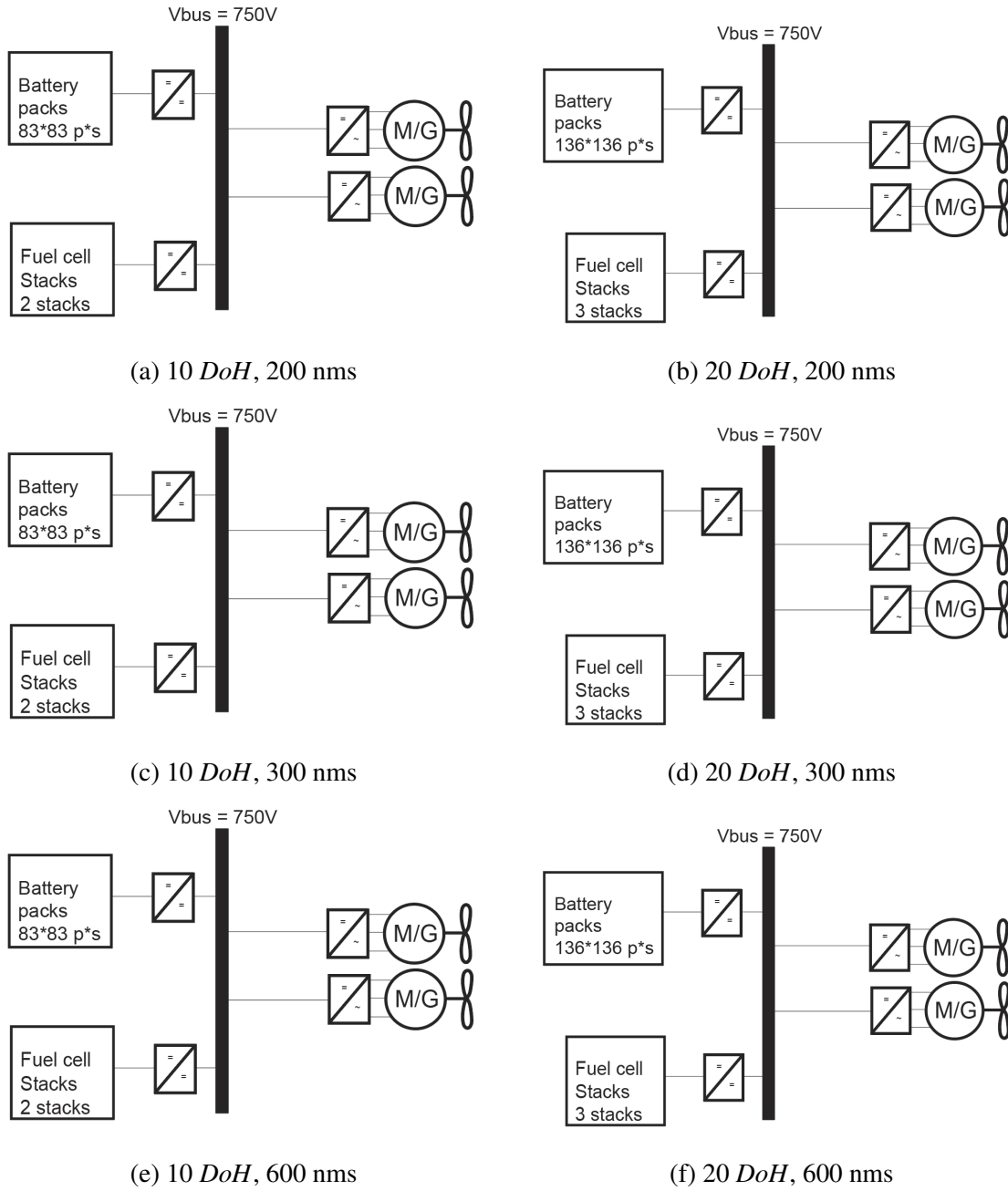


Figure 5.23: Hybrid battery/fuel cell architectures for different EMS and mission lengths.

System weight analysis and comparison for three architectures

Finally, using the above sizing outcomes, a preliminary weight analysis can be conducted. The weights of these three architectures, for 200-, 300- and 600 nms at 10% and 20% hybridisation levels are calculated based on methodologies previously introduced. The results are shown in Fig. 5.24, with star marks indicating the weights and solid lines provide linear weight extrapolations for different mission lengths.

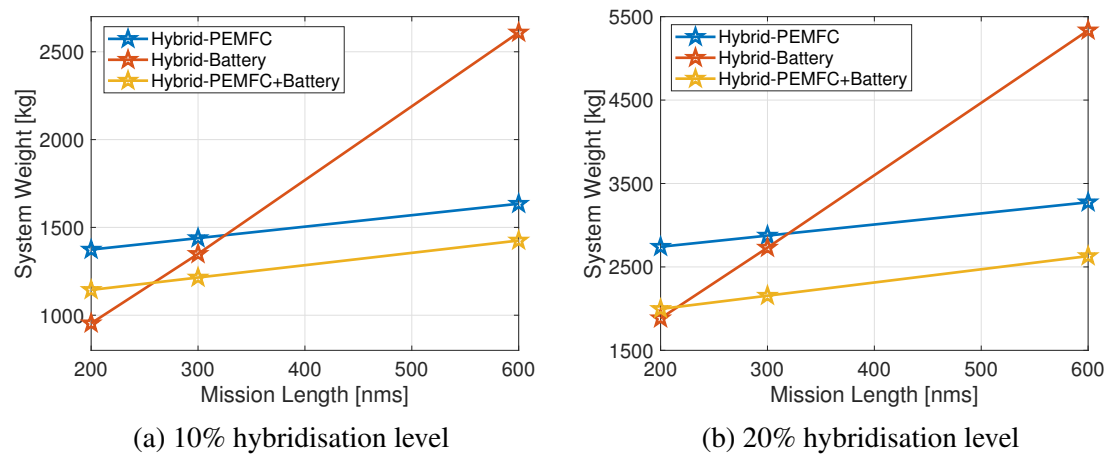


Figure 5.24: Weight comparison between hybrid-battery, hybrid-fuel cell and hybrid-battery/fuel cell architectures for 200-, 300- and 600 nms with (a) 10% *DoH* and (b) 20% *DoH* energy management strategies. The battery specific energy is based on state-of-art and fuel cell is based on off-the-shelf available products.

Under current technology level, hybrid-battery has the lightest weight at 200 nms mission. However, as the mission range increases, the architectures with fuel cell exhibit lower weight. Especially, the hybrid-battery/fuel cell has the lowest mass from 300 nms onwards. This is because: fuel cell weight is only sensitive to power ratings, whereas battery weight is highly dependent on total energy. And fuel cell generally exhibits lower specific power, but its specific energy is high. On the other hand, battery has lower specific energy but high specific power. Therefore, applying ‘battery+FC’ at take-off and climb, and ‘FC only’ strategy for the other phases, both specific power advantages of battery and specific energy strengths of fuel cell system can be exploited. And the FC specific power and battery specific energy disadvantages can be avoided.

5.6 Concluding remarks

In this chapter, three hybrid electric propulsion architectures for the 4 MW regional ATR42 level aircraft are designed and investigated. They are hybrid-battery, hybrid-fuel cell, and hybrid-battery/fuel cell.

Firstly, a real-time flight profile is adopted to for the hybrid-battery and hybrid-fuel cell architectures, each providing a constant 700 kW power to motors. It is found that the weight of hybrid-battery is more sensitive to designated mission length than that of hybrid-fuel cell. Under current technology level, the hybrid-fuel cell has the weight advantage over the hybrid-battery architecture. Pack-level battery specific energy should reach at least 334.4-, 406.2-, and 543.3 Wh/kg to compete against the hybrid-fuel cell for 200-, 300-, and 600 nms. If the water produced by fuel cell is jettisoned, these values are increased to 376.5-, 471.7- and 670.1 Wh/kg. A great battery technology improvement is required as the state-of-art cell specific energy is merely 250 Wh/kg.

Secondly, the battery cycling degradation impacts are studied for a 200 nms, 700kW constant motor power profile. It is found that battery energy is depleted before completing the complete 4090-second mission. For cycling number of 100, 200, 400, and 600, the battery stops working at 3964-, 3855-, 3624-, and 3381 seconds. However, if the battery is over-sized for the cycling impacts, its weight disadvantage becomes more prominent.

Finally, the constant motor power is replaced by 10% and 20% degree of hybridisation EMS, hybrid-battery, hybrid-fuel cell, and hybrid battery/fuel cell architectures are investigated. It is found that, a combination of battery and fuel cell can yield lightest system weight. Battery normally has low specific energy and high specific power, while hydrogen based fuel cell system exhibits low specific power and high specific energy. Therefore, fuel cell is sized for “low-power high-energy” cruising phase and operating at constant low level power throughout the mission. And the battery is utilised to supplement the fuel cell at “low-energy high-power” take-off and climbing phases. This way, their strengths can be used and disadvantages can be avoided.

Chapter 6

Conclusions and Future Work

To conclude, a multi-fidelity, multi-objective performance based simulation framework was developed to model and evaluate the point and holistic mission level propulsion system performance of a 50 PAX, ATR42 like regional aircraft. The system characteristics, component interactions and interdependencies were captured by this framework.

A pure fuel cell architecture ‘PEMFC-EP’ was simulated and evaluated in Chapter 4. Firstly, the effects of air mass flow rate $\dot{m}_{\text{air}}$ and air supply pressure p_{air} on this system efficiency and robustness were quantitatively evaluated. Based on the results, a control strategy over $\dot{m}_{\text{air}}$ and p_{air} was proposed to balance the efficiency and system robustness. Secondly, the imbalance performance amongst fuel cell arrays due to individual stack degradation was quantitatively investigated. A way to mitigate this impact was to carefully select the fuel cell arrays. And this way was demonstrated. Finally, with high fidelity power electronic and motor models, nine possible fuel cell stack configurations were evaluated based on their weights, system performance, and safety redundancies.

Three types of hybrid electric propulsion (‘HEP’) architectures: hybrid battery, hybrid fuel cell and hybrid battery/fuel cell were simulated and evaluated in Chapter 5. Firstly, the effects of four key parameters (mission length, degree of hybridisation, battery cycling number, and S.E.) on hybrid battery system performance and weight were captured and quantitatively analysed. Secondly, a weight comparison between hybrid battery and

hybrid fuel cell architectures was conducted, with the above-mentioned four parameters as variables. Finally, a preliminary energy management strategy was proposed and implemented to the hybrid battery/fuel cell architecture. By appropriately controlling power distribution amongst gas turbine engine, battery, and fuel cell, the system weight can be minimised by adopting hybrid battery/fuel cell as the propulsion architecture.

6.1 Research findings

This study aims to answer the following research questions:

6.1.1 For a typical 50 PAX regional aircraft pure fuel cell propulsion architecture:

- **How to develop a methodology and build a simulation framework to perform sizing, integration, subsystem interdependency and matching investigation, and holistic system performance analysis for regional aircraft pure fuel cell electric system?**

In Chapter 3, the methodology for creating the multi-fidelity/multi-disciplinary simulation framework is presented for PEMFC-EP architecture. As the building blocks of the complete propulsion system, some subsystems are scalable, modular and integrable. The scalability feature allows the matching of component sizing and power rating to the flight mission requirements. The modular characteristics enable some flexibilities in terms of architecture definitions, as they can be used to simulate different propulsion architectures with minor redesigning and adjustment. With different control algorithms applied and proposed, the subsystems can operate at desired states. Moreover, the key electrical inputs/outputs parameters, especially voltage, current and power, are transmitting throughout the whole system. Each component's performance and states are affected by these parameters so that the

subsystem interdependencies are available. The data flows link all subsystems to form the complete simulation framework. Finally, the framework enables mission performance analysis by adopting aircraft-level data such as power profile, altitude variations and ambient conditions.

- **What are the key aspects of the subsystem and system parameters need to be considered?**

Key parameters are identified and summarised in Chapter 3. Clearly, voltage, current and power are the key parameters that bridge different elements in the electric system. And the most significant index to assess component and over system performance is the efficiency. However, these parameters are commonly seen in many top-level studies as well, where the subsystems are treated as zero-ordered black-box. This study fills the research gaps by improving the model fidelity level and increasing its research dimensions: for FC system, its voltage-power, current-power dynamics and efficiencies are simulated, and the effects of power, mission ambient conditions, operation stack temperature, reactants pressure, flow rate, and concentration variations are captured; for converter system modelling, the influence of input/output voltage and power are captured; for motor control system and PMSM, their efficiencies are based on motor torque, rotational speed, bus voltage and current. Only by capturing all these parameters, the component performance simulation can be more realistic and a wider design space exploration are available. Furthermore, the impacts of these important parameters on system design, performance, control, and risk identification can now be studied, as some of them are not fully investigated in previous literature.

- **After identifying these effective key parameters, what fidelity level is suitable to model them?**

Models with different fidelity level are developed to simulate converter, motor control system, and PMSM. Low-fidelity model enables fast simulation when detailed power electronics and motor sizing, operation, and efficiency calculations are not required. Whereas the high-fidelity models provide detailed power electronics and motor sizing results and performance simulation (detailed in Chapter 3). The selection depends on the research aims. For weight comparison hybrid-battery, hybrid-fuel cell, and hybrid-battery/fuel cell in Chapter 5, the low-fidelity level is adequate. While for fuel cell multi-stack design and comparison a more realistic, detailed subsystem level simulation is required. Because the different multi-stack configurations directly decide the capacitive and inductive element design and sizing. The different capacitor and inductor configurations also affect the power electronics performance in return. The intricate difference is only comparable with high-fidelity models. In conclusion, this multi-fidelity simulation framework enables both: rapid system performance assessments and detailed design studies of novel architectures for which little or no historical data exists.

- **Are these subsystem component models validated to acceptable confidence levels?**

In Chapter 3, most of developed components were validated against the experimental data from available literatures. For example, the fuel cell system, the battery system, the IGBTs in switching circuits, the converters and inverters. However, since the high fidelity motor model was adopted from a peer reviewed paper, the validation was not conducted yet. It was still considered these subsystems had high confidence levels. The limitation was the lack of historical or experimental data for the complete propulsion system.

- **Which parameters can cause fuel cell system performance variations (quanti-**

tatively)?

For fuel cell system, the power requirement, stack operation temperature, air/fuel concentration, supply air/fuel mass flow rate, and air/fuel pressure can all affect the system performance. The fuel cell system model can capture these variations quantitatively.

- **For these identified operation variables, is the propulsion system benefited from or detriment to them?**

Chapter 4 (Section 4.5.1), investigates the impacts of supply air mass flow rate and air pressure along the mission. Firstly, it is found the fuel cell system exhibits higher stack/system efficiency at low power requirements. It is beneficial to slightly oversized the fuel cell to achieve higher efficiency. Secondly, the minimum air mass flow rate changes with power requirement. The fuel cell system exhibits highest system efficiency at this flow rate, however the system is highly unstable and risky as a slight air mass supply reduction can cause system malfunction and power shut-down due to “Oxygen Starvation”. This point needs to be avoided. Finally, a reduction in supply air pressure can improve the fuel cell system efficiency. Although the pressure decrease leads to stack efficiency drop, the system efficiency is always increased. Because less compression power is and the stack efficiency decrease is compensated. The propulsion system is hence benefited from lower pressure.

- **By what strategies can these parameters be controlled to avoid the potential risks and improve system performance?**

Three possible types of strategies are proposed and investigated based on the simulation data. One feasible solution is to double the air mass flow rate and maintain the stack pressure to a relatively low value (1.6 bar). This way, a high system effi-

ciency and stable strategy is obtained. The risk of power loss can be avoided. For the first time in the literature, the air mass flow rate and pressure variation impacts on FC performance, the potential risks identification, and the corresponding control strategies over them were shown in this work.

- **What is the impact of fuel cell stack degradation on the system? Can the fuel cell stack configuration help to reduce the impact of voltage and current imbalance performance due to stack degradation?**

In Chapter 4 (Section 4.6), a fuel cell stack with 10% voltage and current degradation is equipped to ‘Parallel-Series’ and ‘Series-Parallel’ configurations. The effect of imbalance performance brought by this single stack is examined. It is found that, this degraded fuel cell loses power during some flight phases in ‘Parallel-Series’ configuration. Because the maximum voltage of the degraded stack is lower than the voltage requirement in the parallel-connection branch. The consequence will cause other healthy stacks overwork and hence efficiency reductions. Most importantly, there is a potential difference between the healthy and degraded stack in one parallel branch. This would cause high current flow between stacks, which will potentially damage the stacks. Therefore, the ‘Series-Parallel’ configuration is recommended in this case. For the first time in literature, the stack imbalance performance impacts on the aircraft propulsion system were investigated in this work.

- **What are the potential fuel cell multi-stack configurations and their corresponding advantages and disadvantages for a regional aircraft propulsion system? How are these different configurations affecting the design for DC/DC converter?**

In Chapter 4 (Section 4.7), nine possible multi-stack configurations are investigated

qualitatively and quantitatively. The assessments are based on their fuel cell stack and system efficiencies, electrical component efficiencies as well as overall system efficiencies, power losses due to component failures, voltage and current performance, converter design challenges, and system weights. Also, the converter is sized for each configuration. It is found that, the multi-stack configuration highly influences the capacitor/inductor topologies of their DC/DC converter and the overall system efficiencies. Throughout simulation, failure analysis, and weight comparison, configuration (h) and (i) are considered two most suitable for the propulsion system. For the first time in literature, the integrated high-fidelity models for aircraft mission-level analysis, the assessments on proposed novel fuel cell configurations, and the in-depth discussions on converter design challenges were shown in this work.

6.1.2 For a typical 50 PAX regional aircraft hybrid electric propulsion architecture:

- **How to develop a methodology and build a simulation framework to perform sizing, integration, subsystem interdependency and matching investigation, and holistic system performance analysis for regional aircraft hybrid electric system?**

The methodology is similar to that of PEMFC-EP architecture, three architectures: hybrid-battery, hybrid-fuel cell, and hybrid-battery/fuel cell are built under this simulation framework. Only by adding a battery module in this case. Moreover, a sizing methodology for battery pack and fuel cell system is developed in Chapter 5. The cell specific energy is treated as a variable for battery, whereas the state-of-art technology level is considered for fuel cell system.

- **How to simulate and validate the battery system from cell to pack level and**

enable them to capture all necessary parameters?

As part of the developed simulation framework, a performance model of battery from cell level is developed in Chapter 3 (Section 3.5.3). The cell-level module is based on equivalent circuit model, where the circuit components and cell voltage are functions of a series of parameters: state-of-charge (*SOC*), temperature, cycling numbers and storage time. These parameters enable the transient performance simulation of the cell under various operation conditions and *SOC*, and the results are validated against experiment data. And cell-level models are integrated to pack level by Kirchhoff's law, with automatic algorithms for pack sizing. Because of these simulation capabilities, hitherto existing research gaps are filled by facilitating the battery model to different propulsion architectures.

- **What are the impacts of mission characteristics, such as power profile, mission length, and hybridisation level on the system weight and sizing?**

In Chapter 5, the mission characteristics impacts on the weight of three architectures are evaluated quantitatively. Various groups of mission profiles with different power, range, and hybridisation levels are used for comparison. It is found that even though the sizing and weights of all architectures increase with mission length, the hybrid-battery is more sensitive to this factor while architectures with fuel cells are less affected. This is because battery has lower specific energy than hydrogen fuel. Therefore, the weight disadvantage of hybrid-battery is more prominent for longer mission. The hybridisation level also affects the sizing, with higher DoH, the system becomes heavier.

- **How does battery degradation affect the system performance, sizing and aircraft mission range?**

Battery storage capacity is prone to cycling degradation. In Chapter 5 (Section 5.4.3), the battery cycling degradation impact is studied quantitatively with the developed methodology in Chapter 3. Since the available battery energy decreases along with usage cycles. For example, for a 200 nms mission, the maximum battery operation time decreases to 3964-, 3855-, 3624-, and 3381 seconds from the required 4090-seconds after 100-, 200-, 400-, and 600 cycles. The battery cannot operate for the complete mission without reducing its power output. To satisfy the power requirements, it is necessary to oversize the battery pack from the beginning. However this measure would increase the system weight, it is predicted that a 2.6%, 5.8%, 12.1% and 19.2% more weight is required to oversize the battery pack for 100-, 200-, 400- and 600 cycles.

- **How to compare hybrid-battery and hybrid-fuel cell architectures in terms of sizing consideration?**

In Chapter 5, a comprehensive comparison between hybrid-battery and hybrid-fuel cell is made with methodologies detailed in Chapter 3 and 5. From the results, the hybrid-battery is at a distinct disadvantage in terms of weight, and this weakness is more prominent with longer mission range and higher usage cycle. The lithium cell specific energy is the main limitation for the battery system. For example, at least 335-, 407-, and 544 Wh/kg of cell specific energy needs to be achieved for hybrid-battery comparable against hybrid-fuel cell for 200-, 300-, and 600-nms mission under on-design operations. When cycle impacts are considered, the target specific energy is even higher. Taking a 200 nms mission, 343-, 353-, 375-, and 400 Wh/kg are required for 100-, 200-, 400-, and 600 cycles. Given that the state-of-art value is 250 Wh/kg, battery is still facing the implementation challenges discussed earlier. One possible solution is to combine fuel cell and battery in the electric storage system.

- **Which architecture yields lighter potential system weight, hybrid-battery, hybrid-fuel cell, or hybrid-battery/fuel cell?**

In Chapter 5 (Section 5.5) it is found that: under state-of-art technology, hybrid-battery exhibits lowest weight for short mission range and low hybridisation level (10 *DoH*). But as the range increases, hybrid-battery/fuel cell architecture gradually demonstrates weight advantages over the others. For higher hybridisation level (20 *DoH*) the similar trend occurs, however, the weight advantage of hybrid-battery over hybrid-battery/fuel cell is diminished. According to the tendency, the hybrid-battery/fuel cell will become the lightest architecture for higher hybridisation level. Therefore it can be concluded that, combining batteries and fuel cells within the architecture would potentially yield the lightest system weight.

- **Can hybrid-battery/fuel cell allow more intelligent energy management strategy so that the system weight can be minimised amongst the three competing architectures?**

The conventional hybrid electric architecture can only change hybridisation level throughout the mission. And this value mainly determines the system weight. However, with hybrid-battery/fuel cell, more energy management strategies (EMS) can be explored as the power split between battery and fuel cell is available. The architecture sizing highly depends on power profile characteristics and EMS, with the additional degree of freedom, the system can be designed and sized in a more intelligent way. Moreover, battery has high specific power and low specific energy whereas fuel cell has low specific power and high specific energy. Therefore the system is designed such that, fuel cell continuously operates at low power level over the mission, and battery supplements it during high power phases (take-off and climbing). This way, the strength of battery and fuel cell can be exploited and shortages can be avoided. In comparison to the other two architectures, the system sizing

is normally based on the short-period maximum take-off power for hybrid-fuel cell and the rest phases are oversized; whereas for hybrid-battery, the long distance always causes the system extremely heavy. By properly allocating the battery and fuel cell power, the fuel cell oversize (overweight) problem can be avoided; and a much lighter battery is adequate as a supplementary power for a short operation time. This way, hybrid-battery/fuel cell not only yields lighter weight than others, it also provides a platform for EMS exploration with an extra degree of freedom.

6.2 Research findings and contribution to knowledge

One major contribution of this work is the developed simulation framework. It helps broadening the modelling capabilities for studying the EP and HEP novel concepts. According to the author's understanding, some specialised models were not seen before in electric aircraft study, such as high fidelity converter module built from IGBTs and LC components, and high fidelity inverter and motor drive system.

With this simulation framework, original understanding and knowledge in the area of regional aircraft electrification. Novel contributions of this study are summarised:

- It was found that, for fuel cell based propulsion system (PEMFC-EP), ‘oxygen starvation’ happened if supplied $\dot{m}_{\text{air}}$ was lower than certain values. ‘Oxygen starvation’ should be strictly avoided. It was found that the minimum $\dot{m}_{\text{air}}$ value that triggered ‘oxygen starvation’ changed along the mission. A 300 nms holistic mission was demonstrated and the minimum $\dot{m}_{\text{air}}$ values for taxiing, take-off, climbing, cruising, descent, and landing were obtained. It was found that operating the FC stacks around these minimum $\dot{m}_{\text{air}}$ values could improve the system efficiency but at the expense of system robustness. The system efficiency could be improved by varying supplied p_{air} . A control strategy over air mass flow rate and pressure was derived to avoid the ‘oxygen starvation’ risk and keep the system efficient. In this novel contribution, the problem associated with FC ‘oxygen starvation’ was firstly

analysed for regional electrified aircraft. The analysis methodology and results can guide the design of control strategy for FC air breathing systems before they are implemented to propulsion system.

- The degradation of fuel cell and the consequent inter stack imbalance performance were investigated for the PEMFC-EP architecture. Two FC stack configurations, ‘Parallel-Series’ and ‘Series-Parallel’ were proposed. A 10% voltage and current degradation was applied to one stack. The influence due to this single degraded stack to the whole FC array was captured. It was found that the single degraded stack of ‘Parallel-Series’ configuration output no power for some flight periods and large current could flow into it. This means the system could lose 1/16 of its power, and a potential damage could be caused. Whereas ‘Series-Parallel’ configuration did not exhibit this hazard. The design of multi-stack configuration can mitigate inter-stack imbalance performance due to degradation.
- The novel high fidelity power electronics and motor models were firstly utilised in this study. With them, different FC configurations were analysed in terms of weight, system efficiency, and safety redundancies. In Section 4.7.6 and 4.7.7, it was found that configurations (h) and (i) were suitable for the PEMFC-EP architecture of 50 PAX regional aircraft.
- For a hybrid electric system providing 700 kW motor power, hybrid fuel cell had weight advantages over hybrid battery architecture. Battery pack level S.E. should be at least 335, 407, and 544 Wh/kg to compete against the hybrid fuel cell for 200, 300, and 600 nms mission.
- Battery was prone to cycling degradation, and the influence on propulsion system sizing was analysed. It was found that the degraded battery depleted its energy before finishing the complete flight mission. A solution was to oversize the battery system, but this resulted in a much heavier load for regional aircraft to carry.

- For 10% and 20% *DoH* hybrid propulsion systems, hybrid battery/fuel cell architecture had potential weight advantages. A preliminary energy management strategy between battery and fuel cell was proposed. It was recommended to size fuel cell for “low-power high-energy” phases, and battery for “low-energy high-power” phases. This way, the strengths of two system could be used and their disadvantages could be avoided.

In conclusion, the success of this research will bring benefits to aviation electrification by providing a novel simulation framework, resulting in wider system performance exploration and reduction in hybrid electric aircraft development cost.

6.3 Recommendations for future work

The thesis focuses on the design and performance evaluation of the electrical system, the other modules are not fully considered within the scope. Some specific avenues for future research are identified:

1. The current investigation assumed retrofit aircraft model, where the same maximum take-off weight (MTOW) and fuselage volume is maintained as aircraft aerodynamics is not re-designed. This is not necessarily the optimal aircraft model choice. For the PEMFC-EP, the propulsion system weight is heavier than that of gas turbine, a re-design of wing shape is required for higher lift coefficient. Moreover, equipped with eight motors distribution propulsion, the improved synergies between airframe and propulsion system can be achievable. The aircraft-level variation would affect the electrical system design and performance, and in return the updated electrical system would influence the airframe design. This integral aircraft/propulsion/aerodynamic design can be further investigated to obtain the optimal design using iteration process.
2. For hybrid system, the gas turbine can be further down-sized as they provide less power. The down-sized impact on its efficiency, carbon and NO_x emission, and fuel

consumption can be further investigated. Also, an emission model to estimate water production and contrail formation from gas turbine and fuel cell system needs to be proposed since contrail is a major contributor to green house gas.

3. For architectures with fuel cell system, high fidelity hydrogen storage system model is required. With it, weight estimation and trade-off studies can be conducted, which also enhance the capability of the framework to conduct more accurate sizing studies and hydrogen tank design space explorations.
4. The current methodology does not include the power cables or subsystem physical placement in the aircraft. The high voltage and current brings challenges for cable designing. Moreover, the physical distribution and connection of different component would in return influence the cable design and system sizing. The future step is to create a logic step for electric cabling and subsystem physical placement study.
5. The current study only considers radial flux PMSM. The simulation framework needs to include the flexibility of integrating different motor configurations, such as radial flux motors with integrated inverter and gearbox, as well as high torque and low speed axial flux PMSM. Also, the scalability of motors to achieve Mega Watt power ratings should be considered.
6. Thermal management system is not considered in the scope of this paper. However, one of the major concerns regarding the EP and HEP is the cooling. Temperature feedback models should be included for subsystems to capture the performance changes associated with changing temperature during operation. Moreover, detailed thermal models are required for thermal management strategy evaluation and design. They have significant impacts on the system and aircraft design.
7. The study in Chapter 4 Section 4.5.2 can be refined by simulating more points from the flight profile. Due to time limitation only single point was picked from each phase. The control strategy for air mass flow rate and pressure is therefore not

accurate enough. Future step is to simulate more points for different flight phases. And the process is repeatable for different flight missions.

8. The study in Chapter 4 Section 4.6.1 only considers a single stack with 10% voltage and current degradation. However, different degradation levels or degraded stack number are not studied. The next step is to propose a more comprehensive investigation on this phenomenon considering different degradation levels, degraded stack number and architectural impacts, as the impact is significant for any propulsion system with fuel cells.
9. An optimiser to perform multi-objective and trade-off studies should be included in the framework. The framework is only performance based, but there are still many areas the system can be optimised. For example, the system power and weight could be optimised for a fixed architecture; the flight time and energy on-board for a constant mission range.

The above avenues for future research can further extend the capabilities of the simulation framework and CHARM. However, the integrated methodology, research cases, and results in the current form are sufficient to address the research questions and meet the stated research objectives.

Appendix A

SVPWM Technique

A.1 Introduction

SVPWM, known as Space Vector Pulse Width Modulation, is a digital modulation technique with the objective to generate PWM load line voltages that are in average equal to a reference load line voltage. This is achieved by properly controlling the inverter switching states and the calculation of the appropriate time period for each state in each sampling period [143]. This advanced technique can generate less harmonic distortion in the output current and voltages in motor windings and provides a higher efficiency use of the DC voltage in comparison to SPWM (Sinusoidal Modulation Techniques). Along with the developments of DSPs (digital signal processors), SVPWM has become one of best techniques for variable frequency drive system despite its intensive computation characteristics [173].

A.2 SVPWM principles

A.2.1 Space vector

In order to illustrate the principles of SVPWM, a discussion on the switch operation of the three-phase inverter is shown by Fig. A.1a.

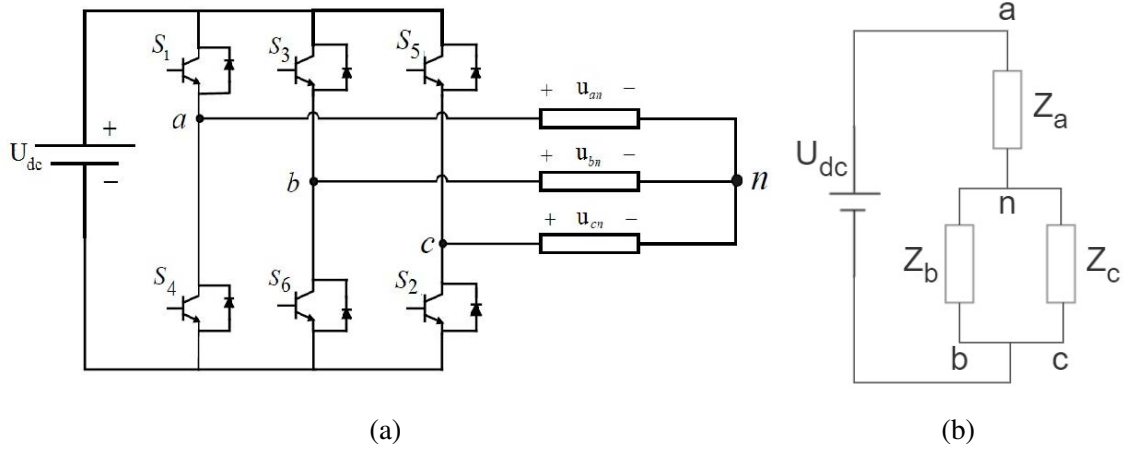


Figure A.1: (a) Schematic diagram of a three-phase inverter adopted from [26]. (b) Winding conduction state of (100).

The switches of any legs cannot be switched on at the same time due short circuit consequence. Therefore, a switching function s_x ($x=a,b,c$) can be defined as:

$$s_x = \begin{cases} 1, & \text{if upper switch is on and lower switch is off,} \\ 0, & \text{if upper switch is off and lower switch is on.} \end{cases} \quad (\text{A.1})$$

where $s_a = 1$, $s_b = 0$, and $s_c = 0$ indicating switches S_1 , S_6 , and S_2 are on while S_4 , S_3 , and S_5 are off. A vector (100) can be used to expressed these switching states. There are eight combinations in total. The winding conduction state is illustrated by Fig. A.1b, and the three phase voltages can be expressed as:

$$\begin{cases} V_{an} = \frac{2}{3}U_{dc} \\ V_{bn} = -\frac{1}{3}U_{dc} \\ V_{cn} = -\frac{1}{3}U_{dc} \end{cases} \quad (\text{A.2})$$

and the resultant space voltage vector is expressed as:

$$U = \frac{2}{3}(V_{an} + V_{bn}e^{j2\pi/3} + V_{cn}e^{j4\pi/3}) \quad (\text{A.3})$$

Apart from (100) state, there are seven more states. All of these switching states and

their phase voltages are shown in Table A.1.

Table A.1: Voltage space vectors, switching vectors and phase voltages for eight switching state combinations.

Voltage vectors	Switching vectors			Phase voltages		
	s_a	s_b	s_c	V_{an}	V_{bn}	V_{cn}
$U_0 = 0$	0	0	0	0	0	0
$U_4 = \frac{2}{3}U_{dc}$	1	0	0	$\frac{2}{3}U_{dc}$	$-\frac{1}{3}U_{dc}$	$-\frac{1}{3}U_{dc}$
$U_6 = \frac{2}{3}U_{dc}e^{j\frac{1}{3}\pi}$	1	1	0	$\frac{1}{3}U_{dc}$	$\frac{1}{3}U_{dc}$	$-\frac{2}{3}U_{dc}$
$U_2 = \frac{2}{3}U_{dc}e^{j\frac{2}{3}\pi}$	0	1	0	$-\frac{1}{3}U_{dc}$	$\frac{2}{3}U_{dc}$	$-\frac{1}{3}U_{dc}$
$U_3 = -\frac{2}{3}U_{dc}$	0	1	1	$-\frac{2}{3}U_{dc}$	$\frac{1}{3}U_{dc}$	$\frac{1}{3}U_{dc}$
$U_1 = \frac{2}{3}U_{dc}e^{j\frac{4}{3}\pi}$	0	0	1	$-\frac{1}{3}U_{dc}$	$-\frac{1}{3}U_{dc}$	$\frac{2}{3}U_{dc}$
$U_5 = \frac{2}{3}U_{dc}e^{j\frac{5}{3}\pi}$	1	0	1	$\frac{1}{3}U_{dc}$	$-\frac{2}{3}U_{dc}$	$\frac{1}{3}U_{dc}$
$U_7 = 0$	1	1	1	0	0	0

Therefore, these voltage space vectors can be categorised into two zero vectors (U_0 , U_7) and six non-zero vectors (U_1 , U_2 , U_3 , U_4 , U_5 , U_6) with modulus length of $\frac{2}{3}U_{dc}$. These eight basic vectors can be mapped to a complex plane as shown in Fig. A.2, and the six non-zero vectors can form a hexagon in this plane. The plane is further divided into six sectors.

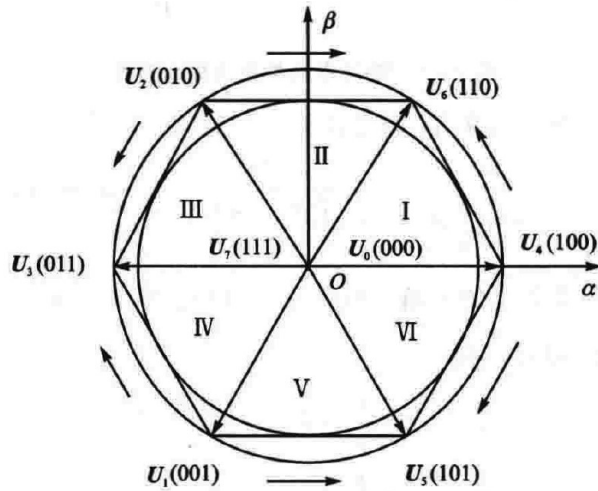


Figure A.2: Voltage space vector hexagon adopted from [27].

A.2.2 Forming a circular rotating voltage vector

Now, in order to make the rotor rotate a rotating magnetic flux needs to be generated by the stators. This is achieved by generating a circular rotating voltage vector. Theoretically, three sinusoidal voltage waves with $\frac{2\pi}{3}$ rads phase differences to each other can be superimposed to form such rotating voltage vector, but only six inverter switches can be controlled. Therefore, the principle is to control them to form equivalent PWM-type voltages to reproduce this rotating resultant voltage. As shown in Fig. A.2, when the output required voltage U_{out} reaches any sectors its value can be obtained by the actuation time of two consecutive non-zero voltage vectors and the two zero vectors. For example at sector I the spatial vector resultant diagram is illustrated in Fig. A.3.

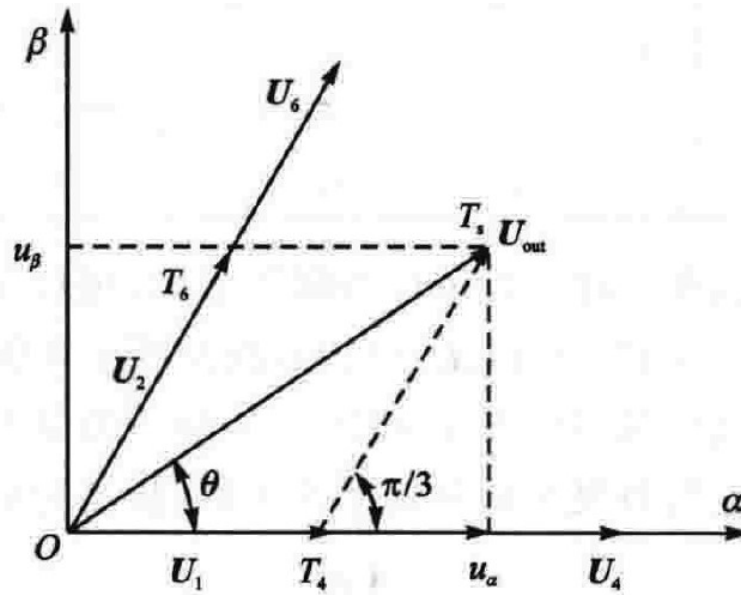


Figure A.3: Voltage space vector hexagon adopted from [27].

According to the volt-second balance principle:

$$T_s U_{out} = T_4 U_4 + T_6 U_6 + T_0 U_0 \text{ (or } T_7 U_7 \text{)}$$

$$T_s = T_4 + T_6 + T_0$$

$$U_1 = \frac{T_4}{T_s} U_4$$

$$U_2 = \frac{T_6}{T_s} U_6$$

(A.4)

where T_s is the switching period, T_4 , T_6 , and T_0 are the actuation time of U_4 , U_6 , and U_0 (or U_7). According to the trigonometry relation of Fig. A.3:

$$\frac{|U_{out}|}{\sin(2\pi/3)} = \frac{|U_1|}{\sin(\pi/3 - \theta)} = \frac{|U_2|}{\sin(\theta)} \quad (A.5)$$

From Table A.1, $|U_4| = |U_6| = \frac{2}{3}U_{dc}$, and suppose the modulus length of reference output voltage is $|U_{out}| = U_m$, the following relations can be obtained:

$$\begin{cases} T_4 = \sqrt{3} \frac{U_m}{U_{dc}} T_s \sin(\pi/3 - \theta) \\ T_6 = \sqrt{3} \frac{U_m}{U_{dc}} T_s \sin(\theta) \\ T_0 = T_7 = \frac{1}{2}(T_s - T_4 - T_6) \end{cases} \quad (A.6)$$

The modulation index can be defined as $m = \sqrt{3} \frac{U_m}{U_{dc}}$. Since U_m must be less or equal to $\frac{2}{3}U_{dc}$, the maximum modulation index can reach around 1.1547. From this derivation, it can be seen that the maximum modulation index of SVPWM is 15% higher than that of SPWM, which consolidates that SVPWM has higher DC voltage usage efficiency. This is a main advantage of it.

A.2.3 Space Vector PWM switching patterns

The actuation time of U_4 , U_6 , and U_0 are calculated to achieve the desired U_{out} . The following step is to physically realise the desired voltage with proper switching sequences. The objective of designed switching pattern is to minimise the switching losses and harmonic components. This is realised by: altering the switch state of only one phase when changing the voltage vector, and allocating the actuation time of zero and non-zero voltage vectors so that the PWM waveform is symmetrical. For example, in sector I the voltage vector activation sequence can be: $U_0 \rightarrow U_4 \rightarrow U_6 \rightarrow U_7 \rightarrow U_7 \rightarrow U_6 \rightarrow U_4 \rightarrow U_0$. This way only one phase switch state is changed at each sequence. For instance, from U_0 to U_4 , the switch vector changes from (000) to (100) so that only phase A changes its state. The sequences for other sectors are shown in Table A.2.

Table A.2: The position of U_{out} and its corresponding three-phase waveforms.

U_{out} Position	Switching sequence	Three-phase waveforms
I ($0 \leq \theta \leq \frac{\pi}{3}$)	$0 \rightarrow 4 \rightarrow 6 \rightarrow 7 \rightarrow 7 \rightarrow 6 \rightarrow 4 \rightarrow 0$	
II ($\frac{\pi}{3} \leq \theta \leq \frac{2\pi}{3}$)	$0 \rightarrow 2 \rightarrow 6 \rightarrow 7 \rightarrow 7 \rightarrow 6 \rightarrow 2 \rightarrow 0$	
III ($\frac{2\pi}{3} \leq \theta \leq \pi$)	$0 \rightarrow 2 \rightarrow 3 \rightarrow 7 \rightarrow 7 \rightarrow 3 \rightarrow 2 \rightarrow 0$	
IV ($\pi \leq \theta \leq \frac{4\pi}{3}$)	$0 \rightarrow 1 \rightarrow 3 \rightarrow 7 \rightarrow 7 \rightarrow 3 \rightarrow 1 \rightarrow 0$	
V ($\frac{4\pi}{3} \leq \theta \leq \frac{5\pi}{3}$)	$0 \rightarrow 1 \rightarrow 5 \rightarrow 7 \rightarrow 7 \rightarrow 5 \rightarrow 1 \rightarrow 0$	
VI ($\frac{5\pi}{3} \leq \theta \leq 2\pi$)	$0 \rightarrow 4 \rightarrow 5 \rightarrow 7 \rightarrow 7 \rightarrow 5 \rightarrow 4 \rightarrow 0$	

A.3 SVPWM realisation and Simulink implementation

In order to implement real-time modulation with SVPWM, it is necessary to find the sector in which the reference output voltage U_{out} (or U_{ref}) locates. Then appropriately use the two consecutive non-zero voltage vectors of that sector and the two zero vectors to compose the reference output voltage vector.

A.3.1 Sector locating

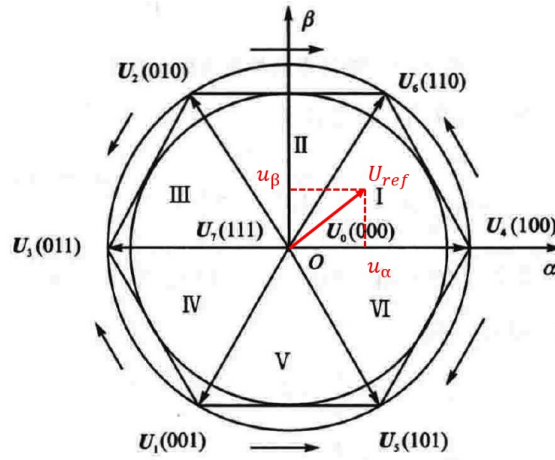


Figure A.4: Voltage space vector hexagon with reference voltage vector.

As shown in Fig. A.4, the reference voltage is represented in the stator reference frame $\alpha - \beta$. Three intermediate variables U_{ref1} , U_{ref2} , and U_{ref3} are defined as:

$$\begin{cases} U_{ref1} = u_\beta \\ U_{ref2} = \frac{\sqrt{3}}{2}u_\alpha - \frac{1}{2}u_\beta \\ U_{ref3} = -\frac{\sqrt{3}}{2}u_\alpha - \frac{1}{2}u_\beta \end{cases} \quad (A.7)$$

Another four intermediate variables A , B , C , and N are defined such that:

- if $U_{ref1} > 0$, $A = 1$, otherwise $A = 0$;
- if $U_{ref2} > 0$, $B = 1$, otherwise $B = 0$;
- if $U_{ref3} > 0$, $C = 1$, otherwise $C = 0$;

Let $N = 4C + 2B + A$, then the relation between variable N and sector number is given by Table A.3.

Table A.3: Relation between N and sector number.

N	3	1	5	4	6	2
Sector	I	II	III	IV	V	VI

The implementation in Matlab/Simulink environment is shown in Fig. A.5

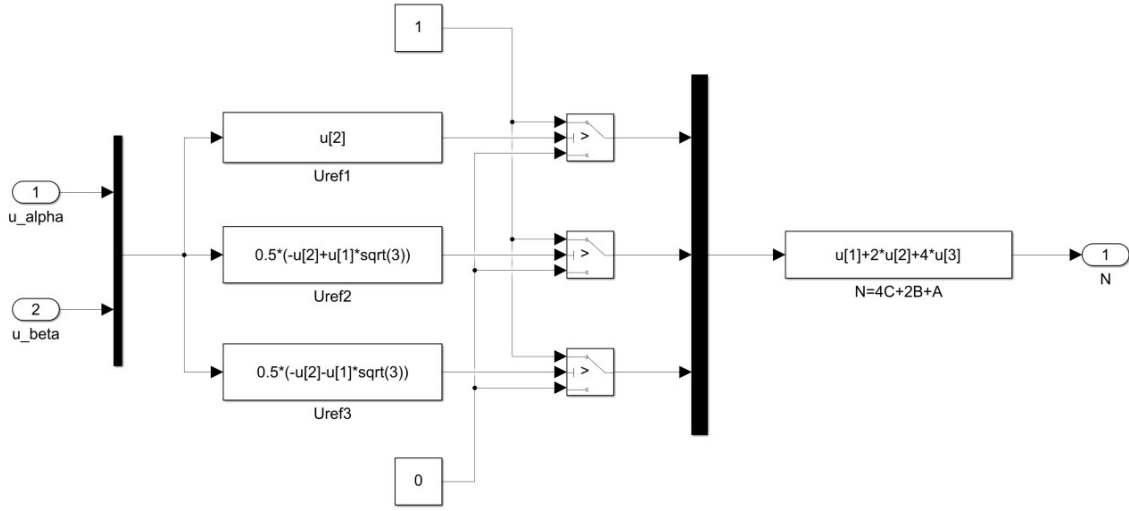


Figure A.5: Sector calculation in Simulink.

A.3.2 Actuation time of zero and non-zero vectors

Referring to Fig. A.3, the sector I volt-second balance in $\alpha - \beta$ plane is:

$$\begin{cases} u_\alpha = \frac{T_4}{T_s}|U_4| + \frac{T_6}{T_s}|U_6|\cos(\frac{\pi}{3}) \\ u_\beta = \frac{T_6}{T_s}|U_6|\sin(\frac{\pi}{3}) \end{cases} \quad (\text{A.8})$$

with $|U_4| = |U_6| = \frac{2}{3}U_{dc}$, the actuation time T_4 and T_6 of non-zero vectors (U_4, U_6) within one switching period are:

$$\begin{cases} T_4 = \frac{\sqrt{3}T_s}{2U_{dc}}(\sqrt{3}u_\alpha - u_\beta) \\ T_6 = \frac{\sqrt{3}T_s}{2U_{dc}}u_\beta \end{cases} \quad (\text{A.9})$$

In order to use the equations similar to sector I for the other sectors, three intermediate variables X , Y , and Z are defined as:

$$\begin{cases} X = \frac{\sqrt{3}T_s}{U_{dc}}u_\beta \\ Y = \frac{\sqrt{3}T_s}{U_{dc}}\left(\frac{\sqrt{3}}{2}u_\alpha + \frac{1}{2}u_\beta\right) \\ Z = \frac{\sqrt{3}T_s}{U_{dc}}\left(-\frac{\sqrt{3}}{2}u_\alpha + \frac{1}{2}u_\beta\right) \end{cases} \quad (\text{A.10})$$

The actuation time for zero- and non-zero voltage vectors of other sectors can be summarised in Table A.4.

Table A.4: Actuation time of zero- and non-zero vectors for each sector.

N	1	2	3	4	5	6
Sector	II	VI	I	IV	III	V
T_{first}	Z	Y	$-Z$	$-X$	X	$-Y$
T_{second}	Y	$-X$	X	Z	$-Y$	$-Z$
$T_0(T_7)$	$T_0(T_7) = (T_s - T_{first} - T_{second})/2$					

T_{first} represents the actuation time of first non-zero voltage vector in counter-clockwise direction and T_{second} is that of the second one. For example referring to Fig. A.4, in sector III, T_{first} is the actuation time of vector U_2 and T_{second} is that of vector U_3 . If $T_{first} + T_{second} > T_s$, over-modulation happens and the resultant voltage will be distorted. In this case, a linear contraction on actuation time is applied to ensure the resultant voltage is within the inscribed circle of the hexagon:

$$\begin{cases} T_{first} = \frac{T_{first}}{T_{first} + T_{second}} T_s \\ T_{second} = \frac{T_{second}}{T_{first} + T_{second}} T_s \end{cases} \quad (\text{A.11})$$

The implementation of these steps are illustrated in Fig. A.6 and Fig. A.7.

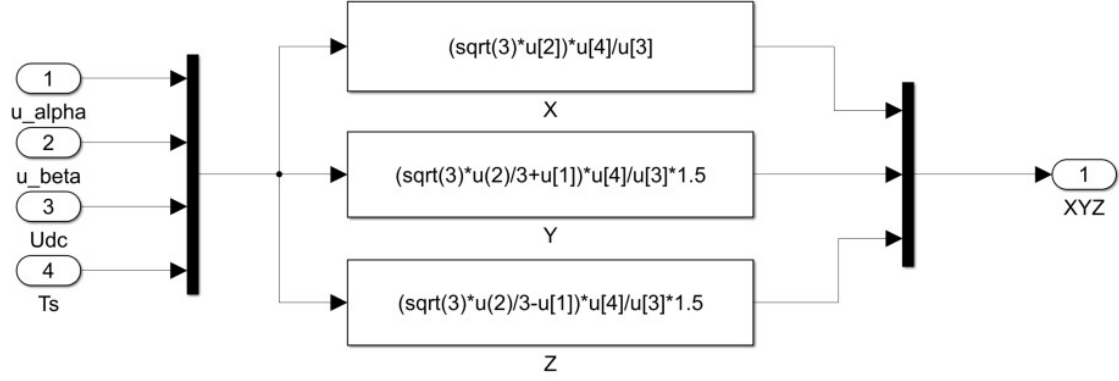


Figure A.6: Obtaining variables X , Y , and Z in Simulink.

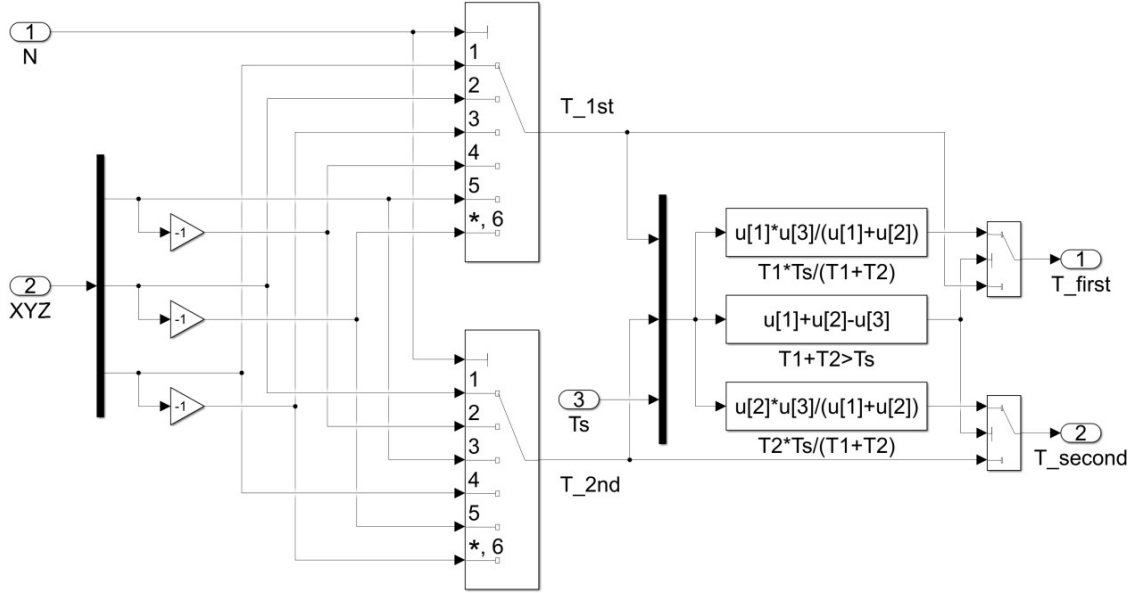


Figure A.7: Calculating the actuation time of non-zero voltage vectors and time contraction for over-modulation in Simulink.

A.3.3 Voltage vector actuation start-time

Now, the actuation time for different vectors is obtained, the next step is to determine at which instants they are actuated. Three intermediate variables t_{aon} , t_{bon} , and t_{con} are

defined as:

$$\begin{cases} t_{\text{aon}} = (T_s - T_{\text{first}} - T_{\text{second}})/4 \\ t_{\text{bon}} = t_{\text{aon}} + T_{\text{first}}/2 \\ t_{\text{con}} = t_{\text{bon}} + T_{\text{second}}/2 \end{cases} \quad (\text{A.12})$$

And the switch state changing instants of three phases for each sector can be illustrated in Table A.5.

Table A.5: Switching state change time for each sector.

N	1	2	3	4	5	6
Sector	II	VI	I	IV	III	V
T_{cm1}	t_{bon}	t_{aon}	t_{aon}	t_{con}	t_{con}	t_{bon}
T_{cm2}	t_{aon}	t_{con}	t_{bon}	t_{bon}	t_{aon}	t_{con}
T_{cm3}	t_{con}	t_{bon}	t_{con}	t_{aon}	t_{bon}	t_{aon}

After calculating T_{cm1} , T_{cm2} , and T_{cm3} for each sector, they are compared with a triangular PWM wave to accurately output the control signals for the inverter. For example in sector I, the three-phase waveforms and its comparison against a triangular carrier wave is illustrated in Fig. A.8.

The triangular carrier wave is set to be a isosceles right triangle, with base length T_s and height $\frac{1}{2}T_s$. At time equals to $\frac{1}{4}T_0$, or more specifically T_{cm1} , the state of phase A needs to be altered from 0 to 1. This is achieved by comparing the value of T_{cm1} against this triangular carrier wave. Once the height of triangular wave is higher than T_{cm1} , the phase A switching state of the inverter is commanded to change from 0 (upper switch off lower switch on) to 1 (upper switch on lower switch off). The same principle applies to phase B and C, and the rest of sectors. For the second half period, the same comparison mechanisms are also achieved, but to obtain a central symmetrical three-phase switching patterns relative to first half. This is how the switching patterns in Table A.2 are physically achieved.

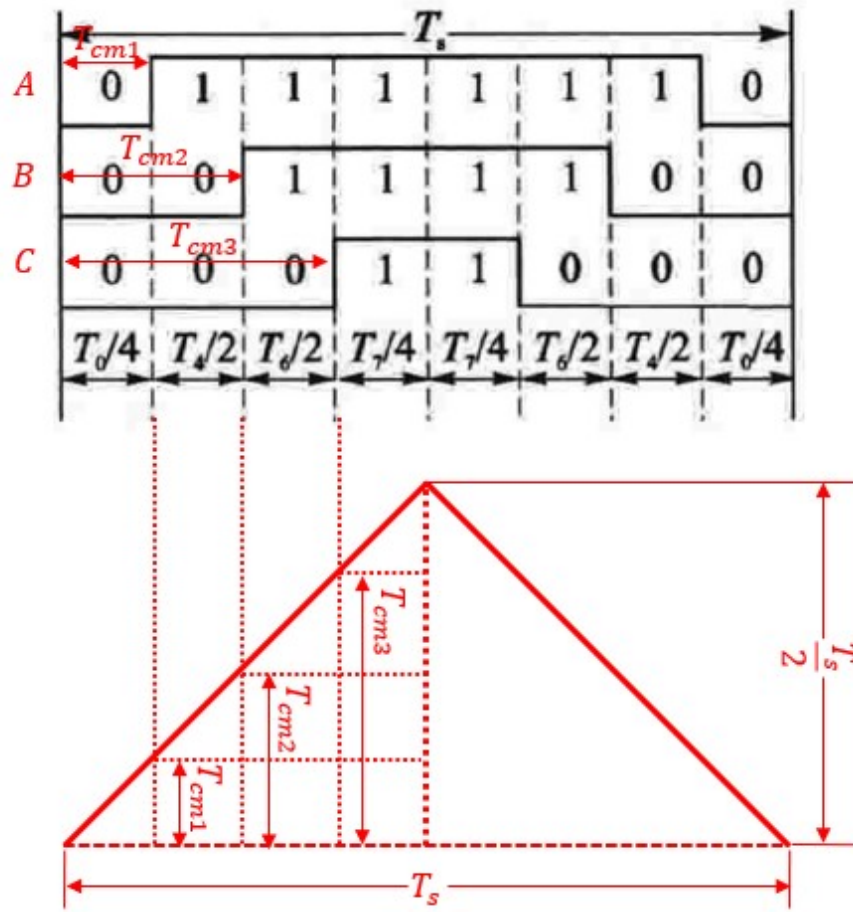


Figure A.8: Comparison the three-phase switching states and isosceles right triangular carrier wave.

The Simulink implementations of this part are illustrated by Fig. A.9, A.10 and A.11. And the complete SVPWM module is shown in Fig. A.12.

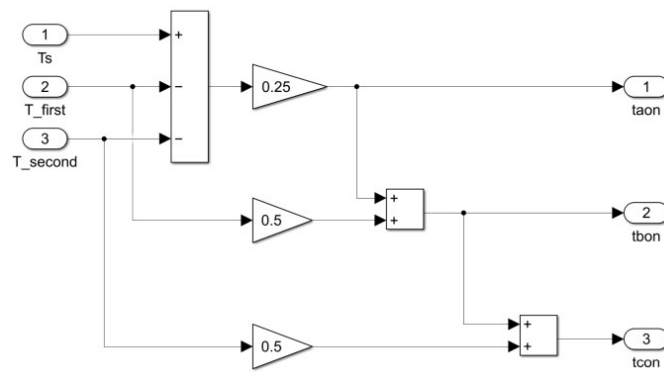


Figure A.9: Calculating t_{aon} , t_{bon} , and t_{con} in Simulink.

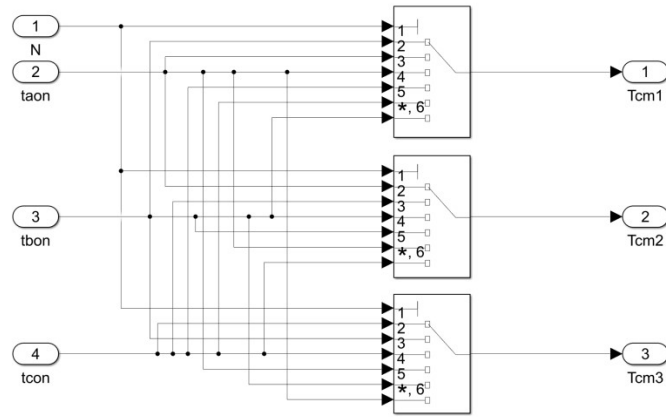
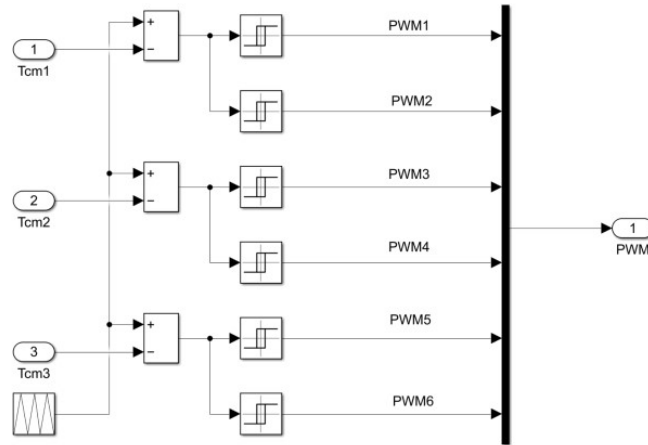
Figure A.10: Calculating T_{cm1} , T_{cm2} , and T_{cm3} in Simulink.

Figure A.11: Obtaining PWM waves for inverter switches in Simulink.

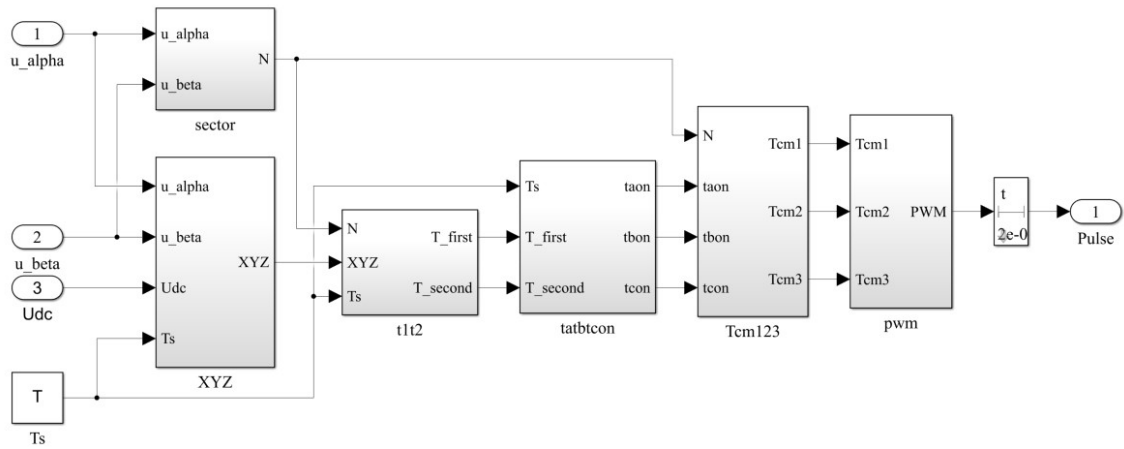


Figure A.12: Complete SVPWM module in Simulink.

Appendix B

Matlab Codes for Performance Maps Generation

B.1 Matlab codes for DC/DC converter map generation

```
%% Configuration a
% 12320V, 300A
% Capacitor 7R3C
% Auxiliary capacitor 2R11C
% Inductor 7R18C

% sweep region
Vo = 2000;
Vi_loop = 8500:200:13000;
Po_loop = 180e3:100e3:2800e3;

%% new IGBT

% define parameters
```

```

eff_loop_sim1 = zeros(length(Vi_loop),length(Po_loop));

% model name
model_name = 'ConverterAuto4';
in= repmat(Simulink.SimulationInput,[1 1]); % automatic
    parallel simulation
in(1) = Simulink.SimulationInput(model_name); % model
    name

% initialization
for i = 1:length(Vi_loop)
    for j = 1:length(Po_loop)
        in(i,j) = Simulink.SimulationInput(
            model_name);
        % setup parameters
        % setVariable('Name','value')
        in(i,j) = in(i,j).setVariable('Vi',
            Vi_loop(i));
        in(i,j) = in(i,j).setVariable('Po',
            Po_loop(j));
    end
end

% run parallel simulations and setup simulation manager
simOut = parsim(in, 'ShowProgress', 'on', '
    ShowSimulationManager','on','
    TransferBaseWorkspaceVariables','on');

```

```

% handling outcomes
for i = 1:length(Vi_loop)
    for j = 1:length(Po_loop)
        eff_loop_sim1(i,j)= mean(simOut(i,j).
            Scope_eta.signals.values(end-10000:end
            ));
    end
end

% save data
save Data.mat

```

B.2 Matlab codes for motor control system map generation

```

%% sweep region
TL_loop = 5:100:4300;
wm_rpm_loop = 100:100:6000;

%% new IGBT

% define parameters
eff_loop_sim1 = zeros(length(TL_loop),length(wm_rpm_loop)
    );
eff_loop_sim2 = zeros(length(TL_loop),length(wm_rpm_loop)
    );

```

```

% model name
model_name = 'Inveter_FEM_auto_v3';
in= repmat(Simulink.SimulationInput,[1 1]); %automatic
    parallel simulation
in(1) = Simulink.SimulationInput(model_name); %model
    name

% initialization
for i = 1:length(TL_loop)
    for j = 1:length(wm_rpm_loop)
        in(i,j) = Simulink.SimulationInput(model_name);
            % setup parameters
            % setVariable('Name','value')
            in(i,j) = in(i,j).setVariable('TL',
                TL_loop(i));
            in(i,j) = in(i,j).setVariable('wm',
                wm_rpm_loop(j));
        end
    end
end

% run parallel simulations and setup simulation manager
simOut = parsim(in, 'ShowProgress', 'on', '
    ShowSimulationManager','on','
    TransferBaseWorkspaceVariables','on');

% handling outcomes
for i = 1:length(TL_loop)

```

```
    for j = 1:length(wm_rpm_loop)
        eff_loop_sim1(i,j)= simOut(i, j).
            Scope_inv_effi.signals.values(end);
        eff_loop_sim2(i,j)= simOut(i, j).
            Scope_motor_effi.signals.values(end);
    end
end

% save data
save Data.mat
```

Appendix C

Electric Aircraft Concepts and Studies Review

Table C.1: Concepts, applications, and key findings of representative **full electric** aircraft.

Concept/Institute	Aircraft types	Specifications	Key findings and achievements
Boeing Aurora Flight [52]	2 PAX eVTOL. Range: 80 km; flight year: 2019.	EM power: 8×75 kW.	The full electric, twin-boom aircraft has eight lift motors, each can angle alternatively outwards and inwards.
Airbus E-Fan [53]	two-seat concept aircraft. Endurance: 60 min; flight year: 2014.	Li-BSE: 207 Wh/kg.	2 EMs, 30 kW each via eight-blade ducted fans, each producing 0.75 kN thrust.
Airbus Vahana [54]	single-seat, tilt-wing eVTOL. Range: 50 km flight year: 2019.	Li-battery energy: 38 kWh; EM power: 8×45 kW.	Full electric vertical flight, with the ability to self-piloting using smart sensors.
Lilium Jet [55]	seven-seat ducted electric vectored thrust (DEV) eVTOL. Range: 250 km; Speed: 280 km/h; Target YEIS: 2024.	Li-BSE: 157 Wh/kg; EM power: 36×9 kW.	Fixed wing, embedded distributed propulsion, and tailless configuration lead to high aerodynamic efficiency. DEVT enables smooth take-off/cruise transition and manoeuvrability.
CleanSky ELICA Naples Univ [56,57]	19 PAX commuter aircraft. Range: 100 to 400 nmi; Target YEIS: 2050.	Li-BSE: 500 Wh/kg; Li-BSP: 1.0 kW/kg; EM SP: 7.7 kW/kg.	For full electric, 16 distributed propellers are required; Wing area is 15% larger and twice as the conventional one for 200 and 400 nmi.
VoltAir [58,59]	68 PAX regional aircraft. Range: up to 900 nmi; Target YEIS: 2050.	Li-air BSE: 1000 Wh/kg; HTS-EM SP: 8 kW/kg; Superconducting cable bus voltage: 1 kV-DC.	Li-air achieves much higher BSE than Li-ion, but reaction products increase weight; Laminar flow and BLI technology, lower slenderness fuselage design improve overall efficiency.
NASA PEGASUS [60]	48 PAX regional aircraft. Range: 200 nmi; Target YEIS: 2030.	Li-BSE: 500 Wh/kg. 1 MW EM SP: 7.3 kW/kg; E-drive/train efficiency: 90%.	Zero NOx and CO ₂ emission released during flight for full electric; 200 nmi flight range is feasible for full electric.

*BSE: battery specific energy, BSP: battery specific power, SP: specific power, EM: electric motor, YEIS: year of entry into service, PAX: passenger, HTS: high temperature superconducting.

Table C.2: Concepts, applications, and key findings of representative **series hybrid electric** aircraft.

Concept/Institute	Aircraft types	Specifications	Key findings and achievements
Siemens/Diamond E-Star [61]	two-seat aircraft; MTOW: 800 kg; flight year: 2011.	Max total power: 70 kW.	30 kW Wankel engine, experimental.
XTI Tri-Fan 600 [62]	Pilot + 6 PAX VTOL. Speed: 300 knots; Range: 600 - 750 nmi; Target YEIS: 2024.		Allows operations from very short runways with front fans in intermediate positions.
Zunum Aero [63]	12-seater regional aircraft. Speed: 340 mph; Range: 700+ nmi; target YEIS: 2020.	Max power: 1 MW variants; Turbogenerator: 500 kW.	Battery mass under 20% of MTOW; emission 0.0 to 0.3 lbs CO ₂ /ASM; Noise 65 EPNdB.
Airbus E-Fan X [64]	100 PAX regional aircraft. Range: 950 nmi; Payload: 7800 kg; Target YEIS: 2030.	EM power: 2 MW; Generator power: 2.5 MW; Wire voltage: 3 kV-DC.	First serial hybrid electric demonstrator aircraft; Gains insights to develop a roadmap on how to progress on decarbonisation targets.
TU-Delft [65]	70 PAX turboprop regional aircraft. Airframe: tube and wing. Target YEIS: 2035.	Distributed propulsion with tip-mounted propellers. BSE: 750 Wh/kg.	28% fuel burn and 14% energy consumption reduction with climb DoH and cruise DoH at 0.58 and 0.22.

*BSE: battery specific energy, EM: electric motor, SP: specific power, PAX: passenger, YEIS: year of entry into service, MTOW: maximum take-off weight.

Table C.3: Concepts, applications, and key findings of representative **parallel hybrid electric** aircraft.

Concept/Institute	Aircraft types	Specifications	Key findings and achievements
NASA PEGASUS [60]	48 PAX regional aircraft. Range: 400 nmi; Target YEIS: 2030.	Li-BSE: 500 Wh/kg; 1 MW Motor SP: 7.3 kW/kg; E-drive/strain efficiency: 90%.	Two methodologies are proposed to analyse PE-GASUS concept; 27% and 39% energy reductions are predicted for two methods; Novel propeller design: parallel hybrid electric at wing tip (decrease down wash), foldable pure electric propeller inboard (decrease windmill effect) and E-propeller at tail.
NASA Langley NASA Glenn [66]	~ 50 PAX regional aircraft. Range: 600 nmi; Target YEIS: 2030.	BSE: 500, 750, 1000 Wh/kg; DoH: 0%, 25%, 50%, 75%.	Twelve different design spaces (DoH and BSE) are studied and compared; BSE should be greater than 500 Wh/kg to save total energy consumption for 600 nmi.
UTRC [67]	30-50 PAX regional aircraft. Range: 250 nmi; YEIS: 2035.	BSE: 355 Wh/kg; EM SP: 13 kW/kg, effi: 97%; motor drive: 20 kW/kg, 98%; Wire voltage: 1000 V.	Using GT only at cruise and parallel motor supplied by battery for boosted take off/climb can reduce fuel burn by 30% and total energy consumption by 25%.
DLR PHA2-TipProp [68]	70 PAX regional turboprop. Range: 800 nmi; Target YEIS: 2035.	BSE: 500 Wh/kg.	4% fuel consumption reduction due to improving aerodynamic efficiency of high-span wing design and wingtip e-drive propellers.
TU-Delft [69]	A320 retrofit. Range: 1000 km; Target YEIS: 2030.	BSE: 600 Wh/kg.	With a take-off and climb DoH of 25% and 14% respectively, the engine can be scaled down to 90%; and 7.5% fuel consumption and 2% block energy consumption can be saved; CO ₂ emission reduces proportionally with fuel savings.

Table C.3: Continued.

Concept/Institute	Aircraft types	Specifications	Key findings and achievements
TU-Delft [65]	70 PAX regional aircraft. Range: 1528 km; Target YEIS: 2035.	Li-air BSE: 1000 Wh/kg; DoH: 34%.	28% fuel consumption reduction with 14% rise in MTOW and wing area.
SAFRAN Conceptual [70]	19 PAX commuter aircraft. tri-prop morphology; Range: 150, 430, 700 nmi; Target YEIS: 2025/2030.	BSE: 500 Wh/kg; Max shaft power: 1.1 MW; powertrain effi: 87%	For BSE above 500 Wh/kg, block fuel savings of 39%, 25% and 10% for 150-nmi, 430-nmi and 700-nmi (maximum range) stage lengths, respectively, could be realised.
Georgia Tech [71]	50 - 210 PAX aircraft. Range: 500 - 1500 nmi; Target YEIS: 2035/2050.	BSE: 250 - 1000 Wh/kg; E-drive effi: 90% - 100%; E-drive SP: 3.30 - 49.3 kW/kg	For 50 PAX regional aircraft, increase in electrical drivetrain SP can compensate for the lower BSE; trade study showing sensitivity with E-drive system efficiency, SP, and in the BSE.
Zhejiang Univ [72]	19 PAX regional aircraft. Range: 500, 1000 km.	BSE: 350, 950 Wh/kg; EM SP: 7.5 kW/kg at 98%; PMAD SP: 20kW/kg at 99%.	For HEP retrofit, max flight ranges reduces at higher DoH for SOA and future battery technology. But proper cruise altitude and speed can increase range to 10% and reduce fuel burn by 2%. For HEP new design, fuel reduced by 50% for 1000km for BSE at 650 Wh/kg.
Siemens Cranfield Univ [73]	50 PAX regional aircraft. Range: 400 + 300 nmi (reserve); Target YEIS: 2035.	BSE: 650 Wh/kg.	Weight impact of e-hybridisation can be balanced out by propulsion system efficiency improvement; energy specific air range increases up to 40% DoH and drops after.

Table C.3: Continued.

Concept/Institute	Aircraft types	Specifications	Key findings and achievements
UIUC [74]	78 PAX ERJ-175 aircraft. Range: 200 - 1500 nmi + reserve.	BSE: 200 - 1500 Wh/kg; motor, converter, and transmission efficiencies: 95%; use MF to define DoH.	BSE at least 700 Wh/kg to reduce CO ₂ emissions; predicted 28% CO ₂ reduction using far-future battery technology (BSE at 1500 Wh/kg) for 0.5 MF.
Bauhaus Luftfahrt [75]	70 PAX, 900 nmi 180 PAX, 1100 - 1700 nmi; Target YEIS: 2035.	70 PAX power: 4.5 MW; 180 PAX power: 8.5 MW.	15% block fuel consumption reduction with BSE 900 - 950 Wh/kg for 70 PAX, tri-fan serial/parallel hybrid; 15% fuel reduction with BSE 1300 Wh/kg for 180 PAX, tri-fan serial/parallel hybrid; No fuel reduction with BSE 1000 Wh/kg for more than 1100 nmi for 180 PAX, quad-fan, discrete parallel hybrid.
Bauhaus Luftfahrt [76]	180 PAX; Range: 900 nmi; Target YEIS: 2035.	BSE: 750 - 1500 Wh/kg.	20% fuel reduction for cruise hybrid electric operation for BSE at 1500 Wh/kg.
Bauhaus Luftfahrt [77]	180 PAX single-aisle; Range: 900 nmi; Target YEIS: 2035.	BSE: 1500 Wh/kg; HTS-EM: 5.1 MW.	16% fuel reduction for 900 nmi using a combination of fuel to electrical energy at 82:18%.

*BSE: battery specific energy, BSP: battery specific power, SP: specific power, EM: electric motor, YEIS: year of entry into service, PAX: passenger, SOA: state-of-art, DoH: degree of hybridisation, PMAD: power management and distribution system, MF: motor factor, MTOW: maximum take-off weight, HTS: high temperature superconducting.

Table C.4: Concepts, applications, and key findings of representative **turboelectric** aircraft.

Concept/Institute	Aircraft types	Specifications	Key findings and achievements
NASA N3-X [78, 79]	300 PAX. hybrid wing-body aircraft. Range: 7500 nmi; Target YEIS: 2040.	Superconducting EM: 16 aft motor-driven fans. 7500V, 50 MW power distribution.	70% fuel reduction in comparison to Boeing 777-200 LR. 50% fuel burn reduction from air- frame improvement and 20% from turboelectric enabled distributed electrical system.
SUGAR Freeze [80]	154 PAX single aisle aircraft. Range: 900 nmi; Target YEIS: 2035.	Solid oxide fuel cell; superconducting EM; cryogenic power system.	56% fuel burn reduction, 70% CO ₂ reduction.
STARC-ABL [81]	154 PAX single aisle aircraft. Range: 900 nmi; Target YEIS: 2035.	Generator: 8 hp/lb and 96%, EM: 8 hp/lb and 96%, EM capacity: 2.6 MW, Inverter: 10 hp/lb and 98%, Power system: 750 - 1000 V.	7% and 12% block fuel burn reduction for the economic and design mission. An approxi- mate 15% improvement in TSFC at the start of cruise condition.
CENTRELINE [82]	300 PAX, A330 twin aisle aircraft Range: 4800 nmi; Target YEIS: 2035.	Generator: 4.6 MW, EM: 8 MW, machine efficiency: 95%.	8% block fuel reduction with turboelectrically driven fuselage aft fans.
ECO-150 [83]	150 PAX single aisle aircraft Range: 1650 nmi; Target YEIS: 2035.	BSE: 400 Wh/kg, EM: 4.5 kW/kg, Generator: 8 kW/kg.	44% and 59% fuel burn reduction with conven- tional and superconducting technology.

*BSE: battery specific energy, EM: electric motor, YEIS: year of entry into service, TSFC: thrust specific fuel consumption.

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