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ELECTRICALLY POWERED LANDING GEAR SYSTEM FOR TRANSPORT AIRCRAFT TAXIING

Ilan Berlowitz
IBAero Engineering, Israel

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Abstract

With the advent of increasing passengers in the recent years, the number of aircraft and flights per day have increased leading to congestions and greater fuel emissions at airports. The aviation industry is looking to reduce the aircraft emissions and noise pollution while performing ground operations such as taxi-in, taxi-out and pushback along with reducing the turn-around time at the airports. The Advisory Council for Aviation Research and innovation in Europe ACARE 2050 has set forth targets for the aircraft entering service in 2050 to reduce ground emissions, reduce noise pollution and save fuel costs. The battery powered taxiing system focuses on these aims and tries to efficiently save fuel and operating costs of the airline to ensure a greener operation while handling ground maneuvers. This work focuses on the preliminary design of a battery powered landing gear taxiing system to analyze the feasibility of implementing such a system into the cargo hold of an Airbus A320 aircraft. A detailed design of the battery pack, the motor and the gear has been discussed along with a brief overview of the battery management system (BMS), cooling system and the cockpit controller for such a system. This work also demonstrates a brief reliability and safety analysis of the system along with the system certification.

Background

The idea of taxi aircraft came from Aerospatiale’s design for “motorized wheels for autonomous taxiing for a 76 tons subsonic aircraft” (Figure 1).

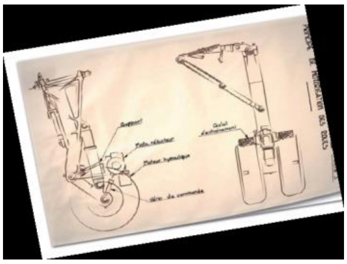

Figure 1: Motorized wheels’ principle designed by Aerospatiale in 1977

Airbus continuously tries to improve its products and environment friendly solutions. Today’s technology is concerned with more electrical equipment power, higher reliability figures and high fuel prices together with a longer taxi time, are making an on-board solution for autonomous taxiing more and more attractive. The e-Taxi system offers:

- Taxi-out and taxi-in with all engines stopped capability,
- A total aircraft autonomy allowing the aircraft to “pushback” without any tractor.

The few important hardware needs to be installed in e-Taxi as it is called an on-board solution. The aircraft would burn the fuel saved on ground, in flight. So, it is intended to propose e-Taxi as an option available for the B737 & A320 Family fleet, only.

Introduction

The global air traffic has increased in the last few years according to the Annual Report of the ICAO Council in 2014. Nearly 3.3 billion passengers have travelled in the airline sector in 2014 which is 5.5 percent higher than in 2013.

As the number of passengers and aircraft increase, there is more congestion at the airports leading to delays. In addition to these, it also raises environmental issues such as emissions from these aircraft that could potentially increase global warming. Although many hybrid-electric aircraft are being considered by major aircraft manufacturers such as Airbus, Boeing and Bombardier, these models are not yet capable of providing a range sufficient enough to carry the required number of passengers to the desired destinations.

Operating cost of the airlines is another major concern due to hike in prices of jet fuel and the fuel usage by the airline account for almost 19.6% of the average operating costs. The ground taxiing is the major phase where the airlines could save fuel, reduce time spend at the airports thus increasing the turn-around-time (TAT), and also decreasing the overall operating costs. The airlines have been constantly improving to reduce the fuel consumption during taxiing and hence come up with various technological solutions to reduce fuel consumption and decrease the gas emissions such as the Electric Green Taxiing System (EGTS), TaxiBot, and WheelTug.

Green taxiing could significantly reduce the environmental impact, ACARE has set forth some rules such that the aircraft movement should be 100 % emission free while taxiing, 75% reduction in CO_2 emissions and a 90% reduction in NO_x emissions.

The main aim of this work is to develop a battery powered electric green taxiing system that would allow the aircraft to pushback and taxi using a battery powered source and not use the jet engines. To perform a reliability study on the use of this system and to ensure its airworthiness while being safe and efficient.

Detailed study about understanding the landing gear and its function along with other methods of electric green taxiing systems is significant. Study of various battery technologies that are available in order to choose the most efficient battery for the system operation are detailed.

In this work, selecting the battery for generating the power required, followed by the motor and gearbox selection are focused. Further the system is then placed into the cargo hold of the aircraft. After placing, the system safety analysis and reliability study has been conducted.

The work consists of the following tasks to be undertaken:

- Study of battery technology,
- Initial basic design of battery - choosing appropriate battery type, its sizing and weight, using calculated power requirements for integration into the aircraft.
- Design of associated components for the effective working of the system and selection of motor for landing gear integration and designing the electrical wiring and connections.
- Integrating the system in the aircraft freight hold.
- Reliability, safety and certification requirements and challenges.

The Airbus A320 NEO aircraft have received many orders for the period from 2017 to 2022, with almost a 100 of them being from EasyJet. EasyJet is the major airline which primarily wanted to focus on the electric green taxiing system and started a project to research on using a hydrogen fuel cell. Airbus also anticipates that it will have a major market share in the near future due to its A320 NEO version.

This work uses the power requirements that has already been calculated by previous researchers to carry on with sizing the chosen battery and integrating it into the aircraft. Since these calculations of the required power are based on an Airbus A320 aircraft, this aircraft has been chosen for this work.

ACARE Vision 2020

The Advisory Council for Aeronautics Research in Europe ACARE aims to create a smooth and efficient air traffic management system that can cope with at least three times the traffic and aircraft movements existing today at the same time ensuring less turnaround time and safety at the airports. The goals are to ensure that 99% of all flights arrive and depart within 15 minutes of the schedule time in all the weather conditions and that aircraft should spent not more than 15 minutes at the airport gate before departure if it is a short-haul flight and 30 minutes if it is a long-haul flight.

Noise pollution is another major issue which needs to be addressed and various measures have been introduced to tackle this issue. The aircraft are to be cleaner and quieter contributing towards a sustainable environment with most of its products made of recyclable materials that have less impact on the environment.

ACARE Flightpath 2050

The pathway to achieve this vision, Flightpath 2050, incorporating objectives provided by the Strategic Research and Innovation Agenda (SRIA) developed and maintained by ACARE. The major goals of Flightpath 2050 are as follows:

- To allow a 75% reduction in CO_2 emissions per passenger kilometer and a 90% reduction in NO_x emissions.
- 65% reduction of the perceived noise emission of flying aircraft near the airports.
- Aircraft movements are to be emission free when taxiing.
- Aircraft are designed and manufactured to be recyclable.

Environmental Impact of Aviation Industry

Every ton of aviation fuel burned produces on an average 3.16 tons of CO_2 which is equivalent to the produce of 7.7 million households in 2012, as the CO_2 emissions are directly proportional to the amount of jet fuel burned by an aircraft.

The experts from various UK airports, airlines and the National Air Traffic Services NATS which is the UK’s air navigation service provider and other organizations developed a “Departures and Ground Operations Code of Practice” which is a code that clearly focuses on few areas that aids to reduce the impact of aircraft departures and operations on the ground to the environment. These advises include using other alternative methods to run the aircraft’s APU (Auxiliary Power Unit) and using other means for taxiing rather than the aircraft engines as much as possible.

Electric Taxiing

Electric taxiing can reduce the fuel consumption while the aircraft is on the ground and hence improve the operational efficiency of the airlines. It can also reduce the pushback and taxi related costs of the airlines at the same time ensuring that carbon emissions to the environment is low and thus providing environmental benefits. The major advantages of electric taxiing are:

- Lower fuel burn,
- Improved on-time performance,
- Greener operation,
- Extends engine life,
- Reduction in noise,
- Enhance safety of ground crew.

TaxiBot

TaxiBot (Taxiing Robot)(Figure 2) is the only operational and certified aircraft taxiing system that is able to take an aircraft to and from the runway when the aircrafts’ main engines have been turned off. This system is currently in use at the Frankfurt airport by Lufthansa Airlines. It consists of two models targeting both the twin-aisle aircraft such as Boeing 747 and Airbus A380 and the single-aisle aircraft such as Airbus A320 and Being 737. The models are known as Wide-Body TaxiBot and Narrow-Body TaxiBot respectively. The main advantages of the TaxiBot are:

- The taxiing operations can be performed with the main engines turned off.
- It eliminates delays at the gate area as the aircraft can be towed away faster.
- Pilot is in control of the aircraft even with the use of the TaxiBot and provides the same handling characteristics with engines.
- The taxiing speed is same as the current taxiing speed of 23 knots.
- It does not shorten the nose landing gear lifetime.
- No modification to the aircraft or its engines.

Figure 2: TaxiBot towing a Lufthansa aircraft

WheelTug

Another electric taxi system which is under development is the WheelTug (Figure 3) by a company known as WheelTug itself which is a subsidiary of Borealis Exploration. TaxiBot is a Ground Support Equipment GSE and WheelTug is an on-board system. WheelTug solution does not require an external tractor or towing vehicle to allow the aircraft to taxi-in and taxi-out of the gate and runway. It also does not require the aircraft engines. WheelTug helps the aircraft to taxi backward and forward using two electric motors that are installed on the wheels of the nose landing gear. These motors are to be powered by the Auxiliary Power Unit (APU) of the aircraft.

Figure 3: WheelTug e-Taxi system

Hydrogen Fuel Cell

EasyJet uses hydrogen fuel cells which is stowed in the aircraft’s cargo hold and this system allows energy to be captured as the aircraft brakes on landing. This energy is used to charge few lightweight batteries when the aircraft is on the ground.

Additionally, the aircraft would have electric motors in the main wheels and there will be various electronic controllers and systems that ensure that the pilot can maneuver and control the speed of the aircraft, direction and braking while it is performing ground operations on the runway.

This system would also eliminate the need to use aircraft tugs to tow the aircraft in and out of the runway as well as the main aircraft engines, thus increasing the turn-around-time and ensuring that flights are on-time.

Electric Green Taxiing System (EGTS)

EGTS (Figure 4) helps to save the fuel while on the ground, leading to reduced costs for the airlines and thus decreased CO_2 emissions. It consists of a motor that is powered by the APU and attached to the wheels of the main landing gear. Each wheel has an electromechanical actuator along with a control unit. It is similar to a hybrid car that uses two power sources to increase the efficiency. The system weighs approximately 300 kg and was to be installed in the aircraft to perform ground operations of pushback and taxi. It can work in all weather conditions and it is an onboard system.

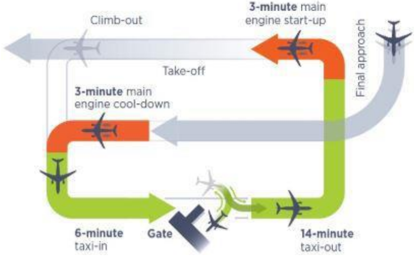

Figure 4: Electric taxiing by Safran

Battery Electric Vehicle

A battery electric vehicle (BEV) is a type of all electric vehicle that uses the chemical energy stored in battery packs that are rechargeable. These types of vehicles make use of electric motors and its associated controllers to move rather than internal combustion engines. The power for their propulsion comes entirely from battery packs and thus do not have any engines or fuel tanks. The electric motor is powered by the electricity stored in the rechargeable battery packs and turns the wheels of the vehicle. Once the battery is depleted, they can be charged again using electricity from another source such as a wall socket or other charging units.

Electric cars are greener and do not cause environmental pollution as they do not produce harmful emissions such as carbon monoxide, oxides of nitrogen, hydrocarbons, soot or aerosols compared to the traditional internal combustion engines.

Electric Vehicle Battery

The Electric Vehicle Battery (EVB) is the battery that is used in the electric vehicles for their propulsion. They are rechargeable batteries that can be recharged when their energy is depleted. They are used in many devices such as forklifts, electric motorcycles, cars, trucks and other electric vehicles. At present, the rechargeable batteries used in electric vehicles typically include lithium-ion batteries, nickel-cadmium batteries, nickel-metal hydride, etc.

Fuel Cell vs. Battery

The hydrogen fuel cells have many disadvantages than the battery usage like high initial cost, high fueling cost. Hydrogen fuel cells lack refueling stations.

Lithium-ion batteries are considered to give more voltage for lesser number of cells compared to others. In the case of a non-rechargeable batteries, the batteries will not produce any current when all the electrodes have migrated to the cathode from the anode. In rechargeable batteries, the redox reaction takes place can be reversed by the process of charging them. This drives all the electrons back to the anode allowing the battery to be charged to be used again. When the cycles designed for it to be recharged is over, the battery must eventually be replaced.

Batteries for Aviation

Batteries that are used or aviation requirements can be either primary (non-rechargeable) or secondary (rechargeable). Batteries that are used for aerospace applications must be lightweight, have high energy density, more reliable, require very minimal maintenance and must be able to operate in different environment types such as cold and icy conditions, or hot and humid conditions. Different manufacturers are constantly striving to develop more battery technologies for use in the aviation industry.

Battery types include Lead Acid, Nickel-Cadmium (NiCd), Nickel-Metal Hydride (Ni-MH) and Lithium-ion batteries. Among all, Lithium is the lightest metal of all and thus provides largest energy density per weight. At present, these batteries are the fastest growing batteries and being used in many applications including the aviation industry. Lithium-ions batteries have twice the energy density of nickel-cadmium batteries. It does not require much maintenance and memory, indicating no necessity of scheduled charging or discharging to increase its battery life. Even the self-discharge is half as compared to that of NiCd.

Future Battery Types include Gold Nano-wire Batteries**,** Lithium-Air Batteries**,** Lithium-Sulfur Batteries and “Tesla” Batteries**.**

Design Requirements

This part focuses on the design requirements of the system for aircraft taxiing and describes the performance targets and the calculations of power required for both the normal and the critical conditions.

Ground Maneuvers

Ground maneuvers of the aircraft is often mistakenly just thought as simple taxi-in, taxi-out and pushback from the gate. In reality, it involves more complex maneuvers and the aircraft has to make turns to exit the runway or the taxiway. It includes both 90° and 135° turns. Figure 5 shows the different ground maneuvers that the aircraft takes categorized according to the speed.

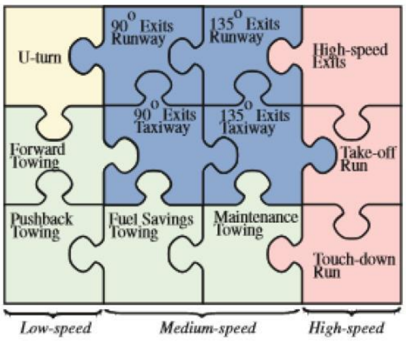

Figure 5: Types of ground maneuvers

The performance target of the system and the power calculations should be accounted for these maneuvers; hence the taxiing system can be more reliable for the aircraft ground operations.

Performance Target

The maximum taxiing speed of an Airbus A320 aircraft is 25 knots on straight taxiways, 15 knots in turns and 10 knots when approaching gates or parked areas. Thus, the average speed of 23 knots has been taken as the target speed for the power calculations. During pushback, the average speed of the aircraft should not exceed the normal walking speed of a person which is kilometers per hour. Hence, the pushback speed has been chosen as 3.24 knots. The target acceleration has been taken as 0.18 m/s^2 because on the taxiway, the aircraft should be able to reach a speed of 20 knots within a timeframe of 90 seconds. Additionally, there might be cases where the aircraft has to cross the runway. If that is the case, then it should be able to do so as soon as possible. The performance targets of the system are detailed in the Table 1 and Figure 6 below.

Table 1: Performance targets of the system

Phase	**Targets**	
Pushback	Speed	3.24 knots at MTOW
	Acceleration	0.18m/s^2
Taxi-out	Speed	23 knots at MTOW
	Acceleration	0.18m/s^2
Taxi-in	Speed	23 knots at MLW
	Acceleration	0.18m/s^2

*MTOW - Maximum Take-Off Weight
**MLW - Maximum Landing Weight

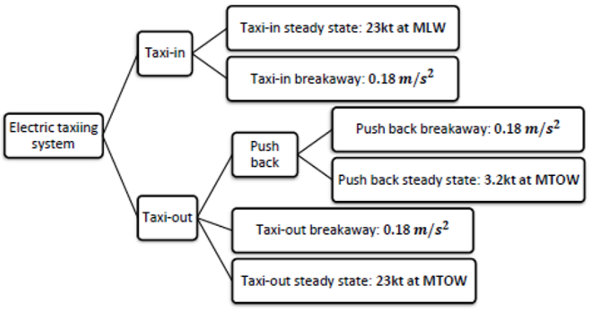

Figure 6: Performance targets of the electric taxiing system

System Power Requirement

Power analysis for the system is significant as it influences the components selection. It determines the battery selection, its sizing and the motor as the power generated by the battery pack should last for the desired taxi duration. The additional battery power is also required during unforeseen circumstances.

Input Parameters

The various input parameters that are used for the calculation of power are frictional coefficients, aerodynamic drag and aircraft static load. On an average the value of rolling friction coefficient varies from 0.008 to 0.020 on various surfaces. In particular, the rolling friction coefficients has been found to be 0.02-0.05 for dry surfaces and 0.05 for wet surfaces. Hence, rolling friction coefficient of 0.02 will be considered for normal operation and 0.05 for critical condition. The static coefficient of friction has been chosen as 0.3.

While considering the drag of the aircraft, only the area of the wings has been considered here, with the assumption that there would not be a large difference in the drag force at 23 knots even if the fuselage drags had been included.

For calculating the power, the main force needed to move the aircraft, which is in turn the mass of the aircraft acting on the wheels of the aircraft, is known as the static load. For taxi-out and pushback, the MTOW is taken and for taxi-in the MLW is considered. The values of MTOW and MLW for Airbus A320 is given and the input data for the power calculations are also summarized in Table 2.

Table 2: Input data for power calculations

Description	Symbol	Data	Unit
Maximum Take of Weight	$MTOW$	78,000	kg
Maximum Landing Weight	MLW	66,000	kg
Drag coefficient	C_D	0.0121	
Velocity (23 knots)	V_t	11.83	m/s
Velocity (3.24 knots)	V_t	1.67	m/s
Wing Area	A	122.6	m^2
Density of air	ρ	1.23	kg/m^3
Aerodynamic drag @ 23 knots	d	127.16	N
Aerodynamic drag @ 3.24 knots	d_p	2.52	N
Tire diameter	T_d	1.17	m
Tire radius	r	0.58	m
Rolling friction coefficient	f_r	0.02	-
Static Friction coefficient	f_s	0.30	-
Angular speed @23 knots	ω_t	20.25	rad/s
Angular speed @3.24 knots	ω_{tp}	2.85	rad/s
Acceleration	α	0.18	m/s^2
Gravity	g	9.81	m/s^2

Power calculations - Taxi-out, Taxi-in and Pushback

The steps below describe the calculation for power required for taxi-out phase. The rolling friction is given by,

$$R_F = MTOW \cdot g \cdot f_r = 15{,}303\ N$$

Breakaway calculations

The total resistance during breakaway at taxi-out stage is given as follows.

$$Taxi\text{ - }out_{resbreakaway} = (MTOW \cdot \alpha) + d + R_F = 29{,}470\ N$$

Torque required for taxi-out breakaway,

$$Torque_{taxi\text{ - }outbreakaway} = taxi\text{ - }out_{resbreakaway} \cdot r = 17{,}217\ Nm$$

Power required for taxi-out breakaway,

$$Power_{taxi\text{ - }outbreakaway} = torque_{taxi\text{ - }outbreakaway} \cdot \omega_t = 349\ kW$$

Steady-state calculations

Similarly, for the steady state, the total resistance is given by,

$$taxi\text{ - }out_{ressteadystate} = d + R_F = 15{,}303.6 + 127.2 = 15{,}431\ N$$

Torque required for taxi-out at steady-state,

$$Torque_{taxi\text{ - }outsteadystate} = taxi\text{ - }out_{ressteadystate} \cdot r = 9{,}015\ Nm$$

Power required for taxi-out at steady-state,

$$Power_{taxi\text{ - }outsteadystate} = torque_{taxi\text{ - }outsteadystate} \cdot \omega_t = 183\ kW$$

In the same way, the torque and power calculations for taxi-in and pushback are calculated using the input data given in the Table 2. Table 3 summarizes the torque and power requirements for taxi-out, taxi-in and pushback.

Table 3: Power requirements of system

Taxi-out	Steady-state	Torque	9,015 Nm
		Power	183 kW
	Breakaway	Torque	17,217 Nm
		Power	349 kW
Taxi-in	Steady-state	Torque	7,639 Nm
		Power	155 kW
	Breakaway	Torque	14,580 Nm
		Power	259 kW
Push back	Steady-state	Torque	8,942 Nm
		Power	26 kW
	Breakaway	Torque	17,144 Nm
		Power	49 kW

Batteries power is used to drive the wheels of the aircraft through a motor and a gear. As no motor and gear has 100% efficiency, their losses have to be accounted for while calculating the energy required from the batteries. Motor efficiency varies between 70 and 98%. Considering a 96.2% motor efficiency and 98% gear efficiency, the power requirements are shown in Table 4.

Table 4: Power requirements with efficiency of motor and gearbox

Phase	Steady state/ peak	Torque/power	At wheels	At motor (98% gearbox efficiency)	At battery (96.2% motor efficiency)
Taxi-out	Steady-state	Torque (Nm)	9,014	9,199	9,562
		Power (Kw)	183	186	194
	Peak	Torque (Nm)	17,217	17,658	18,262
		Power (kW)	349	356	370
Taxi-in	Steady-state	Torque (Nm)	7,639	7,795	8,103
		Power (kW)	155	158	164
	Peak	Torque (Nm)	14,580	14,877	15,465
		Power (kW)	295	301	313
Pushback	Steady-state	Torque (Nm)	8,942	9,124	9,485
		Power (kW)	26	26	27
	Peak	Torque (Nm)	17,144	17,494	18,185
		Power (kW)	49	50	52

Energy Requirements

The energy requirements are characterized by the power required by the wheels and the time for taxi in each of the different phases. The average taxi time of an Airbus A320 is considered as 21 mins here and it includes all the three phases. The time allocated for each of these phases is shown in Figure 7.

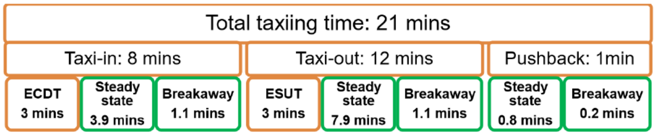

Figure 7: Taxiing time allocation

Energy calculations - Taxi-out, Taxi-in and Pushback

The energy required for performing a specific taxi phase at steady state is given by,

$$Energy_{steadystate} = power \cdot taxitime$$

The energy required for performing a specific taxi phase at breakaway is given by,

$$Energy_{breakaway} = PeakPower \cdot Taxitime/2$$

Thus, the energy required for taxi-out steady-state and breakaway is given by,

$$Energytaxi\text{ - }out_{steadystate} = 25.5\ kWh$$

$$Energytaxi\text{ - }out_{breakaway} = 3.4\ kWh$$

In the same way, energy requirements for taxi-in and pushback are calculated by using the input data from Table 2. Tables 5 & 6 below summarize the energy requirements for taxi-out, taxi-in and pushback.

Table 5: Energy requirements of system

Phases	Steady state (kWh)	Break away (kWh)	Total (kWh)	Total (kJ)
Taxi-out	26	3.4	29	103,984
Taxi-in	11	2.9	14	48,730
Push back	0.4	0.09	0.45	1,610
Grand Total			**43.45**	**154,324**

Table 6: Critical condition power and energy requirements

Phase			**At wheels**	**At motor**	**At battery**	**Energy**
Taxi-out	**Steady-state**	Torque	22,425			
		Power	454	463	482	63.42
	Peak	Torque	30,627			
		Power	620	632	658	12.06
Taxi-in	**Steady-state**	Torque	18,986			
		Power	384	392	408	26.51
	Peak	Torque	25,926			
		Power	525	535	557	10.21
Pushback	**Steady-state**	Torque	22,352			
		Power	63	65	68	0.90
	Peak	Torque	30,554			
		Power	87	89	92	0.31
Total Energy required (kWh)						**113**

Requirements of the Battery Pack

The requirements for the battery pack are classified into: mechanical, service, safety and cost requirements.

The mechanical requirements for the design cite in the battery pack is that it should be mechanically stable and fixed and provides stiffness and mechanical strength to the battery modules. It includes the battery management systems, switch box and other electrical and mechanical interfaces to the external subsystems. Insulation is also required to protect against high voltage accidents that may cause fatalities.

The different safety requirements for the system are crash and abuse testing. The design must be to deform under tested crash loading cases in a way that it does not come in contact with the battery modules or cells. An envelope of all worst load cases is tested. A pressure equalizer can be used to control the over-pressure at the above-mentioned load cases. The system must ensure that the cooling system remains intact without any leakage, leading to a short circuit in the high voltage system.

The battery pack service requirements include the interchangeable battery packs and its recycling and second life usage. It should also be easily replaceable for maintenance and service conditions. The maintenance should only be done by highly skilled personnel with enough training in service stations that work in a controlled environment and use a traceable maintenance logging system.

Cost requirements is an important aspect during designing battery system. As lithium-ions cells are very expensive, the cost of the remaining components needs to be handled in a very cost-effective manner without making any compromise in safety, reliability or certification requirements.

System Design

The electrically powered landing gear mainly focuses on battery powered electrical energy. This system uses a battery pack to provide electrical power to a motor that is housed on the main landing gear wheels of the Airbus A320 aircraft to drive the wheels to move forward or backward through a gearbox attached to it. The system consists of a battery pack, motor, gear, motor controller and the cockpit controller. The system architecture is shown in Figure 8.

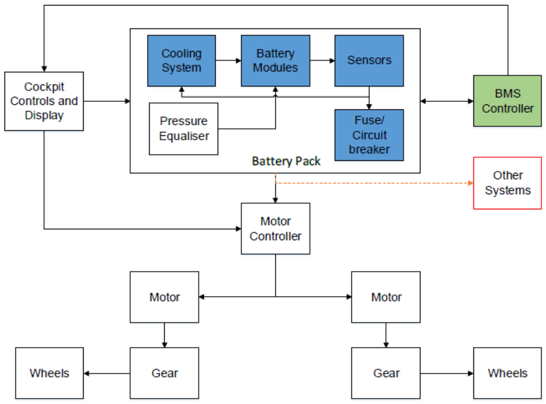

Figure 8: System architecture

The system consists of a cockpit interface unit which enables the pilots to control it and move the aircraft for taxiing. The battery pack which is the power source of the system, will be placed in the cargo hold of the aircraft (Airbus A320). The battery pack consists of individual modules connected in series which in turn consists of hundreds of cells in both series and parallel combinations. The battery modules are efficiently managed by the battery management system which includes temperature sensors, pressure sensors, circuit breakers, fuses and cooling system to maintain optimum temperature. This work focuses on the sizing of the battery, preliminary design of cooling system and battery management system and sizing of the motor and the gearbox.

Aircraft Braking System

The aircraft braking system is on the main landing gear wheels along with the electric taxiing system. These two systems are complimentary in working and its control is provided by the cockpit interface system. The integrated working is not demonstrated. Figure 9 shows the system block diagram together with the braking system and the electric taxiing system.

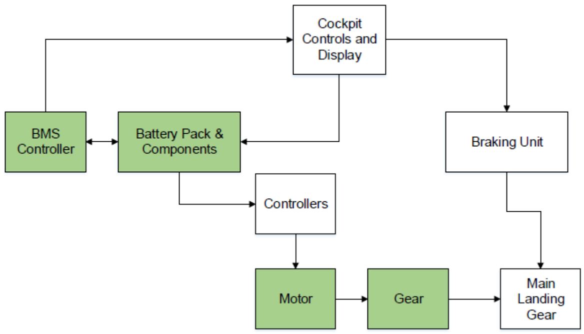

Figure 9: Schematic representation of taxiing system and braking control unit

The main electrical power system of the aircraft is independent from the electric taxiing system. A major advantage that the existing electrical architecture of the aircraft does not need to be altered and the electric taxiing system will not interfere with the working of the other aircraft systems. Even if the electric taxiing system fails, the pilots can still taxi using the traditional method of using the main engines.

System Sizing

The battery pack of the system is the most important subsystem of the electrically powered landing gear system and needs to be highly efficient for powering the landing gear for taxi operations. The selection of the battery is a very challenging process as the design must decreasing the overall costs and also must increase the energy density & efficiency without affecting the system safety and battery lifetime.

Choosing the Battery

While designing the battery pack for the system, choosing the battery is the most important step in the design process. The battery pack should provide enough energy for system energy requirements as well should have enough back up energy for any additional power requirements. Figure 10 describes the energy densities of few battery cells.

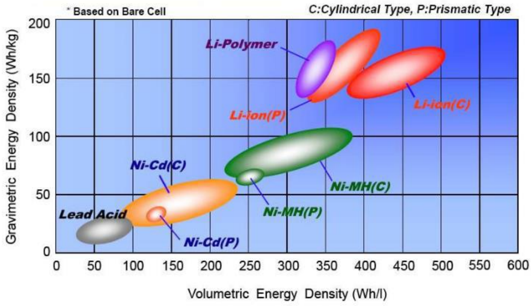

Figure 10: Volumetric and gravimetric energy densities of battery cells

Storing energy and power for applications have led to the need for high voltage batteries. At present, lithium-ions batteries are most commonly used owing to its high energy and power densities compared to the other batteries such as nickel-metal hydride or lead-acid batteries. Due to various applications, energy densities and life cycles of Lithium-ions batteries they have been selected for use in the aircraft electric taxiing.

There are different types of lithium-ions batteries available varying in the type of the anode and cathode materials used in it that gives rise to a range of specific power density from 300 to 1500 W/kg. Hence, the next step is to choose the appropriate lithium-ions battery. Table 7 shows the different types of lithium-ions batteries.

Table 7: Lithium-ion batteries

Chemical Name	Material	Abbreviation	Notes
Lithium Cobalt Oxide	$LiCoO_2$	LCO	High capacity for mobile, laptop, camera
Lithium Manganese Oxide	$LiMn_2O_4$	LMO	• Safe, long life, lower capacity than Lit-cobalt but high specific power • For power tools, e-bikes, medical, electric vehicle EV, etc.
Lithium Iron Phosphate	$LiFePO_4$	LFP	
Lithium Nickel Manganese Cobalt Oxide	$LiNiMnCoO_2$ (10-20% Co)	NMC	

Lithium Nickel Cobalt Aluminum Oxide	$LiNiCoAlO_2$	NCA	Moderately safe, long life, used in applications such as power train, grid storage, electric vehicle EV, etc.
Lithium Titanate	$Li_4Ti_5O_{12}$	LTO	

The most commonly used batteries among types are the lithium cobalt oxide ($LiCoO_2$). Lithium nickel cobalt batteries are moderately safe, have long life and are good for electric vehicle applications and where the battery pack needs to be portable. Research is still going to improve the thermal stability and the performance of the cobalt-based lithium-ions batteries. Simultaneous reduction in the cobalt content and increase in the nickel content of the battery has improved the performance of the lithium-ions batteries and has led to an increase in the energy density. Different batteries have been considered for the sizing (Table 8).

Table 8: Comparison of battery cell characteristics

Characteristics	**Panasonic NCR18650PF**	**"Tesla" 18650**	**"Tesla" 2170**	**TB-44**	**Ansmann 2447-3099-20**
Voltage (V)	3.6	3.7	3.7	26.4	14.8
Charge (mAh)	2,700	3,400	5,750	46,000	13,800
Capacity (Wh)	9.7	12.6	21.3	1,214.4	204.2
Diameter (mm)	18.5	18	21	-	-
Height (mm)	65.3	65	70	-	-
Dimensions (mm)	-	-	-	276 · 266 · 257	74 · 74 · 72
Weight (g)	48.0	45	66	-	776

Although TB-44 and Ansmann batteries have very high energy density, owing to their large dimensions and weight they have not been selected. The battery chosen here is "Tesla" batteries because of their small size, large volumetric energy density and its use in the electric vehicles. "Tesla" 2170 is the newer version of "Tesla" 18650 cells in which the cobalt content is reduced and increased the nickel content, maintaining the thermal stability of the cell. The cylindrically shaped "Tesla" 2170 battery cells contain three thin sheets of material rolled up in a 'jelly roll' model and a separator existing between the anode and the cathode ensures that they do not touch each other while the ions are passing through them. This 'jelly roll' which is the cathode, is made up of lithium NCA oxide (lithium nickel cobalt aluminum oxide) which stores the energy of the battery. They can be arranged in a combination of series and parallel connections which enables them to increase their voltage and current ratings respectively Table 9.

Table 9: "Tesla" 2170 battery characteristics

Property	**Value**
Length	21 mm
Diameter	70 mm
Volume	24.250 mm^3
Weight	66 g
Voltage	3.7 V
Charge	5,750 mAh
Energy density	877.5 Wh/l
Specific Energy	322 Wh/kg
Density	2.7 kg/l

A single battery cell would not have the necessary voltage range and current output required by the system and hence, multiple battery cells are needed to fulfill the power requirements of the system. This constitutes a battery module. Several battery modules together form a battery pack.

Designing the Battery Pack

The energy required for electric taxiing has been calculated as 43.45 kWh. From Table 8 above, it can be seen that the "Tesla" 2170 batteries have a capacity of 0.0213 kWh. This means that to generate 43.45 kWh, approximately 2015 batteries need to be connected together. Typical motor voltages are in the range of 350 - 650 V and hence the battery pack shall have a 350 V at its output.

The battery pack is designed to have several modules connected in series to generate the required output voltage. The individual modules will not have more than 60 V each. Splitting up of the pack into several modules has various notable advantages such as easy handling of the individual batteries during production and transportation, easy to install the battery modules, never dealt with high voltages by maintenance personnel, easily replaceable during any component failure within the modules rather repairing the whole pack, and handling each module individually by the battery management systems rather than the pack.

The batteries in the module are stacked in a rectangular pattern (length & width wise). Each module consists of battery cells that are grouped together. The cells within a group are connected in series. A group has 12 cells and there are 60 such groups which are connected parallel to generate a current of approximately 345 Ah per module. When cells are connected in parallel there is an increase in the current capability of the cell group which in turn increases the power output. When cells are connected in parallel, failure of independent cells do not affect other cells and they can still provide the output required, whereas in the case of cells that are connected in series, if one of them fails, the entire group of cells will not provide any output. The connection in parallel assures that the lifetime of the battery module is increased and provides adequate protection from failure of individual cells. Three groups are arranged in a row and there are 20 such rows. This combination of cells along with the other components constitutes a module. The other components such as the battery housing, cell interconnections, and battery management systems are explained in detail (Table 10).

Table 10: Battery module structure

No. of cells in a module	720
No. of cells in series	12
No. of series groups	60
No. of parallel connections	60
Output voltage	44.4 volts
Output current	345 Ah
Capacity	15.3 kWh
Weight	47.5 kg

To arrange them together as a module an engineering approximation of 1.8 d gap has been chosen between rows where d = 21 mm, diameter of the cell. Thus, 37.8 mm is the pitch of two batteries in a row. Each row contains 36 batteries which gives a total length as calculated below.

$$length = 35 \cdot (1.8 \cdot d) + d = 1{,}344\ mm$$

The next row of batteries is arranged in a slightly staggered manner to ensure the row of batteries do not touch each other and to give sufficient space for the cooling to take place. 0.85d has been assumed as their separation distance. There are 20 such rows arranged together to make a battery module.

$$width = 19 \cdot (0.85 \cdot d) + d = 360\ mm$$

The height of the battery pack without the housing is the height of the batteries itself $height = 70$ mm.

Each module consists of an outer casing known as module housing to protect from external surrounding and to ensure that they get adequate cooling. The module housing should ensure the module is mechanically stable and holds the cells together by acting as a fixture. The outer casing should have enough space for the battery management systems and cell interconnections so that the batteries can be connected in series and parallel. Battery management systems like heat sensors have also been included in the casing to detect whether the batteries are getting hot. As an engineering approximation, 5% has been added to the length of the pack for the casing, 70 mm (35 mm each side) additional width and 40 mm (20 mm each side) additional height. Thus, the overall dimensions of one battery module are 1,411 mm · 430 mm · 110 mm.

The individual modules are electrically connected in series through the module connectors interfaced to it. This ensures that the voltage of the pack increases and thus provides sufficient voltage as the battery output. Each module generates an energy of 15.3 kWh. To generate an energy of 43.45 kWh, we require, 43.45/15.3 = 2.8 modules. Rounding up, this gives a total of 3 modules.

Although the system requirement is only 3 modules to generate the power needed for an average taxi time of 21 mins, a total of 8 modules has been chosen for the battery pack. There may be cases where additional power/energy is required. Hence limiting the battery to exactly the required energy would not be safe while sizing the battery. Due to this reason, eight modules have been chosen for the sizing of the battery and eight modules connected in series gives a pack voltage of 355 V which is the input voltage required for most motors. The total energy of the battery pack is 122.5 kWh. This caters to the power requirements during the critical condition of wet runways as well as additional ground power to run other systems (Table 11).

Table 11: Battery sizing

Number of modules	8
Energy of 8 modules	122.4 kWh
Weight of 8 modules	380.2 kg
Output current	345 Ah
Output voltage	355.2 Volts

Electric Motor

Motors convert electrical energy to mechanical energy and hence the electric taxiing system requires a motor to translate the power into rotational motion of the wheels and generate the required taxi speed (Figure 11).

$$P_{electrical} = P_{mechanical} + P_{loss}$$

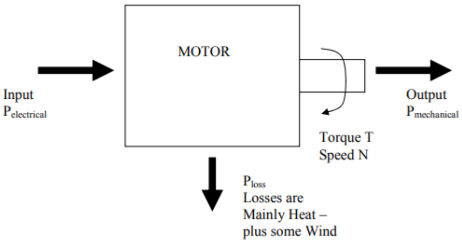

Figure 11: Input, output and losses in a motor

The total power and torque calculated required at the motor pertains to both the wheels together and hence only half of that is required for each set of wheels. There would be two motors which would be attached to the aircraft landing gear to move the aircraft. Thus, the power and torque required for each set of main landing gear wheels from the motor is given in Table 12.

Table 12: Torque and power required from motor for each wheel

Taxi-out	**Nominal**	Torque	4,599 Nm
		Power	93 kW
	Peak	Torque	8,784 Nm
		Power	178 kW
Taxi-in	**Nominal**	Torque	3,898 Nm
		Power	79 kW
	Peak	Torque	7,439 Nm
		Power	151 kW
Pushback	**Nominal**	Torque	4,562 Nm
		Power	13 kW
	Peak	Torque	8,747 Nm
		Power	25 kW

Various motors have been considered for the sizing. Table 13 below lists the specifications of two motors from GKN which conforms to the power requirements needed for each set of wheels.

Table 13: Motor specifications comparison

Motor specifications	**AF-140**	**AF-230**
		
Maximum speed (rpm)	5,000	8,000
Peak torque (Nm)	600	700
Nominal torque (Nm)	260	580
Peak output (kW)	220	280
Nominal output (kW)	94	128
Weight (kg)	42	57
Diameter (mm)	380	300
Voltage (V)	300 - 720 VDC	300 - 650 VDC

Owing to the large weight of AF-230, the motor AF-140 has been used in the calculation process.

The additional weights at the wheels would only increase the amount of fuel needed for the other different phases of flight. The motor itself has liquid cooling for enhancing its performance. The speed of the motor or the number of revolutions per minute is calculated using the formula,

$$N = P \cdot 60/(2 \cdot \pi \cdot T)$$

where, P is the power required and T is the motor torque. The motor nominal torque is 260 and the peak torque is 600. The number of revolutions per minute (rpm) for each phase is given in Table 14.

Table 14: Motor speed requirements

Phase	**Nominal/peak**	**Revolutions per minute (rpm)**
Taxi-out	Nominal	3,421
	Peak	2,832
Taxi-in	Nominal	2,899
	Peak	2,398
Pushback	Nominal	479
	Peak	398

From Table 14, it is clear that the number of rpm for both nominal and peak in all the three phases are < 5,000 rpm which is the maximum speed of the motor. This confirms that the selected motor is ideal for generating the required speed.

The required torque in all the cases is greater than the nominal and peak torque of the motor. This means that there should be a gear to adjust the torque and provide the required torque to the wheels.

Gear Design

A gearbox is basically a part of the transmission within a machine or system. The transmission within a system includes the gearbox, the clutch and the shaft to which the wheels are connected.

Gearboxes are mainly used to transmit the torque provided by a motor to the wheels of any system or vehicle. It can provide different transmission ratios so that the torque from the motors can be adjusted to make the system/vehicle adaptable to different situations. They usually increase the torque provided by the motor to the traction torque required for the wheels to overcome the motion resistance of the vehicle.

In the taxiing system, the motor selected can only provide a limited amount of torque which is not sufficient for the operation of the system and cannot move the wheels of the aircraft. Thus, a gearbox needs to be fitted between the wheels and the motor. The gearbox consists of two gears: the driving gear and the driven gear. The driving gear drives the driven gear and transmits the power to it. Gear sizing is obtained by calculating the gear ratio. It is also known as the torque ratio. It is given by,

$$Gear\ ratio = \frac{Output\ torque\ required\ at\ wheels}{Input\ torque\ provided\ by\ motors}$$

The gear ratio for taxi-out nominal is given by,

$$Gear\ ratio = \frac{4599.31}{260} = 17.69$$

The gear ratio for taxi-out peak is given by,

$$Gear\ ratio = \frac{8784.09}{600} = 14.64$$

Taxi-out is the phase which requires the highest amount of torque and power and hence this has been used for calculating the gear ratio. The largest of the above values is 17.69 and hence gear ratio of 18 has been selected. The scaled nominal and peak torque are given by,

$$Scaled\ nominal\ torque = 18 \cdot 260 = 4{,}680\ Nm$$

$$Scaled\ peak\ torque = 18 \cdot 600 = 10{,}800\ Nm$$

The input voltage required for the motor is 350 VDC. The voltage generated by the pack is 355 V which means that there is no need of any inverter or converter between the pack and the motor. The selection results of the motor and the gearbox is given in Table 15.

Table 15: Motor and gearbox results

Electric Motor GKN AF-140	**Data**
Maximum speed (rpm)	5,000
Peak torque (Nm)	600
Nominal torque (Nm)	260
Peak output (kW)	220
Nominal output (kW)	94
Weight (kg)	42.5
Diameter (mm)	380
Voltage (V)	300 - 720 VDC
Gear Ratio	18
Scaled nominal torque (Nm)	4,680
Scaled peak torque (Nm)	10,800

Current Drain and Charging the Battery

Two factors that govern the lithium-ions batteries are: power capacity and power capability. Lithium-ions batteries are usually rated at 1 C but with new batteries such as the “Tesla” 2170 batteries, they have increased the capacity to approximately 2 C. But with high discharge current there will be some heat losses. Usually, the protection circuits of lithium-ions batteries from discharging more than 1 C. But lithium-ions cells that use active materials such as nickel, cobalt or manganese can have discharge rates up to 10 C. The battery pack designed has a current rating of 345 Ah and if they are discharged at 1 C at 355 V, they can provide charge of 345 A for 1 hour. Hence, the batteries designed have the capability to provide the required discharge for the electric taxiing.

The charging time required for a battery is determined by the capability of the battery. The charging process of the battery thus also depends on the C rates. Lithium-ions batteries are usually charged from a current limited fixed voltage source. Overcharging of lithium-ion batteries seriously causes damages and reduces its lifecycle drastically. The battery pack designed can be charged using a 1 C rate which means with an input current of 345 A and a constant fixed input voltage. The charging of the battery cannot be completed within the required turn-around time of the aircraft and hence there should be multiple batteries for the aircraft. The pack designed can be used for three taxiing cycles, but assuming that either of the taxiing cycles utilizes more power, the number of taxiing cycles possible is two. This means that the aircraft can return to its originating destination with enough power for taxi-in to the hangar. Here, the battery pack can be replaced with a charged battery.

Fast charging options are possible, but there is a trade-off between the battery capacity, heating and the time. With fast charging option the battery charges very quickly but the capacity reduces to 50-70% of the total capacity. Also, the internal temperatures of the batteries increase when fast charging is done. Hence, a trade-off has to be done whether to go for a faster charging option to save time and compensate on the capacity or to get full capacity with normal charging.

Additional Power Requirements

The critical condition is calculated on the basis of a higher value of friction coefficient. Situations for the requirements of an additional power include an increase in aerodynamic drag of the aircraft, an increase in the frictional force between the tires and the ground due to a wet runway, an increase in resistance of the aircraft to move due to worst weather, proper steering of the aircraft during icy conditions and preventing the aircraft from slipping on the taxiway, and during aborted taxiing.

Power Requirement for Other Systems on Ground

The battery powered taxiing system provides power only to the landing gear motors for taxiing, especially for ground operations. The APU needs to be running for other systems such as the ECS, electronics equipment E/E cooling systems, etc., by using fuel and hence only the taxiing part of the ground operations is green. If the whole of the ground operations must be green and avoid using any fuel, every system working on the aircraft whilst on the ground should be powered using green energy.

According to ACARE 2050, green technology must be adopted for every aircraft entering service whilst on the ground. The various other systems require electric power whilst on the ground include landing gear steering, environmental Control System (ECS) and actuators on the wing.

Landing Gear Steering

The power required for steering the nose landing gear in an Airbus A320 is approximately 4 kW. As the energy is provided by the battery pack, the energy required is calculated from power. The approximate usage of steering system for 10 minutes would require energy of 666.67 Wh or 0.67 kWh. From the sizing of the battery pack, it is evident that the battery pack will be able to provide this energy requirement.

Environmental Control System

The power required for ECS of an Airbus A320 is approximately 200 kW. This value is an average value of the power required in all flight phases and is not the actual power requirement for taxiing phase. Once the aircraft is in the air, the power required to maintain the pressure inside the cabin would be more. On the ground, this can be taken as the air conditioning requirement only. Hence, during taxiing operations, the air conditioning system can provide power to the ECS. The power required by the air conditioning system for taxiing phase is approximately 85 kW for narrow body aircraft. The typical power requirements for air conditioning units used in an aircraft are given in Table 16.

Table 16: Typical power requirements of air conditioning units in aircraft

Air Conditioning Model	Power (kW)	Suited for
Foxtronics Fox Air 60	7	-
TLD ACU-802S-CUP	404	All types
TLD ACU-804-CUP	229	Narrow & medium body aircraft
TLD ACU-808-DUP	528	Large Aircraft in adverse conditions
TLD ACU-401-CAP	116	Fighter, C-130
Foxtronics Fox Air MAX	17	G650
TLD ACU-302-CUP	84.4	Narrow-body aircraft

Since the ECS has to be operating all the time while the aircraft is taxiing, the total taxiing time of 21 mins is taken as the time of operation. The energy required for ECS is 29.8 kWh. This energy amount can be provided by the designed battery pack during normal conditions, but in the critical condition it will not be able to. This means that a battery pack with more energy output needs to be designed if the ECS is to be powered by the pack in critical conditions.

Control Surface Actuators

Although all the control surfaces in the aircraft would not be used while taxiing, there are few of them which will be used. In modern aircraft, the actuators are controlled by flight control computers through fly-by-wire method. This means that there will be the need for some amount of electrical power for these systems. The conventional deflection rate of the wing fold mechanism which is 10°/second is to be activated during the taxi phase of the aircraft.

Approximately, the power required for the actuators while taxiing is 65 kW. Considering a time of 5 minutes for the actuators, the energy requirement would be 5.41 kWh. This energy can be supplied by the battery pack designed in both the critical conditions as well as the normal conditions.

Electric Taxiing System Weight

The weight of the battery pack containing 8 modules is 380.2 kg. To calculate the weight of the system, the individual weight of the components needs to be included. Approximating another 15 kg for the BMS, cooling system, battery housing and wiring, the total weight of the battery pack is 400.2 kg.

The weight of the chosen AF-140 motor is 42.5 kg. This gives the total weight of the electric taxiing system to be 485.2 with two motors and assuming 5 kg for the gears. The weight of the 85 kWh "Tesla" battery pack is 540 kg. This includes the cooling system and the battery management systems and does not include the motor or the gear. Comparing to the weight of the "Tesla" battery pack, there is a 25.8% decrease in the weight for the taxiing system.

Design of Battery Cooling System

This heat generation has crucial impact on the lifetime of the battery pack. The heat damage to the lithium-ions cells is irreversible. Figure 12 shows the variation of the battery power of lithium-ions cell with the change in temperature. As can be seen, the maximum power from the cell is obtained at a specific temperature range (20 °C to 40 °C) which is known as the optimum working temperature range.

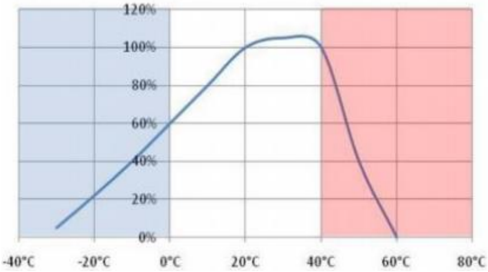

Figure 12: Variation of battery power with temperature

At lower temperatures and higher temperatures, the cycle life of the batteries decreases. Thus, cooling system ensures that the optimal working range is maintained by heating the system under low temperature environment and alternatively cooling the system at high temperature environment. The heat dissipated by the batteries is given by the formula,

$$H = I^2 \cdot R \cdot t$$

where, I is the current flowing through the batteries, R is the internal resistance of the batteries and t is the duration for which the current flows. As the internal resistance information of the "Tesla" 2170 batteries are not available, typical lithium-ions internal resistance (320 mΩ) will be used for the calculations. The current rating of each cell is 5.75 A. Thus, the heat load of the cells in the pack is,

$$H = 5.75^2 \cdot 320 \cdot 10^{-3} = 10.6\ W$$

Lithium-ions batteries' performance will be seriously impacted by increase in temperature and will not provide the necessary power output. In general, lithium-ions batteries do not perform well if they are hot or cold. If sufficient cooling is not provided, they may heat up very quickly and lead to fire hazards or explode or they may become so cold and not work properly.

The method of cooling the battery cells and the direction of cooling is also very important to improve the performance of the cells over time. Three types of battery thermal management systems are as follows:

- Convection to air either passively or forced.
- Cooling by flooding the battery with dielectric oil which is then pumped out to a heat exchanger system (direct contact cooling).
- Cooling by circulation of water-based coolant through cooling passages within the battery structure (indirect contact cooling).

Convection method of cooling using air is not adopted for applications that require high performance from the batteries. Between direct contact cooling and indirect contact cooling, indirect contact cooling is preferred by most manufacturers for isolating the cells from the coolant liquid, which would increase the safety factor as well as provide easy access to the cells for maintenance and installations. Research is ongoing for a new type of cooling system known as the Direct Expansion Cooling System. This system uses the same coolant or refrigerant that is being used in the vehicle's cooling system and hence eliminates the need for additional coolant and its associated system. In the aircraft, this could involve using the same refrigerant/coolant that is being used for cooling the various aircraft systems such as avionics systems. Thus, use of liquid glycol could be avoided and an existing system would mean less additional circuitry and components.

Cooling Structure Selected

In the design of the electric taxiing system, the indirect contact method of thermal management has been chosen. The battery packs are designed in such a manner that the coolant passes in between the batteries through a serpentine structured cooling pipe, hence providing sufficient cooling and absorbing the heat generated by the batteries. The positioning of the battery cells has been designed to maximize the surface of the cells in contact with the coolant tube, so that maximum heat can be absorbed by the coolant liquid. The cells are in thermal contact through the sides of the cooling tube through which a coolant such as water-glycol coolant is passed. It is indirect contact cooling where the coolant liquid passes through the thin tube surrounding the batteries which are arranged in a staggered manner maximizing the contact area with the sides of the individual cells (Figure 13).

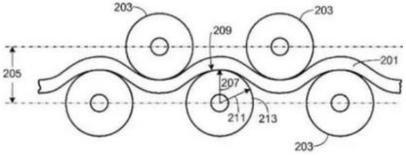

Figure 13: “Tesla” patent 20110212356 cooling tube system

This method is used in the “Tesla” car models and is patented by “Tesla” Motors Inc. Hence to use it for applications such as aircraft taxiing, might be acceptable (Figure 14).

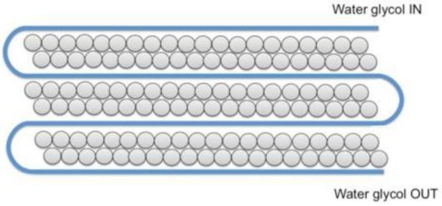

Figure 14: Direct contact cooling using water glycol as coolant

The coolant absorbs the heat generated by the cells and exits the battery modules to a heat exchanger system which in turn absorbs this heat from the coolant so that the coolant can be circulated through the battery modules again (Figures 15 & 16).

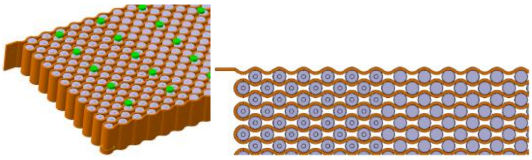

Figure 15: Electric taxiing serpentine structure cooling tube (left); Cooling structure top view (right)

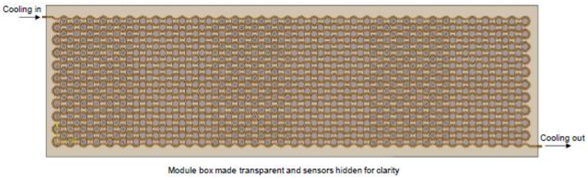

Figure 16: Cooling structure inside module box

The detailed design of the cooling system involving the heat exchanger and other components is beyond the scope of this work and hence has not been designed here.

Selection of Coolant

There are certain factors about coolant, must be having high thermal conductivity & specific heat, low viscous nature, low burst point and meting point, very high boiling point, highly non-flammable nature, high dielectric properties, anti-corrosive property and non-toxic nature.

In the “Tesla” car model, the coolant used is liquid propylene glycol. Hence propylene glycol can be selected as the coolant.

Battery Management Systems

Lithium-ions batteries are sensitive to temperature conditions that when exposed to non-operational temperature ranges can result in failure of the system. Similarly, any fluctuations in voltage (over-charge/discharges) or currents within the battery cells can limit the overall lifetime of the battery packs. Any damage inducing fluctuations of temperature, voltage and current needs to be monitored to avoid system failure or degradation. This is done by a battery management system within the battery modules or the battery pack as a whole. This monitoring is carried out by the electronic components such as sensors within the battery pack that ensures safety and reliability of the system by sending signals and readings to the control system computer onboard the aircraft. It is also designed to be clever enough to disconnect the battery pack in case of failure to prevent any accidents.

The various components of the battery management system include cell supervision circuit, switch box, cooling management system and current sensor.

Cell Supervision Circuit (CSC) - consists of sensors that detect the temperature and voltages of the cell groups and sends signals to the cooling management system and control system computers for cooling and monitoring purposes respectively. The CSC are placed near the battery modules inside the housing at specific points above the cell groups to effectively monitor the cell temperatures and voltages. The number of temperature sensors needed for the battery module is selected depending upon the number of cell groups and parallel connections to efficiently manage the cells within the module. Calculating the approximate location and estimating the appropriate number of sensors required for the module is beyond the scope of this work. The design of the battery management systems could be undertaken as an extension to this project at a later stage. The CSC should also have multiple redundancies so that even if one of the sensors fail, the CSC should be able to provide correct values of temperature and voltages of the cells/cell groups. Additionally, the CSC also consists of balancing system to equalize the charges of the individual cells if they have any charge imbalances during its operation. This is achieved by using a passive resistor which dissipates heat to balance the system (Figure 17).

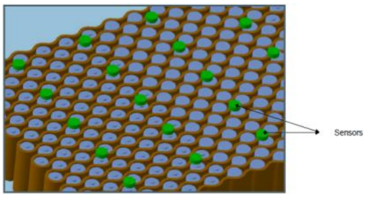

Figure 17: Temperature sensors inside the battery module

Cooling Management System - controls the cooling pump and the coolant flowing in between the cells. It receives signals from the cell supervision circuit about the temperatures of the cell groups and hence controls the working of the coolant system.

Current Sensor - this sensor determines the total current passing through the module. This is achieved by measuring the voltage drop across a resistor in the sensor. This same sensor can measure the battery pack voltage in some cases. The signal from the sensor is an analog signal and hence it is converted into digital signal to be sent to the control system computers.

Battery Housing

The battery housing is the outer covering of the module and is also important in the design process. This outer casing provides mechanical support to the module and houses all the battery cells in the module. The casing is crucial as it has to withstand the acceleration forces of the aircraft and should be able to absorb any forces that the system is subjected to during the course of its operation.

The design of the battery packs mainly depends on the cell type that has been chosen and the battery module structure. This is mainly because the cells expand and contract with changing temperatures during its operation and the casing needs to be precisely designed for the same.

Lithium-ions cells are highly susceptible to expansion and contraction due to changing temperatures as well as when the state-of-health of the cell’s changes. Lithium-ions cells are known to undergo an expansion while being charged and contraction when discharged. They also expand gradually over their lifetime due to the increasing loads and charge-discharge cycles.

The battery module housing should also be designed bearing in mind the application of the battery pack and how it is to be transported or to be placed. In the aircraft taxiing system, since they are being placed in the LD3-45 container inside the cargo hold they should be designed to be possible to be placed inside the container.

The various other components of the battery pack are integrated on to this battery housing for efficiently managing the battery cells. Most importantly, the battery housing provides mechanical strength, thermal insulation and electrical interface to the neighboring modules. It consists of a high voltage plug or adapter interface, an interface for the signals to and from the control system computers and the thermal interface for the cooling system.

The most common materials that are used for manufacturing the module housing are steel, aluminum and plastics. They are chosen based on the needs of the system. Plastics are most commonly used for the outer casing owing to the reduced weight compared to steel and aluminum casings and the stiffness and high strength that it has.

There are various methods for the design of the battery module housing. They can be made of carbon fiber reinforced and glass reinforced plastics (CFRP and GFRP). The housing has sufficient inlet and outlet slots for the coolant tube to pass through them. The major disadvantages of using a plastic housing are its very low melting point which can hinder the safety of the battery pack and its electromagnetic compatibility.

Alternative to using plastics is aluminum casing which is lighter than using steel casing. Aluminum battery housing can be easily designed to reduce the thickness of the housing and easily integrate the battery module components (Figures 18 & 19).

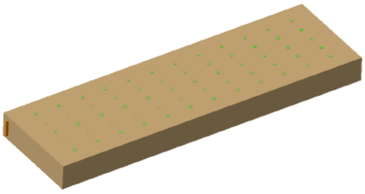

Figure 18: Battery module packaging

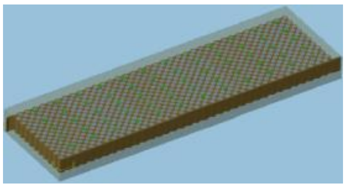

Figure 19: Battery module packaging - housing made transparent

Pressure Equalizer

Since the battery module housing is designed to provide enough space for the expansion and contraction of the cells to take place, there is sufficient gap between the cell structure and the casing. This means that there is an enclosed air volume inside the module. Due to the pressurization of the aircraft and the changing atmospheric pressures on the ground at various places, the sealed housing can be susceptible to damages or breakages due to the pressure imbalances outside and inside the battery module. Hence, it is necessary to balance this pressure inside and outside of the casing to protect the housing from any damages. This gives rise to the need for a pressure equalizing element within the module.

Porous membranes can act as a medium for the exchange of air between the casing and the outer surroundings and also helps in reducing the pressure inside the casing in case of over pressures. The membrane is usually integrated into plastic housing. They rupture when a pressure difference between the two medium is detected to allow air flow through them into or out of the module.

In addition to equalizing the pressure difference between the system and the outside air, adequate ventilation is also required inside the battery pack to let the hazardous gases within the battery pack to be exhausted out. The air inside the aircraft can be used as a medium for this exchange. In some cases, the air ventilation system can also include heating and cooling functions.

The exhaust gases that have been removed from inside the module cannot be permitted back into the module again through the ventilation provided. Hence, the system should include a heat recovery unit or heat exchanger for this exhaust to be removed. This exchanger can prevent the exhaust gases from mixing with the intake air of the battery module.

Condensation Controller

Since the temperatures of the aircraft environment can change with different location and altitude, the battery pack has to be designed to prevent any condensation that may occur. Air molecules has a certain amount of moisture content in it known as humidity and this moisture can cause condensation when exposed to certain low temperatures. At high altitudes, even with cabin pressurization, the water molecules in the air may condense.

Even though the temperature of the aircraft environment is ambient enough, the temperature of the cooling system might be low which can cause the humidity in the module housing to form condensation droplets and get deposited near or within the cell and its interconnections. These droplets can accumulate inside the battery module over time. Condensation within the battery module can cause corrosion and damage the components such as sensors and cell interconnections. Hence, there should be methods to avoid this condensation within the module to ensure safe operation of the battery packs and increase its lifetime. The condensation can be controlled in a variety of ways:

- The cooling temperature of the coolant could be kept at a temperature which is greater than the dew point of the air-water molecules inside the battery housing.
- Water outlets can be provided inside the casing to allow any condensation droplets to flow out of the battery casing.
- Pressure equalizer can also be used to remove the condensation if the humidity is very low.

Control Systems

The control system should be designed to effectively integrate the taxiing control system and the braking and steering control together. The controller should also include displays so that the outputs from the various sensors of the BMS and the BMS controller can be displayed which will enable the pilots to see if there are faults and monitor the working of the system. The displays and cockpit controls can be added to the spare space that is available at the bottom of the central pedestal in the Airbus A320. These controls will be integrated using power electronics and sophisticated software algorithms. This software has to be developed by using proper aerospace software development life cycles and should adhere to RTCA DO-178C [*Software Considerations in Airborne Systems and Equipment*]. They can be placed into the avionics bay of the aircraft along with the control software of other avionics components.

Cables and Connectors

There are three major types of interconnection system within the battery module are the cell connectors, the module housing and the wiring harness.

Cell connectors - it is of the main component of the battery module as they electrically connect the different cells to generate the required current or voltage and form the battery module as such. They enable the cells to be connected in series or parallel depending on our requirements. They can be made of copper or aluminum alloys. The number of cell interconnections are same as there are number of series cells. The overall resistance of the battery module is contributed by this cell interconnections and their contact resistances. The electrical resistance of the battery module is given by:

$$R_{Module} = \Sigma R_{Cell,i} + \Sigma R_{Connector,i}$$

The resistance of the cell connectors is given by,

$$Rconnector = R_{Contact,1} + \rho \cdot l/A + R_{Contact,2}$$

$\rho \cdot l/A$ is the internal resistance of the cell connector. It depends on the material density (ρ), the length of the connector (l) and the area of its cross section (A). The most common method used for interconnecting cells within a battery module is resistance spot welding.

Wiring harness - it consists of the temperature sensors attached to the battery module, the voltage sense wires that are connected to the cell connectors as well as a plug or header as the interface to the CSC of the battery module.

Cable sizing - while designing cables for a system, type of installation, conditions for service, ambient operating temperature, allowable voltage drop, current requirement of the load and the load type are included. Thus, while calculating the insulation needed for the cable, it is better to use the maximum voltage that is available rather than using the nominal output voltage. The selection of the cable is based on the following factors:

- Current carrying capacity,
- Voltage drop,
- Short circuit rating,
- Insulation.

The formula for calculating the thickness of the wire needed is given below:

$$V_{drop} = R_{cable} \cdot I$$

$$R_{cable} = p \cdot length/CrossSectionalArea$$

Where p is the electrical resistivity of the material, length is the length of the cable used and R_{cable} is the resistance of the cable.

For a round cable,

$$R_{cable} = p \cdot length/(\pi \cdot radius^2)$$

Putting this in equation,

$$V_{drop} = p \cdot length/(\pi \cdot radius^2) \cdot I$$

Therefore,

$$radius = \surd[(p \cdot length \cdot I)/(Vdrop \cdot \pi)]$$

Considering a 10-metre copper cable being used for the battery pack, the electrical resistivity, p is $1.68 \cdot 10^{-8}$. The current taken by the load through the cable for 6 modules in series is 345 A.

Assuming a voltage drop of 1 V in the cable is allowable,

$$radius = \sqrt{[(1.68 \cdot 10^{-8} \cdot 10 \cdot 345)/(1 \cdot \pi)]} = 4.29\ mm$$

Hence, we require a copper cable with a minimum radius of 4.29 mm for connecting the battery pack to the motor. This is approximately equal to 6 American Wire Gauge (AWG).

Insulator Sizing

Insulators generally have a very high dielectric strength so that they do not breakdown at high voltages. Solid insulators have more dielectric strength than gaseous insulators. The conductor required was approximately 6 AWG, the corresponding insulator requirement is 6.36 mm. However, the insulator needs to have a high dielectric strength that will not breakdown at 300 - 400 VDC. Usually, in high voltage systems, liquid insulation is used to prevent electrical arcing. Other methods include ceramic or glass wire holders and vacuum.

System Packaging

There are certain containers that are certified to be put in the cargo hold of an Airbus A320. LD3-45 is one among them. Hence this container has been chosen to put the battery pack in the aircraft. The dimensions of the LD3-45 container are given in Table 17 & Figure 20 below.

Table 17: Dimensions of LD3-45 container

	Length	Width	Height
Outside dimensions (mm)	1,562	1,534	1143
Inside dimensions (mm)	1,448	1,448	1,118
Dimensions of top shell outside (mm)	2,438	1,534	
Dimensions of top shell inside (mm)	2,388	1,448	
Door opening (mm)	-	1,422	1,041
Standard weight (kg)	85		
Maximum weight (kg)	1,134		

Figure 20: LD3-45 container

Since 8 modules have been chosen, the possible arrangement is 2 · 4 or (2 · 3) + 2 stacking width wise and height wise for fitting inside the container. The dimensions for both the arrangements are given in Table 18.

Table 18: Arrangement of modules inside the container

	2 x 4 arrangement	(2 x 3) + 2 arrangement
Length (mm)	1,411	1,411
Width (mm)	860	1,290
Height (mm)	440	330

Both arrangements are shown in Figures 21 & 22.

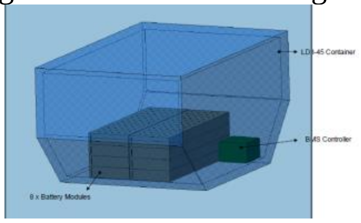

Figure 21: Arrangement (1) of modules inside the container

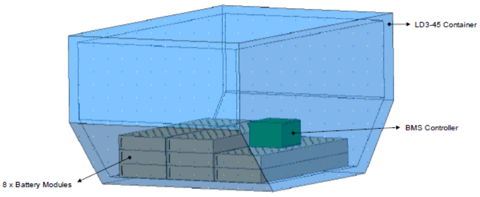

Figure 22: Arrangement (2) of modules inside the container

The dimensions of the BMS Controller are assumed to be 250 mm · 250 mm · 250 mm.

Power Transmission Trade Study

This section discusses the trade-off between high voltage battery pack and a high current battery pack for use in the electric taxiing system. Based on the study, the reason for choosing the high voltage option for the aircraft taxiing system is briefly explained.

High Voltage or High Current

The term high voltage is used when the voltages are above 60 Volts for DC and 30 Volts for AC. Usually high voltages are preferred for battery packs. This is because according to the basics of electricity in physics,

$$P = V \cdot I$$

The power losses in the cable are given by the equation,

$$P_{Loss} = I^2 \cdot R_{cable}$$

As can be seen, the power loss is proportional to the square of the current. Hence, it is imperative to decrease the current and increase the voltage rather than the other way around. High currents, also mean that they require cables having a greater cross-sectional area, i.e., thicker cables. This felicitates the need for heavy wiring or cables and increases the weight of the whole system. If the system is to be designed for minimal weight, then choosing lighter cables would be better. This means that higher voltage rather than higher current is a better idea.

The taxiing system motor that has been selected required 350 VDC and hence it needs to be decided whether the battery pack will generate the required voltage or a DC-DC voltage converter needs to be used for stepping up the lower voltage to the required input voltage for the motor.

The chosen "Tesla" Lithium-ions 2170 batteries can be easily arranged to generate the nominal input voltage required by the motor. The nominal voltage of the battery cell is 3.7 Volts. Thus, 96 cells in series will be required to provide a voltage of 355 V. This eliminates the need for a DC-DC converter and the current rating of each module in this case is 46 Ah. This arrangement not only reduces the need for DC-DC converter, but also eliminates the need for thicker cables to carry heavier current as the current rating of each module is lower.

Mass Analysis

If a low voltage option is chosen, then the system would need a DC-DC converter to step up the battery pack voltage to the voltage required by the motor. In case of AC motors, it would involve the use of an inverter to convert the DC output voltage of the pack into the AC input voltage of the motor (Figure 23).

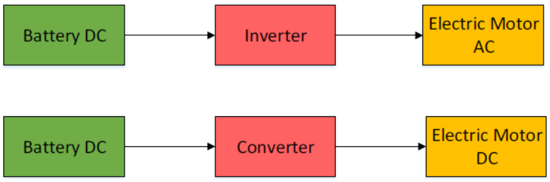

Figure 23: Block diagram representation of using inverter and converter

Adding an inverter/converter would mean additional weight for the system. This would not only increase the number of components but having an additional component will also decrease the overall reliability of the system. Additionally, low voltage option means a high current option. This calls for the need for high superconducting cables to carry high ampere current through it. This would also increase the weight of the system. If a high voltage option is chosen, then the current would be low eliminating the need for High Temperature Superconducting HTS cables and as well as a converter in case of DC motors. AC motors will still need an inverter. For this reason, a DC motor has been chosen for this design.

Insulation Issues

When a high voltage option is chosen, insulation of this system is a major issue. This is because at very high voltages, the insulators breakdown and start conducting. The property of a material that keeps it from breaking down is known as its dielectric strength. Insulators have a very high dielectric strength.

With high voltages, the insulation required would be very high. The cables should have adequate insulation to prevent the user or maintenance technician from getting a major/fatal electric shock. This means that a trade-off has to be considered while choosing between additional insulation for high voltages or heavier cables for higher currents. If the weight and cost of the additional insulation is lesser than the weight and cost of the required cables, then the obvious choice is to go for higher voltages rather than higher currents.

System Assessment and Safety Analysis

The electric system needs to be assessed for safety so that it can be certified as fit to fly. Any system aboard the aircraft needs to adhere to some safety requirements and should be certifiable. This section focuses on safety analysis which includes the functional hazard assessment and the fault-tree analysis, a brief study of the reliability and the certification requirements of the system. The safety analysis of the system has been conducted in accordance with the SAE ARP 4761 [*Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment*]. This includes the FHA and the FTA.

Functional Hazard Assessment (FHA)

The FHA is a preliminary safety assessment process to determine the potential failures of the system and to classify these hazards into failure conditions. The different failure conditions are classified as: no safety effect, minor, major, hazardous and catastrophic starting from the least adverse to the most adverse. The main goal of doing the FHA is to analyze the possible scenarios of failure conditions associated with a system and its subsystems so that appropriate measures can be taken to prevent the failure condition and to assess the severity of the event. Table 19 shows the FHA of the electric taxiing system at both the system level and the subsystem level.

Table 19: Functional hazard assessment (FHA)

System/ Sub-System Function	**Failure Condition**	**Effect**	**Classification**
Battery powered landing gear system	Failure to drive both main landing gears.	Aircraft will not be able to taxi-in or out or pushback without ground assistance methods or main engines.	Minor
	Failure to drive one main landing gear.	Aircraft cannot taxi in or out but with one actuator working, the wheels would rotate and aircraft would turn out of the taxiway at one spot. Could lead to excursion/incursion.	**Hazardous**
	Reduced power input to both main landing gear.	Aircraft will not be able to accelerate and achieve the required speed for taxiing.	Minor
	Fire in the battery pack.	Battery cells could catch fire and explode leading to loss of aircraft while on the ground.	**Catastrophic**
Motor, gearbox and clutch which drive the MLG wheels	Failure of both the motors.	Aircraft will not be able to taxi-in or out or pushback without ground assistance methods or main engines.	Minor
	Failure of one motor.	Aircraft cannot taxi in or out but with one motor providing torque, the wheels would rotate and aircraft would turn out of the taxiway at one spot. Could lead to excursion/incursion.	**Hazardous**
	Fire in any one of the motors.	Could lead to fire spreading and damaging the aircraft.	**Catastrophic**
	Failure of both the gearboxes.	Wheels would not get required torque for taxiing in or out and aircraft would require ground assistance or have to use main engines.	Minor
	Failure of one gearbox.	One wheel would not get enough torque and can lead to aircraft turning and causing incursion/excursion.	Major
	Failure of the clutch mechanism.	Wheels would not get required torque for taxiing in or out and aircraft would require ground assistance or have to use main engines.	Minor
Battery Pack	Failure to provide enough power.	Aircraft will not be able to accelerate and achieve the required speed for taxiing.	Minor
	Fire in the battery module.	Battery cells could catch fire and explode leading to loss of aircraft while on the ground.	**Catastrophic**
	Failure of module interconnection.	Motor will not get sufficient input voltage and will not work and hence taxiing system will not work and aircraft have to use ground assistance or main engines for taxiing.	Minor
	Temperature Sensor	Temperature of cells may increase leading to fire and explosion.	**Hazardous**

	Failure of battery management system.	Pressure equalizer	Pressure imbalance inside the module casing leading to failure of BMS.	Minor
		Condensation controller	Could cause condensation inside the pack or module leading to degradation of the cells.	Minor
		Series Cell interconnection	Module will not provide sufficient input voltage.	Major
		Parallel cell interconnection	Module will not provide necessary power output.	Minor
	Breakage on the battery housing.		Pressure equalizer and other systems might fail.	Minor
Cooling system	Leakage of coolant within the module.		Coolant seeping through the cells might damage it.	Minor
	Leakage of coolant outside the module within the pack.		Cooling system might fail and cause temperature of the batteries to rise.	Major
	Leakage of coolant outside the pack.		Cooling system failure and pack temperature increases. Could cause potential fire event.	**Hazardous**
	Failure of coolant circulation system.		Temperature of the pack could increase and potential fire event.	**Hazardous**
Module interconnections	Failure of cables.	Damage to conductor.	Reduced power input and increased heat loss.	Minor
		Damage to insulator.	High voltages can damage the unprotected surrounding and affect people handling the pack.	Major
Control system computers	Failure to provide signals to both the actuators on the wheels.		Aircraft will not be able to taxi-in or out or pushback without ground assistance methods or main engines	Minor
	Failure to provide signal to one of the actuators on the wheels.		Aircraft could taxi put of the taxiway and cause incursion/excursion.	**Hazardous**
	Failure to provide signal to the battery pack controller.		Aircraft will not be able to taxi-in or out or pushback without ground assistance methods or main engines.	Minor
	Failure to provide correct command to braking system controller.		Aircraft braking will not take place properly.	Major

Fault Tree Analysis (FTA)

FTA provides a thorough analysis of the possible faults of the system and is used as a method to conduct the safety, reliability and maintainability of the system. It uses a top-down approach to determine the causes of possible failure of a system function or component. The failures can be due to a single event or multiple events.

Logic OR and AND gates are used to represent the outcome of multiple events and the events are fed as input to these gates. The OR gate is used when failure of any one of the lower-level component results in the failure of the major component whereas the AND gate is used to represent a group of components that must fail together for the main component to fail. The probability of failures is assigned to these events from the FHA performed and then divided in a top-down manner (Figures 24 & 25).

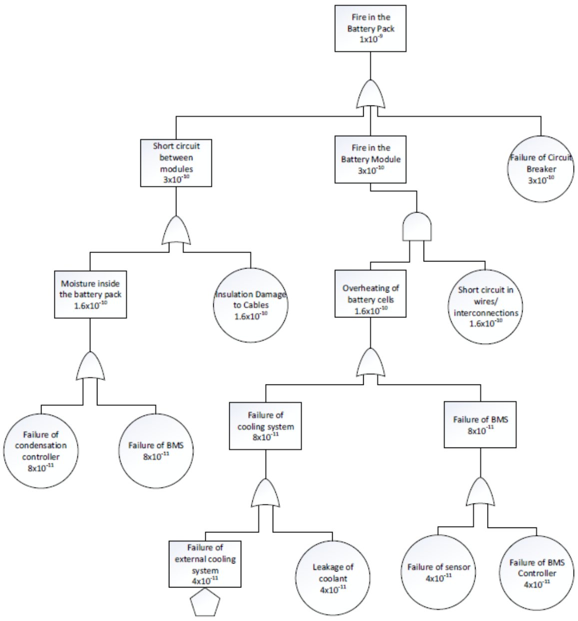

Figure 24: FTA of fire occurring in the battery pack

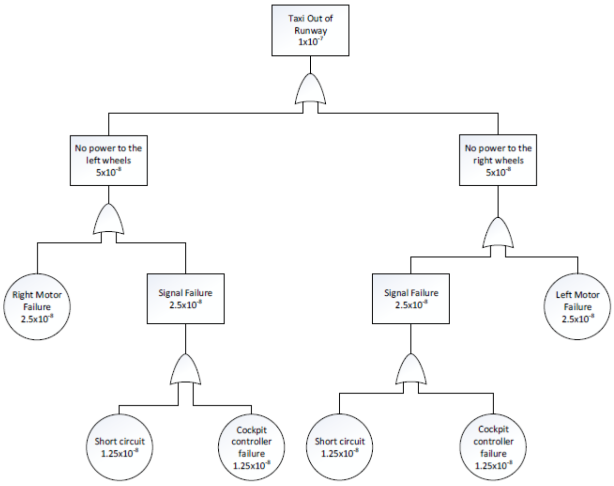

Figure 25: FTA of taxi-out of runway

Reliability

Reliability of a system is calculated at the very early stages of a design process. This is used as a guide for not only understanding how reliable the system is but also as an initial assessment of safety. The reliability analysis is performed at a very early stages of design process to decrease the cost and to avoid any unknown failures. This is because, once the system has been fully designed, rectifying a defective part or mistake could cost time and money. The battery module should be tested for reliability for efficient use onboard the aircraft.

The reliability of the taxiing system is carried by reliability block diagram method which is normally used in the early design stages. The overall reliability of the system is analyzed by combing the various elements of the system into one block and then either treating them as parallel or series blocks.

1. Assign an overall reliability target for the taxiing system: this would mean establishing the number of operational defects allowed in 1,000 hours. For the taxiing system the assumed operational defect rate is 1 defect/1,000 hours.

$$Operational\ Defect\ Rate,\ D_O = 1/1{,}000\ hours$$

2. Identify the different components of the system: the different components that can fail in the battery powered taxiing system including: battery, motor, circuit breaker, fuse, heat exchanger (cooling system), temperature sensor, switch, clutch, BMS controller, relay contacts, cooling system sensor, pressure difference sensor and gear.

3. Assign relative percentage allowances for each component: this step includes setting an allowable failure/defect percentage to each of the components depending on their criticality and how important they are for the overall working and safety of the system (Table 20).

Table 20: Component level relative percentage allowances

Component	Relative Percentage Allowance (P_R) (%)
Battery	10
Motor (per motor)	10
Circuit breaker	0.5
Fuse	0.5
Heat exchanger	1
Temperature sensor	1
Switch	5
Clutch	30
BMS controller	1
Relay contacts	1
Cooling system sensor	5
Pressure difference sensor	5
Gear	20

For the simplicity of calculations, all components have been assumed to be 1 in quantity. In reality there is multiple numbers of these components.

4. Obtain failure rate of each component from a database: the defect rate of a component used in this section are typical values made as an initial assumption. The failure rates are per hour hence they are converted to per 1,000 hours (Table 21).

Table 21: Typical failure rates of different components

Component	**Defect rate/hour**	**Defect rate/1,000 hours**
Battery	$3.84 \cdot 10^{-6}$	0.00384
Motor (per motor)	$1.5 \cdot 10^{-5}$	0.015
Circuit breaker	$1.8 \cdot 10^{-7}$	0.00018
Fuse	$1.1 \cdot 10^{-6}$	0.0011
Heat exchanger	$9.41 \cdot 10^{-6}$	0.0094
Temperature sensor	$3.15 \cdot 10^{-6}$	0.00315
Switch	$1.59 \cdot 10^{-6}$	0.00159
Clutch	$2.6 \cdot 10^{-5}$	0.026
BMS controller	$4.9 \cdot 10^{-6}$	0.0049
Relay contacts	$1.01 \cdot 10^{-6}$	0.00101
Cooling system sensor	$1.42 \cdot 10^{-4}$	0.142
Pressure difference sensor	$2.15 \cdot 10^{-4}$	0.215
Gear	$3 \cdot 10^{-7}$	0.0003

5. Calculate the target reliability of each component: this is calculated from the target reliability of the overall system and the relative percentage allowances of each component. This is then compared to the failure rates of each component. The failure rate of each component should be less than the target set, otherwise that component would not be reliable. Table 22 shows the comparison of the target reliability and the defect rate.

Table 22: Target reliability of each component vs. defect rate

Component	**Target Reliability ($P_R \cdot D_O$)**	**Defect rate/1000 hours**
Battery	0.1	0.00384
Motor (per motor)	0.1	0.015
Circuit breaker	0.005	0.00018
Fuse	0.005	0.0011
Heat exchanger	0.01	0.0094
Temperature sensor	0.01	0.00315
Switch	0.05	0.00159
Clutch	0.3	0.026
BMS controller	0.01	0.0049
Relay contacts	0.01	0.00101
Cooling system sensor	0.05	0.142
Pressure difference sensor	0.05	0.215
Gear	0.2	0.0003

It is evident from Table 22 that the failure rate of cooling system sensor and the pressure difference sensor is more than the reliability target set for it.

6. If there are any unreliable components, it needs to be replaced by a more reliable component: if replacing them is not an option, then they can be duplicated so as to increase the operational reliability. This means that more than one control system sensors and pressure difference sensors can be put in the battery module so that the overall operational reliability increases. Adding two of these sensors would change the reliability to the values as shown in Table 22. When two systems are in parallel, the reliability R is,

$$R = 1 - (\lambda t)^2$$

where, λ is the defect rate/1,000 hours and t is the number of hours. Assuming $t = 1$ hour, for cooling system sensor, $\lambda = 0.142$

$$(\lambda t)^2 = 2.01 \cdot 10^{-8}$$

$R = 0.999999979$ and the new defect rate/1,000 hours is

$$(\lambda t)^2 \cdot 1000 = 0.000020$$

The new defect rate is calculated in a similar manner for the pressure difference sensor (Table 23).

Table 23: New reliability of cooling system sensor and pressure difference sensor

Component	**Target Reliability ($P_R \cdot D_O$)**	**Defect rate/1000 hours**
Cooling system sensor	0.05	**0.000020**
Pressure difference sensor	0.05	**0.000046**

The system components are now reliable and meets the reliability targets that are set.

Windchill software is one of the software which can be used to predict or accurately determine the reliabilities of the system components and of the overall system. It contains a database of most of the electrical and mechanical components. All the calculations and values for the defect rates of components are representative examples and can only be used as an initial assessment for the reliability of the system.

Certification

Various tests such as external short circuiting, overcharge cycles, impact damages and crash tests are very challenging for the battery pack design if they must be certified for use inside the aircraft. The battery cells would have to withstand certain amount of vibrations and pass shock tests if they must obtain appropriate certification from aviation authorities.

The Airbus A320 falls under the large aircraft category for commercial aircraft regulations i.e., CS-25. The regulations are governed by FAA (Federal Aviation Administration) in the USA and EASA (European Aviation Safety Agency) in Europe. For the green electric taxiing system to be successfully certifiable, it would require adhering to the regulations set forth by the above agencies. Few of the main regulations and test requirements have been considered in the following sections.

- **Electrical equipment and installations (CS 25.1353)**
- **Circuit Protective Devices (CS 25.1357)**
- **Electrical Systems Tests (CS 25.1363)**

Since the battery-operated taxiing system is a newly developed concept, additional tests and study would be required to provide full confidence and compliance for the system.

Summary & Conclusions

A detailed study was conducted and involves using a battery powered system to provide sufficient torque to the two motors housed in the main landing gear wheels for the aircraft through a gearbox to perform ground operations such as taxi-in, pushback and taxi-out.

A general review involving the various taxiing systems both existing and currently being developed was investigated. The target performance of taxiing speed 20 knots and the required power for the ground operations were set in the beginning and the design process ensured that these targets were met and the system could effectively work in even critical load conditions.

The system has been designed in a similar manner to the EGTS using an electric motor on the main landing gear wheels to provide the torque required to move the wheels. The source of power for the motor is a battery pack that contains eight battery modules connected in series to generate the required motor output voltage of 350 V and efficiently thermal managed by a cooling system and battery management system consisting of relays, circuit breakers, fuses and sensors. The pack voltage is 355 V and current capacity is 345 Ah with a power output of 123 kWh.

The battery modules with dimensions 1,411 mm · 430 mm · 110 mm and associated BMS controller have been placed into an LD3-45 container to be fitted into the cargo hold of the aircraft and hence can be replaced and effectively recharged at aircraft hangars. It is easy for maintenance personnel to install, handle and carry out repairs by taking out the container and hence the system. Also, the system disconnects from the motors and switches off the power supply as soon as the taxi-out stage or taxi-in stage is complete so that it does not work and remains isolated from the aircraft electrical system.

The total weight of the battery pack is 400 kg and of the total system is 480 kg. This is a 25.9% decrease in weight compared to the “Tesla” battery pack and also shows a significant reduction in weight compared to the previously researched system using fuel cell. Safety assessment involving functional hazard and fault tree analysis reveals that any leakage from the batteries or heating up of the batteries could be potentially dangerous to the aircraft and could result in loss of the aircraft hull and be fatal to passengers onboard if there is fire or an explosion.

A preliminary reliability analysis was conducted for the system to ensure that the system can be said as reliable. Although the values are purely representative and cannot be used for real life purposes, the study has shown that the system is reliable if some components are duplicated.

References

- ACARE Flightpath 2050 Vision for Aviation *Protecting the environment and the energy supply*.
- Battery University. *Advantages and limitations of the Different Types of Batteries* (2017).
- Dubois, T. (2014) *WheelTug, Safran-Honeywell and IAI Offer Three Rival Solutions for Airline Engine-off Taxiing.*
- Bougad, H. (2017) *Feasibility study of a fuel cell powered green taxiing system on conventional A320 class airliner*. Unpublished Work, Cranfield University.
- Skybrary (2018) *Aircraft Batteries*.

- Chandler, D. L. (2016) *New lithium-oxygen battery greatly improves energy efficiency, longevity*, MIT News.
- SAE Aerospace (2012) "*ARP 4761 - Guidelines and Methods for Conducting The Safety Assessment Process on Civil Airborne Systems and Equipment*".
- SAE Aerospace (2011) "*ARP 4754A - Guidelines for the Development of Civil Aircraft and Systems*".
- *European Aviation Safety Agency (2017) "Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes CS-25*".
- Geethu Chandramohan. MSc Thesis (2018) "*Powered Landing Gear System for Taxiing"*. Cranfield University.
- Harrison, J. (2018) *A Look at Tesla's Latest Battery Technologies, Maxim Integrated*.
- Bougad, H. (2017) *Feasibility study of a fuel cell powered green taxiing system on conventional A320 class airliner*. Cranfield University.
- Liu, Z. (2017) *Research on the Performance Impact of Introducing Fuel Cell Powered Green Taxiing System on Conventional A320 Class Airliner*. Cranfield University.
- Vadla, N. (2018) *Design of Cooling System for High Power Avionics*. Cranfield University.

Contact Author Email Address

The corresponding author, Ilan Berlowitz can be contacted at the email address below: iberlowitz24@gmail.com

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