

**Energy model for propeller-powered aircraft  
hybrid propulsion system**  
(versão final após defesa)

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## **Abstract**

In order to respond to a highly demanding industry, the search for new systems of propulsion is increasingly intense due to the environmental impact as well as the performance of such systems. This work aims to explore several flight and work conditions of a hybrid propulsion system in a propeller-powered aircraft by developing a program that simulates the system.

Hybrid propulsion systems can be classified into five categories: series, parallel, series-parallel, complex and fuel cell. In this work the series, parallel, parallel decoupled and parallel coupled configuration are analyzed. By modelling and analyzing how the subsystems work individually and how they perform together, it is possible to analyze the performance of the hybrid system.

To make this application the software used for the programming was the compiler JetBrains PyCharm Community Edition and the language used was Python. Implementing subsystem models with functions and Python loop, the code simulates the performance.

Since the amount of output data is large (from each subsystem), the program shows graphs, and it will automatically create a file with the data so that the user can compare with other configurations or other specifications of the models. For this work, three out of four configurations were simulated: series, coupled with two propeller and coupled with one propeller. By comparing the performance of the systems under the same flight condition, i.e., altitude and velocity, allows to perceive how each configuration works. Being able to compare different configurations allows the user to identify, for example, the system that consume less, the subsystems that can be downsized (like the motor or the engine) or the system that has the higher endurance.

## **Keywords**

Hybrid parallel propulsion; Hybrid propulsion models; Hybrid propulsion system; Hybrid series propulsion; Propeller

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## **Resumo**

Com o intuito de responder a uma indústria altamente exigente, a procura de novos sistemas de propulsão é cada vez mais intensa devido ao impacto ambiental, bem como o desempenho desses sistemas. Este trabalho visa explorar várias condições de voo e de trabalho do sistema de propulsão híbrido numa aeronave movida a hélice, desenvolvendo um programa que simule o sistema.

O sistema propulsivo híbrido pode ser classificado em cinco categorias: série, paralelo, série-paralelo, complexa e célula de combustível. Neste trabalho são analisadas as configurações em série, paralelo, paralelo acoplado e paralelo desacoplado. Ao modelar e analisar como os subsistemas funcionam individualmente e como funcionam em conjunto, é possível analisar o desempenho do sistema híbrido.

Para fazer esta aplicação, o software utilizado para a programação foi o compilador JetBrains PyCharm Community Edition e a linguagem utilizada foi Python. Implementando os modelos do subsistema com funções e ciclos, o código simula o desempenho.

Visto que a quantidade de dados de saída é grande (de cada subsistema), o programa mostra gráficos e criará automaticamente um ficheiro dos dados para que o utilizador possa comparar com outras configurações ou outras especificações nos modelos. Para este trabalho, foram simuladas três em quatro configurações: série, acoplado com duas hélices e acoplado com uma hélice. Comparando o desempenho dos sistemas para a mesma condição de voo, i.e., altitude e velocidade, permite perceber como cada configuração funciona. Ser capaz de comparar diferentes configurações permite ao utilizador identificar, por exemplo, o sistema que consome menos, os subsistemas que podem ser reduzidos (como os motores) ou o sistema que tem a maior autonomia.

## **Palavras-chave**

Hélice; Modelos de propulsão híbridos; Propulsão em série híbrida; Propulsão paralela híbrida; Sistema de propulsão híbrido

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## **Acronym List**

ICE	Internal Combustion Engine
EM	Electric Motor
HEPS	Hybrid-Electric Propulsion System
SFC	Specific Fuel Consumption
UAV	Unmanned aerial vehicle

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## Nomenclature

$a$	Power setting coefficient	
$C_{batt}$	Battery capacity	A s
$C_{actual}$	Actual battery capacity	A s
$C_D$	Drag coefficient	
$C_L$	Lift coefficient	
$C_p$	Power coefficient	
$C_{po}$	Power coefficient at a null advance ratio	
$C_p (J)$	Propeller power coefficient	
$C_{pr}$	Reduced power coefficient	
$C_{pro}$	Reduced power coefficient value at J=0	
$D$	Propeller diameter	inch
$dt$	Step	s
$G_{t,belt}$	Belt transmission gear ratio	
$G_{t,ICE}$	Engine transmission gear ratio	
$G_{t,EM}$	Motor transmission gear ratio	
$g$	Gravitational acceleration	m/s <sup>2</sup>
$I$	Electric current	A
$I_{charge}$	Electric current charging	A
$I_{discharge}$	Electric current discharging	A
$I_{ESC}$	ESC electric current	A
$I_{ESC,EM,in}$	ESC electric current input	A
$I_{ESC,EM,out}$	ESC electric current output	A
$I_G$	Generator electric current	A
$I_{max}$	Maximum current	A
$I_o$	No load current	A
$J$	Advance ratio	
$J_{max}$	Maximum advance ratio	
$k$	Percentage coming from the Generator	
$K_t$	Motor torque constant	Nm/A
$K_v$	Motor velocity constant	rpm/V
$m_{aircraft}$	Aircraft mass	kg
$m_{battery}$	Battery mass	kg
$m_{fuel}$	Fuel mass	kg
$\dot{m}_{fuel}$	Mass flow rate of the fuel	kg/s

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$m_{fuel0}$	Initial mass of the fuel	kg
$N_{EM}$	Motor speed	rpm
$N_{engine}$	Engine speed	rpm
$N_{engine,new}$	Generator speed input	rpm
$N_{min}$	Minimum speed	rpm
$N_{max}$	Maximum speed	rpm
$N_t$	Transmission speed	rpm
$n$	Rotational speed	rev/s
$P_{batt,in}$	Battery power charging	W
$P_{batt,out}$	Battery power releasing	W
$P_{EM}$	Motor power	W
$P_{engine}$	Engine power	W
$P_{engine,new}$	Generator power input	W
$P_{ESC,EM,in}$	ESC power input	W
$P_G$	Generator power	W
$P_{in}$	Motor power input	W
$P_{max}$	Maximum power	W
$P_{min}$	Minimum power	W
$P_{prop}$	Propeller propulsive power	W
$P_{req}$	Required power	W
$P_t$	Transmission power	W
$p$	Propeller pitch	inch
$Q$	Motor torque	Nm
$R_{batt}$	Battery resistance	$\Omega$
$R_{EM}$	Motor resistance	$\Omega$
$R_{ESC}$	ESC resistance	$\Omega$
$R_G$	Generator resistance	$\Omega$
$S$	Wing reference area	m <sup>2</sup>
$sfc$	Specific fuel consumption	kg/(w s)
$sfc_o$	Full throttle specific fuel consumption	kg/(w s)
$SOC$	Battery state of charge	
$T_{prop}$	Propeller propulsive thrust	N
$U_{batt,max}$	Battery maximum voltage	V
$U_{batt}$	Battery voltage	V
$U_{ESC}$	ESC voltage	V
$U_{ESC,EM,in}$	ESC voltage input	V
$U_{ESC,EM,out}$	ESC voltage output	V

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$U_G$	Voltage	V
$U_{max}$	Maximum voltage	V
$V$	Velocity	m/s

### Greek letters

$\beta$	Number of blades	
$\rho$	Air density	kg/m <sup>3</sup>
$\rho_o$	Air density at sea level	kg/m <sup>3</sup>
$\delta_{ESC}$	ESC power setting	
$\delta_{ICE}$	ICE power setting	
$\eta_{EM}$	Motor efficiency	
$\eta_{max}$	Maximum efficiency	
$\eta_r$	Reduced efficiency	
$\eta_{rmax}$	Maximum reduced efficiency	
$\eta_{t,belt}$	Generator transmission belt efficiency	
$\eta_{t,ICE}$	Engine transmission efficiency	
$\eta_{t,EM}$	Motor transmission efficiency	
$\eta_p (J)$	Propeller propulsive efficiency	



# 1. Introduction

## 1.1. Motivation

Over the last years, the propulsion system of drones and unmanned aircraft has improved considerably because of the concern towards the environment impact and the performance of such system. The advantages of a hybrid system are that the internal combustion engine guarantees a long endurance and the electric motor has silent features [1]. On the other hand, there are small/light aircraft that have also improved their propulsion systems and use a more environmentally friendly approach such as the Eviation, an electric aircraft [2]. The concern about the environment has been one of the most debatable issues worldwide and the aeronautical industry is one of the biggest industry polluters. In 2019 the aeronautical industry had almost the same quantity of emissions as the South American continent [3]. If aviation were a country, it would rank 17<sup>th</sup> in the world [4], with such concern the electric and the hybrid propulsion system were options to make a more sustainable approach.

In the late 1880s two French officers, Charles Renard and Arthur Krebs, tried to make an airship, La France, moved with electricity but they encountered problems when the heavy accumulators needed to store the electricity, severely limiting the speed and range of the early airship [5]. It took 100 years to have batteries that could be used in an aircraft, making the concept more realistic [6]. Since the 1970s, electric aircraft exist but they were not manufactured until the power source of the electrical system was more viable.

Batteries are the main problem for the electric and hybrid propulsion systems. The need for a smaller battery with a big specific energy is enormous. Specific energy is the measure of the battery energy per unit mass. Batteries can generally be classified into different categories, types, sizes and chemical composition but under all these they are divided into two major types, primary and secondary. The primary batteries are batteries that cannot be recharged once depleted. These batteries are made of electrochemical cells whose reaction cannot be reversed. This type of battery has a high specific energy and is used commonly in everyday life, but it has low load current. It is mostly known as the alkaline battery and although is environmentally friendly it is used with devices that have low current requirement like a remote control or a flashlight. The other type, the secondary, is made of electrochemical cells that can be reversed by applying a certain current to the battery in the reversed direction, also referred as rechargeable batteries. Low capacity secondary batteries are capable of powering small devices like mobile phones and high capacity batteries are capable of powering electric vehicle and other high drain application. The secondary battery is commonly classified based on their chemistry because it determines some of the attributes such as the specific energy and life cycle [7]. Among the current batteries technology shown in Table 1, the main four chemistry rechargeable batteries are the Nickel-Cadmium, Nickel-

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Metal-Hydride, Lithium-Ion and the Lead-Acid. The Lead-Acid does not have portable application due to its weight.

**Table 1 - Current Batteries Technology, adapted [8]**

Battery technology	Energy Density	Specific Energy
Nickel-Cadmium (Ni-Cd)	50-150 Wh/L 1.2 V per cell	40-60 Wh/kg
Nickel-Metal-Hydride (Ni-MH)	140-300 Wh/L 1.2 V per cell	60-120 Wh/kg
Lithium-Ions (Li-ion)	250-693 Wh/L	100-365 Wh/kg
Lithium Iron Phosphate (LiFePO <sub>4</sub> )	325 Wh/L 3.2 V per cell	90-160 Wh/kg
Lithium Polymer (LiPo)	250-730 Wh/L	100-265 Wh/kg

Petrol has a specific power of 12.5 kWh/kg, which makes the battery storage only 5% of the petrol. To compensate, an electric aircraft must be efficient i.e., high L/D (aerodynamics efficient) and/or lightweight and/or low speed [9].

When the Nickel-Cadmium was invented the first flight with an electric motor, MB-E1, took off but only lasted 15 minutes [10]. In the 1980s John B. Goodenough, invented the first Lithium-Ion batteries [11] and they could store more power than ever before leading to an evolution on the electric planes, like the Solar Impulse 2 in 2015 [12] that only used solar energy but flew at an average speed of 45 to 54.1 km/h [6].

As the electric propulsion system evolved, so did the combustion system, from the most rudimentary to the actual complex engines. Most aircraft engines are either piston engines or gas turbine [13] and the first one to fly was a 4-cycle engine by Wright Flyer in 1903. From there the engines started getting better, therefore other types started to appear, like the V-type piston engine, radial and rotary piston engines, and gas turbine engines. Despite being around for 100 years these types have passed through many upgrades.

There are three phases that helped the evolution of the electric plane. The first phase was from Slovenian company Pipistrel in 2007 the world's first two-seater full electric plane by putting an electric engine in a glider, and today these planes are used in pilot training (Pipistrel Alpha electro 'LN-ELA'). The second phase was with Aimpaire, a Los Angeles company, replaced one of the two engines in a 1973 Cessna with an electric one, proving that a hybrid airplane can fly. The third phase, an electric motor manufacturer MagniX and Vancouver-based airline Harbour Air flew a retrofitted 62-year-old plane (C-FJOS De Haviland Canada DHC – 2 Beaver). A 15-minute test flight in December 2019 made it the world's first all-electric commercial plane to fly.

With the limitations of the range and time duration of a full electric plane, a hybrid system can be a solution and it will be the focus of this work. Combining the combustion engine and the electric

motor it can improve the range of the aircraft while reducing the noise, the environment impact, the fuel consumption and having short take-offs and landings [14]. The hybrid system works best with small propeller planes and unmanned aircraft by using the best features of each part (combustion and electric). Having only the electrical system would limit the system performance due to the battery.

However, the technology is advancing and there are companies that have and/or are working to make a fully electric aircraft like the Eviation or a hybrid aircraft like the Cessna. The Pipistrel E-81 was the first electric aircraft engine to be awarded a type certificate by EASA and it powers the Pipistrel Velis Electro, the first electric EASA type-certificated airplane [15]. In the case of the hybrid system the UAV has more applications and are more palpable. The hybrid powertrain can be parallel, series and series-parallel. In this work, the series and the parallel will be addressed [1].

### **1.2. Objective**

With the concept of hybrid propulsion system from the Motivation section, this dissertation has the objective of studying the performance of these systems and create an application that can show the power being used on the system according to the configuration used and the type of equipment used in the models.

By analyzing the flow of energy that each subsystem produces and the interaction with each other at different flight conditions, such as different altitudes, the user can have an idea of how much energy the system is consuming at different points of the flight without re-entering the data so that the program is more efficient.

To make the energy model of the hybrid propulsion system the language used was Python and the software compiler JetBrains PyCharm Community edition. Although the program provides graphs it also creates a file so that the user can have the data saved for further analyses.

### **1.3. Dissertation structure**

The work outline is as follows: Section 2 describes the types of configurations that exist. Section 3 presents the layouts that are going to be analyzed and the models with its algorithms and how they interact with one another. The models are the ICE, EM, Battery, Generator, Controller, Transmission and the Propeller. Section 4 the code implementation is presented. Section 5 the results are presented and discussed and finally, conclusions and a possible future work are presented in Section 6.

## 2. State of the art

Traditionally, small civilian UAV or small aircraft are mostly powered by an internal combustion engine (ICE), but at the best performance the ICE has a 40% thermal efficiency. With the concern to the environment, a more efficient powertrain has been sought.

The electric motor (EM) is a popular alternative that can have an operation efficiency close to 100%, however it is negated by the necessity of having a big power supply or a battery. The battery in most cases is the largest component representing a large weight penalty, also it has limits with the operation duration and it takes a relatively long time to recharge. Despite with the advancement of the battery technology which have reduced the impact these drawbacks had on the use of the EM, it still was not enough [16].

To mitigate the disadvantages of each propulsion system technology individually, the promising solution is to combine both technologies, integrating an ICE with an EM, thus forming a hybrid system or Hybrid-Electric Propulsion System (HEPS). Hybrid propulsion has been through a big research in the automotive industry, where hybridization yields increased in the fuel efficiency, which have sparked a grow interest in the aviation industry. In contrast with the automotive industry the research in hybrid propulsion system in aircraft is relatively recent making most of the concept theoretical, especially on controls methods and the effect on the aircraft. The main power source for this type of system is coming from the ICE that is supplemented by some form of electric energy, usually coming from batteries. The electrical systems can provide with energy to help the take-off and climbing phases thus helping to reduce the fuel consumption [8].

In larger aircraft the energy storage is one of the fundamental technologies that is essential to support the hybrid propulsion. Fossil fuel can store energy in liquid form which has the advantages of acting as storage in the most complex places like the wings. Alternative storage devices have active investigations in innovative ways to accommodate, e.g., batteries.

Various sources of energy have been explored for the HEPS such as active generators, solar panels, fuel cells and batteries. Generator systems still depend on fossil fuels to generate kinetic energy to transform into electric energy. While this concept does not mitigate the dependency on the fossil fuels it has a greater flexibility with respect to the propulsion system. Photovoltaic solar panels are another popular option that are most likely applicable on large wing aircraft as there is more space to put the solar panels. Flying at a high altitude, above the clouds, allows to avoid any kind of atmospheric block so that it can maximize receiving the solar exposure. For example, the Solar Impulse 2 and the High-Altitude Pseudo-Satellites (HAPS) [17].

Hydrogen fuel cells are another possibility for hybridization since they are thermodynamically more efficient, however, require pressurized hydrogen as the main fuel source before reacting

with oxygen to create electricity, since it is stored in a pressurized vessel which allows high energy per unit mass properties, in contrast relatively low energy per unit volume. This results in large storage components which will have a significant effect in the design modification. Aircraft with hydrogen-based system have been explored by adapting the existing electric aircraft to carry fuel cell technology. The AeroViroment Puma AE aircraft [18] was a successful platform that incorporated fuel cell technology and had an improvement of 300%, i.e., the endurance of the aircraft went from 3h to 9h [19].

The Batteries are considered the mainstream of electric storage technology. The rapid evolution of the batteries has been used in traditional and emerging consumer electronics applications, spanning from smartphones to electric cars. Table 1 from the Motivation chapter lists the specific energies achieved by various battery technologies. There are some innovative battery technologies that show promising potential like the Lithium-Air, Lithium-Sulphate, Zinc-Air, Aluminum-Air, Magnesium Ions and Graphene [20].

Due to low specific energy of batteries, remote controlled aircraft suffer from poor endurance and range when compared with the ICE. Nonetheless, in recent years there has been several attempts in the development of the hybrids designs with different sizes. Since electric motors can deliver additional thrust required in the take-off, landings and climbing phases operations, the ICE could be reduced in size, overall reducing the aircraft weight. In 2011, Siemens AG, Diamond aircraft and EADS took flight in the World's first manned hybrid-electric series configuration [21]. The aircraft propeller was driven by a 70 kW electric motor running on batteries with the primary source being a 30 kW combustion engine generator. This configuration concept is similar to the submarine hybrid-propulsion technology where the ICE runs at its most efficiency rotational speed to charge the batteries. The flight test demonstrated that the series configuration saved significant fuel consumption, since the series configurations allows the engines to run at its ideal speed. It also demonstrated lesser noise on take-off when in electric phase.

### **2.1. HEPS configurations**

In a hybrid propulsion system two or more power sources are combined to increase the efficiency of the vehicle. There are various hybrid powertrain configurations currently in use and it can be divided into five categories: series hybrid, parallel hybrid, series-parallel hybrid, complex hybrid and fuel cell hybrid [22]. The most common configuration being used are the following three: series, parallel and series-parallel. In the following descriptions, the focus is on configurations that have the gasoline (ICE) as primary power source. However, others power sources such as diesel, fuel cell and gas turbine are being used in UAVs [16].

#### **2.1.1. Series configuration**

In the series powertrain configuration, shown in Figure 1, the EM is the only one connected to the mechanical drive train providing power source. This means the ICE can operate in an optimum torque and speed range, regardless of its role as an auxiliary power unit to drive the EM. Usually,

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the ICE is the primary power source and the energy storage system or Battery acts as the secondary. The series configuration performs best at low-speed, high-torque applications such as in buses and other urban work vehicles. However, because the energy goes from the ICE to the Propeller it passes various components, such as the Generator, the Battery and the EM. From the ICE, comes mechanical energy where is converted in the generator to electric energy to be passed to the EM and then lastly converted to mechanical energy to power the propeller. In the process of converting energies between the mechanical and electric system there are losses. In the series configuration, although the ICE is typically smaller because it only needs to meet average power demands, the EM and the Battery generally need to be sized larger to accommodate the peak power demands. With the Generator, this configuration has a significant weight penalty. According to the manufacturers, the DA-36 E-Star – developed by Siemens AG, Diamond Aircraft and EADS – decreases fuel consumption and carbon emission by 25% when compared to the conventional [16].

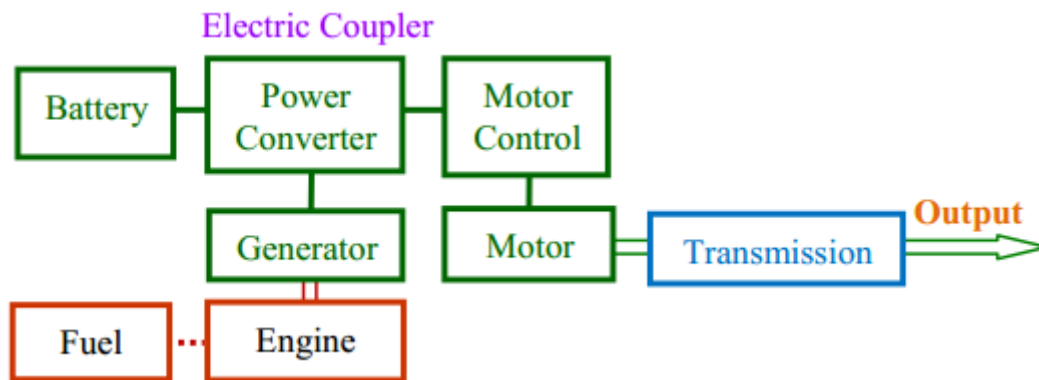


Figure 1 - Series hybrid drive train, adapted [22]

### 2.1.2. Parallel configuration

The parallel configuration shown in Figure 2 enables the powering using the ICE alone, the EM alone or both, depending on the flight operation condition. This configuration has a lot of benefits that can be applied to the civilian and the military. This configuration can be seen in various ground commercial vehicles, such as the Honda Insight, Civic and Accord hybrids [23]. In this configuration is most likely that the ICE cannot operate in its most efficient region, because it is directly coupled to the wheels in ground vehicles or the propeller shaft in aerial vehicles through a transmission consequentially limiting the energy efficiency. One of the solutions to mitigate the problem is implementing a Continuously Variable Transmission (CVT) in lieu of a conventional transmission. However, this presents additional difficulty with the control strategy to schedule the torque from individual or combined power sources to maximize the efficiency [24,25]. There can be innumerable approach with this configuration, and one of them is sizing the ICE to the cruise speed, with an EM and Lithium-Ion battery pack sized for endurance. The main power source like the series configuration comes from the ICE.

A German aircraft manufacturer, Flight Design, coupled a 29.8 kW (40-hp) EM with an 85.8 kW (115-hp instead of a 116-hp) Rotax 914 aircraft ICE, in a parallel HEPS configuration for a lighter-sport aircraft [26]. The EM provides a boost of approximately of 5 minutes during take-off and climbing which allowed the downsized of the ICE.

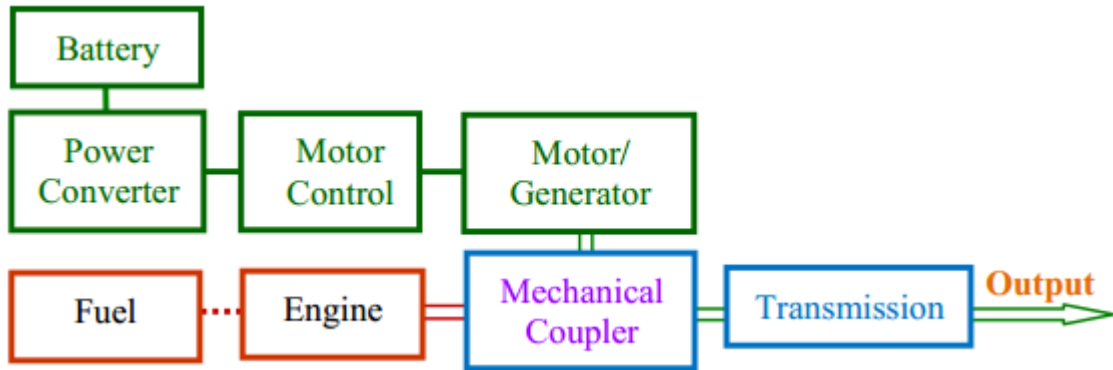


Figure 2 - Parallel hybrid drive train, adapted [22]

### 2.1.3. Series-parallel

The power-split hybrid or series-parallel hybrid, Figure 3, are parallel hybrids that incorporate power-split devices allowing the planetary gear set to transfer the power generated by the ICE and/or EM to propel the aircraft. There is not a direct connection between the various power plants and mechanical drive train. This configuration is used in many ground vehicles such as the Toyota Prius [27] and the Ford Hybrid Escape but there is not any knowledge of being used in aviation for now. The advantage of a power-split over the other configurations is the efficiency at reducing the fuel consumption and the emission, because of its ability of combining the power sources. However, the design is very complex making the cost and the control strategies that are required to operate difficult [16].

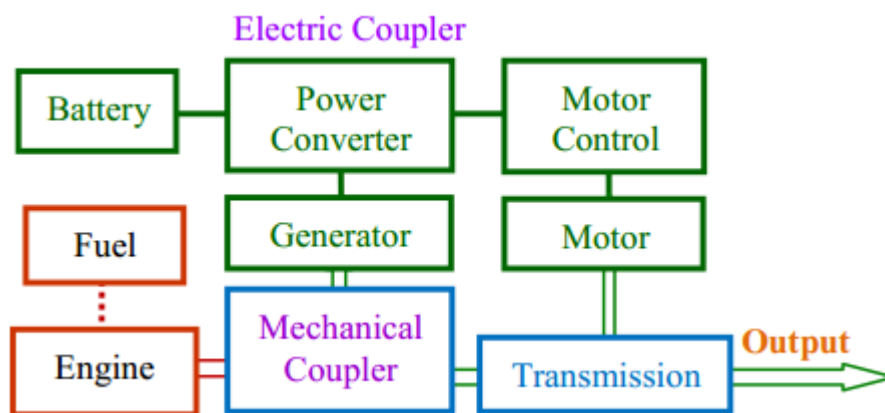


Figure 3 - Series-parallel hybrid drive train, adapted [22]

### 2.1.4. Complex hybrid

The complex hybrid, Figure 4, drive train also consist of both mechanical and electric couplers similar to the series-parallel but with an additional power converter. This configuration has the features of both series and parallel configurations, allowing it to work with only the ICE, the EM or both [22].

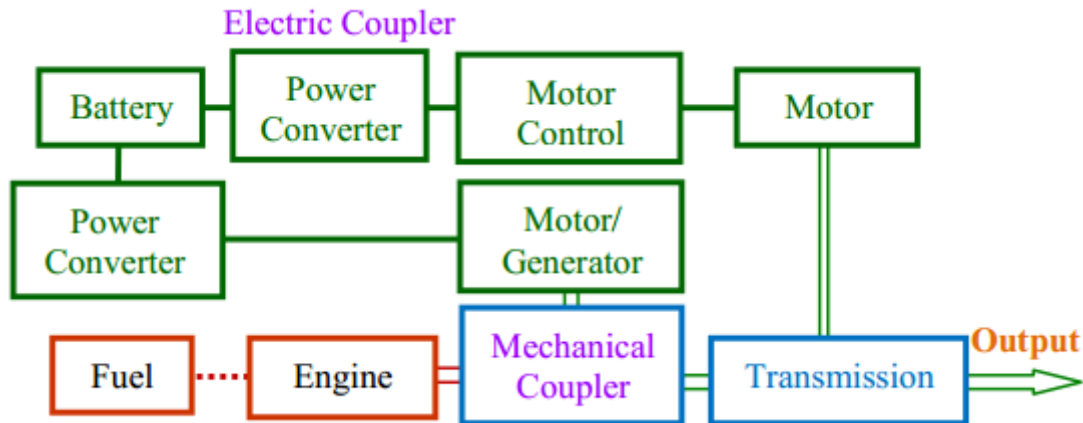


Figure 4 - Complex hybrid drive train, adapted [22]

### 2.1.5. Fuel cell hybrid

The configuration of the fuel cell hybrid is like the series configuration that was approached (Figure 1). The power lines are electrical coupled and when applied to UAVs, the system takes the shape shown in Figure 5. The successful flight of the fuel cell hybrid model conducted by NCKU (National Cheng Kung University) on May 13, 2010, proved that this fuel cell hybrid drive train could be effectively implemented in a UAVs but, as already mentioned, the problems with the fuel cells are that they need to be pressurized and they need to use a larger compartment [22].

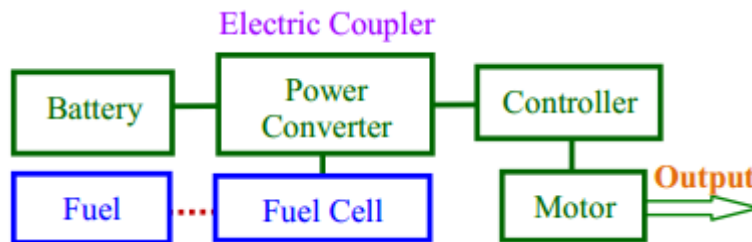
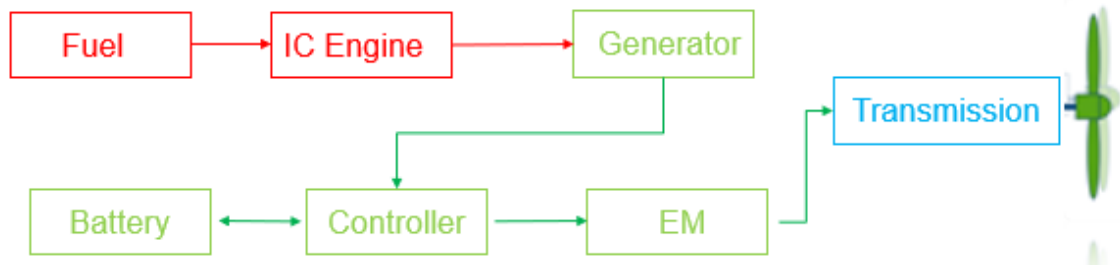


Figure 5 - Fuel cell hybrid electric power train, adapted [22]

### 3. Configurations to be analyzed

With five types of configurations, only two of them are presented here, series and parallel. But within the parallel type, there are three different layouts presented: parallel hybrid, decoupled hybrid and coupled hybrid.

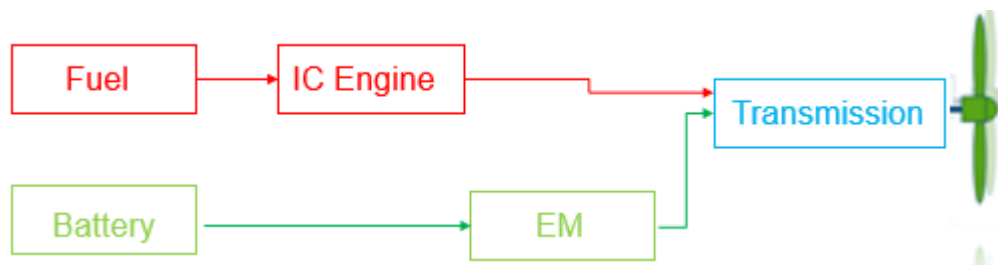
Similar to Figure 1, the models presented in the layout shown in Figure 6 are: Fuel, ICE, Generator (electric), Battery, Controller, EM, Transmission and Propeller. It works as a normal series configuration, by having the ICE as the main power source which works best at low speed and high torque.



**Figure 6 - Series configuration**

Different from the series configuration, the parallel configuration does not have the combustion and the electric parts separated, allowing the ICE to be downsized. Depending on the parallel configuration, these parts can be connected through the same transmission.

The most common parallel configuration, Figure 7, has one propeller with a transmission connecting the two motors like the 1973 Cessna Empire. This configuration presents difficulty with the EM and with the ICE as they are not working in their most efficient region. The Fuel and the ICE are parts of the combustion, and the Battery and EM are parts of the electric.



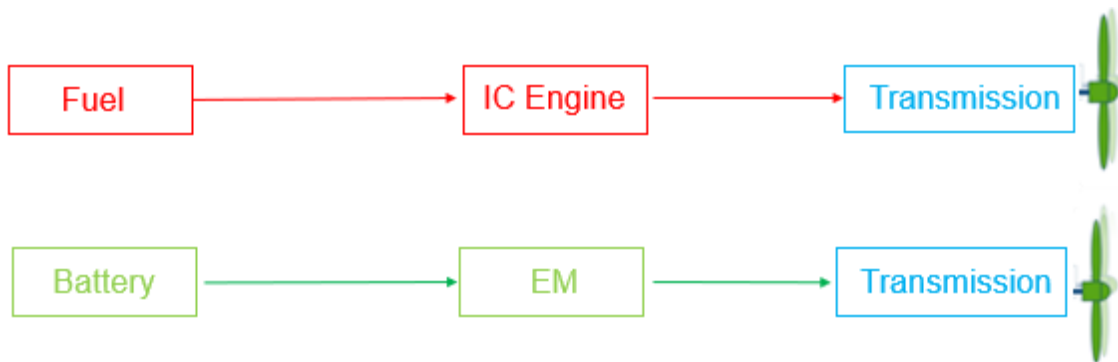
**Figure 7 - Parallel Configuration**

The distributed propulsion system has been a milestone for aircraft since it is based on dividing up the thrust for the beneficial gain of noise reduction, shorter take-off and landing, enhanced

## Energy model for propeller-powered aircraft hybrid propulsion system

specific fuel consumption and flight range [14]. With a hybrid there is a weight penalty due to the battery since the greater the battery capacity, the heavier it is.

The parallel decoupled configuration, shown in Figure 8, uses the milestone of distributed propulsion system. The HEPS could have both propellers working at the same condition, such as velocity and thrust, depending on the power source and the power that the ICE and the EM can produce. Each motor is connected to a propeller making them work independently. The quantity of fuel, battery capacity and the engine and motor specification will dictate the period that will work. Depending on the aircraft performance, if either the ICE or the EM stops working before the other due to Fuel or Battery depletion it could be fatal. The remaining component will begin, if it can, an emergency landing with the power that it has left.

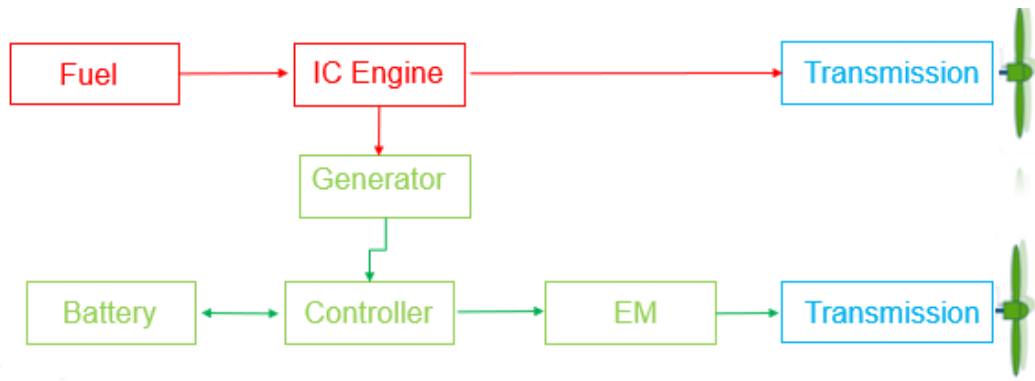


**Figure 8 - Parallel decoupled configuration**

In this case having one of the subsystems, electrical or combustion, producing more power than the other one is not the ideal solution. But since they both work at a specific required power, they will always have the same output. The best solution is to have both at the same working time.

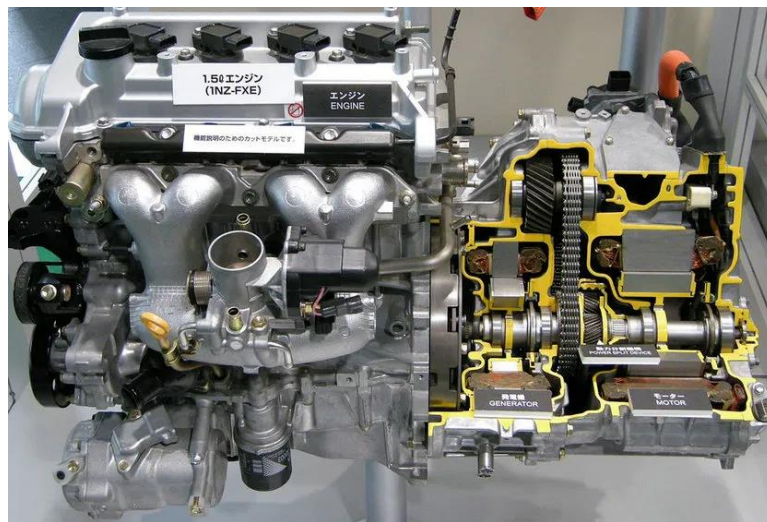
The parallel coupled configuration, Figure 9, is similar to the series-parallel hybrid drive train (Figure 3) and the decoupled configuration, but the main difference is that the two subsystems are connected and have two propellers. With the electric Generator present, the power that the ICE is producing is directed to the propeller through the Transmission and through a transmission belt to the Generator (Figure 10).

## Energy model for propeller-powered aircraft hybrid propulsion system



**Figure 9 - Parallel coupled configuration**

The combustion subsystem also acts as an auxiliary power source to the electrical subsystem besides making its own propeller work. With the help from the ICE, the size and the weight of the batteries can be mitigated allowing this configuration to work a more extended period of time or/and having the batteries depletion reduced.



**Figure 10 - Motor and Generator connected through a transmission belt, adapted [28]**

### 3.1. Subsystem model

The hybrid propulsion system algorithm is constituted by several subsystems models, with the purpose of estimating the energy flow. To further understand the flow of energy, the system will be divided by its subsystems. Being subsystems, they are connected with each other, therefore they will not act totally independent. Figure 11 represents the general concept of a model. Having the  $X_{input}$  as the function of the inputs of the model, the  $X_{data}$  as the information of the model in question such as the specifics of flight or the conditions of work of the subsystem, the  $X_{control}$  (if present) acts as the one that controls the flow of energy and the  $X_{output}$  is what is coming from the model (output). A color code is used to identify the various subsystems. Red represents the combustion subsystem, green represents the electrical subsystem, blue represents the Transmission and the propeller.

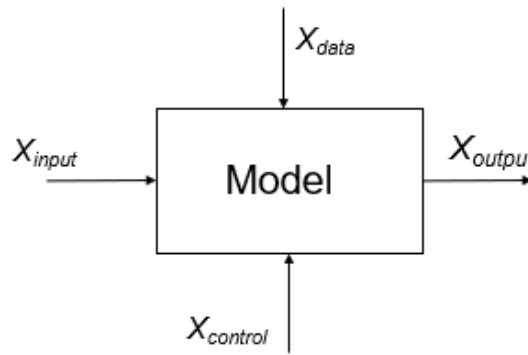


Figure 11 - Model Variables

### 3.2. Individual subsystem

#### 3.2.1. Fuel subsystem

The ICE works while the Fuel subsystem has fuel since it is the ICE only power source. The Fuel model, Figure 12, has the objective of calculating and presenting the quantity of fuel left in the tank.



Figure 12 - Fuel Model

## Energy model for propeller-powered aircraft hybrid propulsion system

To calculate the level of fuel in the tank, it is necessary to know the input and the output variables. In Figure 12 the input and output variables of the subsystem are listed.

The remaining fuel mass in the tank is obtained by subtracting the integral of the fuel mass flow rate over a time interval from the initial fuel mass. By having the initial quantity of fuel and the quantity being consumed, it shows the current level in the tank. Equation 1 represents the output of this subsystem.

$$m_{fuel} = m_{fuel0} - \int \dot{m}_{fuel} dt \quad (1)$$

Almost all the inputs are provided by the user, as shown in Table 2. The mass flow rate,  $\dot{m}_{fuel}$ , is an input only known by the ICE, being an input to the Fuel but an output for the ICE subsystem. The step is represented by  $dt$  and  $m_{fuel0}$  is the initial fuel mass.

### 3.2.2. ICE subsystem

A piston engine performance depends on the engine characteristics, the Fuel subsystem and the flight condition such as the altitude, and the throttle to calculate the power produced. Knowing the  $X_{input}$  and  $X_{data}$ , this model is one of the few that has a  $X_{control}$  for regulating the power being produced.

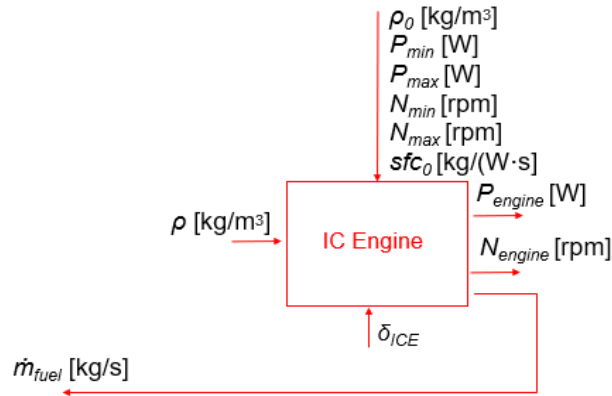


Figure 13 - ICE Model

As presented in Figure 13 one of the variables in  $X_{output}$  is going to the  $\dot{m}_{fuel}$  for the Fuel subsystem as mentioned previously. The  $X_{control}$ ,  $\delta_{ICE}$ , known as the power setting, is a way of controlling the engine's power by regulating the engine inlet manifold pressure. The specific fuel consumption is a function of the power setting (Equation 2) [29] and is given by

$$sfc = f(\delta_{ICE}) sfc_0 \quad (2)$$

Equation 3 is a simpler equation of the function of the power setting.

$$f(\delta_{ICE}) = \delta_{ICE}^a \quad (3)$$

Coefficient  $a$  depends on the type of engine [30]. Table 2 presents some examples.

**Table 2 – Examples of some coefficient  $a$  for different engines, adapted [30]**

Type of motor	$a$
2-cycle gas	0.8
Turbocharged 2-cycle gas	0.670
Turbocharged 4-cycle gas	0.243
Turbocharged 4-cycle gas-diesel	0.183
Turbocharged 4-cycle diesel	0.031

The value of  $\delta_{ICE}$  is within  $0 \leq \delta_{ICE} \leq 1$ . Figure 13 shows all the variables used in the model and its units.

The engine shaft power can be expressed as shown in Equation 4, where it depends on the flight condition,  $\rho$ , and the ICE characteristics.

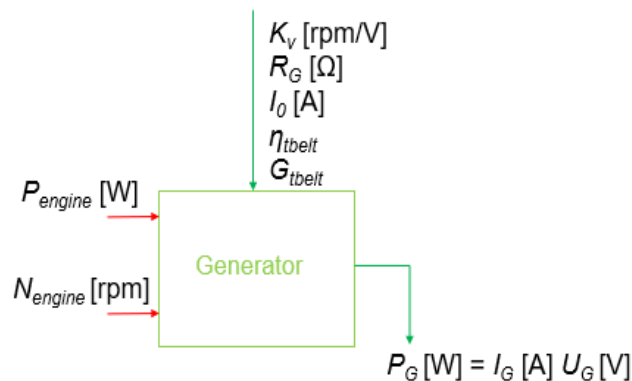
$$P_{engine} = \delta_{ICE} \frac{\rho}{\rho_0} \left[ P_{min} + \frac{P_{max} - P_{min}}{N_{max} - N_{min}} (N_{engine} - N_{min}) \right] \quad (4)$$

With the results from Equation 2 ( $X_{control}$ ),  $sfc$  is known and with  $P_{engine}$  from Equation 4 ( $X_{output}$ ) the fuel mass flow rate can be calculated with Equation 5 [29].

$$\dot{m}_{fuel} = sfc P_{engine} \quad (5)$$

### 3.2.3. Generator subsystem

A generator is a device that converts mechanical energy into electric energy and is used to help the electric part work, so that the demand from the battery is not too high, or to supply for the entire system. The generator, Figure 14, act as a reversed model of the electric motor.



**Figure 14 - Generator Model**

With the mechanical energy provided by the ICE the generator produces the electric energy associated, but this motor does not have a way of controlling the energy that is sending to the

electrical subsystem. The ICE will be serving as a regulator to the generator in for the series configuration. For the parallel coupled the generator will not have a regulator, since it connects the ICE and the generator through a transmission belt. The Generator can only contribute what is producing at some extent when working as an auxiliary power source.

The generator has a different way of working in the coupled parallel configuration, where it uses a transmission belt like in the automotive industry (Figure 10), in hybrid cars. Starting with the most common electric generator model used in the series configuration, the energy conversion is done with the same principles of the electric motor but in reverse.

With the transmission belt, the process is the same but only before calculating the torque,  $Q$ , it is necessary to know how much power is going to the generator.  $G_{tbelt}$  is the gear ratio of the transmission belt and  $\eta_{tbelt}$  the belt efficiency.

$$P_{engine,new} = \eta_{tbelt} P_{engine} \quad (6)$$

$$N_{engine,new} = G_{tbelt} N_{engine} \quad (7)$$

### 3.2.4. Battery subsystem

The starting point of the electric part is the battery (Figure 15), like the fuel it is a power source, but this is for the electric motor.

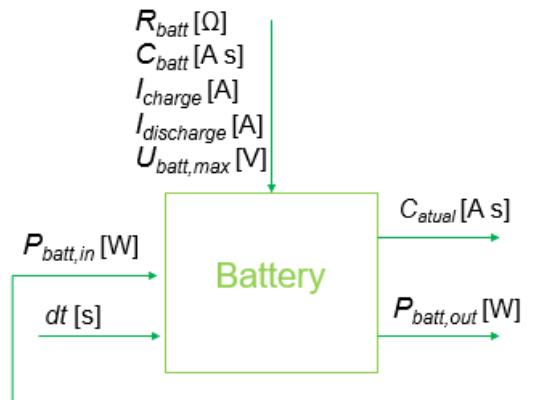


Figure 15 - Battery Model

The main function of the battery is to provide the required current and voltage to the electrical motor. Additionally, it can be recharged, if necessary, when the ICE is generating excess power to that of what is required at specified altitude. There are two configurations that have the option to recharge, and they are the coupled parallel configuration and the series configuration.

One of the  $X_{output}$  is estimated by knowing the voltage and the current load that the battery is releasing.

$$P_{batt,out} = U_{batt} I_{discharge} \quad (8)$$

Equation 9 represents the voltage being released. Where  $U_{batt}$  is the voltage being released,  $U_{batt,max}$  is the actual voltage in the battery,  $I_{discharge}$  the discharge current and  $R_{batt}$  the resistance of the battery.

$$U_{batt} = U_{batt,max} - R_{batt} I_{discharge} \quad (9)$$

The state of charge (SOC) is the available capacity and expressed as a percentage of its rated capacity and a way to calculate the SOC is by using the coulomb counting method [31]. A simplified version with the coulomb counting method is used to calculate the remaining capacity by accumulating the charge transferred in or out of the battery.

$$SOC = 100 \left( 1 - \frac{\int_0^t I_{discharge} dt + \int_0^t I_{charge} dt}{C_{batt}} \right) \quad (10)$$

The other  $X_{output}$  is estimated by knowing what is consuming and what is releasing.

$$C_{actual} = C_{batt} SOC \quad (11)$$

### 3.2.5. Controller subsystem

This system only exists in two configurations and its purpose is to redirect the energy flow depending on what the system is demanding.

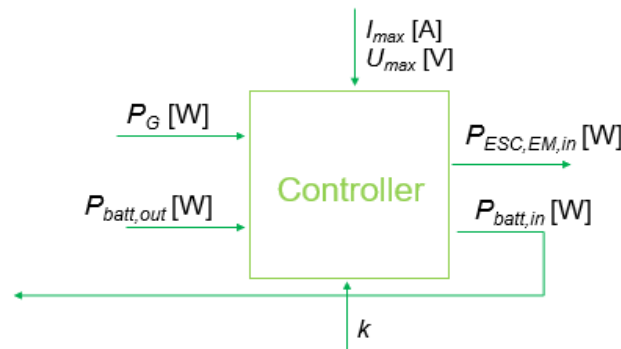


Figure 16 - Controller Model

Figure 16 shows the power is entering from the Generator and the Battery, and it is leaving to the battery (if recharging) and to the ESC-EM. It may be overlooked the importance of the Controller but depending on the configuration and condition its use is unique and can benefit the propulsion system. The HEPS Controller carries out the required control functions for the Battery, Generator

and EM. Knowing what the EM needs, the Controller redirects what the Generator and the Battery is producing to the EM. The power produced by the Battery and the Generator changes depending on what the system needs i.e., the current. When the Battery is recharging the same principle of redirecting the power is applied, by having the Controller sending the required power to the EM and at the same time recharging the Battery. The voltage associated with charging and depleted are set in the input file, making the current vary.

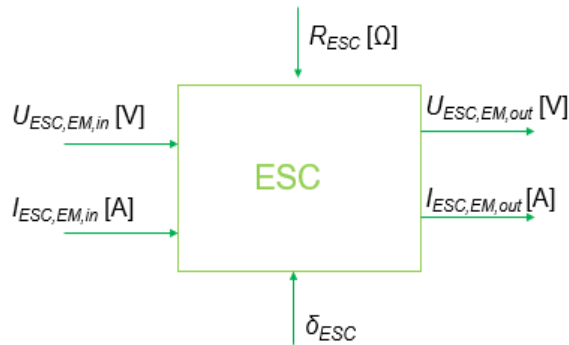
**Table 3 – Controller: different situations**

	Charging	Not charging	Only the Battery	Only the Generator
$P_G$	$U_G I_G$	$U_G I_G$	-	$U_G I_G$
$P_{batt,out}$	$U_{batt} I_{discharge}$	$U_{batt} I_{discharge}$	$U_{batt} I_{discharge}$	-
$P_{batt,in}$	$U_{charge} I_{charge}$	-	-	-
$I_{discharge}$	$(1-k) I_{ESC,EM,in}$	$(1-k) I_{ESC,EM,in}$	$I_{ESC,EM,in}$	-
$I_{charge}$	$I_{charge}$	-	-	-
$U_{charge}$	$U_{charge}$	-	-	-
$I_G$	$k I_{ESC,EM,in}$	$k I_{ESC,EM,in}$	-	$I_{ESC,EM,in}$

Table 3 has different situations where the Generator and the Battery are working and  $k$  represents the percentage coming from the Generator, e.g., 0.35. If it is not charging  $I_{batt,in}$  and  $U_{batt,in}$  are equal to zero. When the Controller current and/or voltage are higher than what the EM can tolerate,  $I_{ESC,EM,in}$  will have the value of  $I_{max}$  and/or  $U_{ESC,EM,in}$  will have the value of  $U_{max}$ .

### 3.2.6. Electric Motor subsystem

In contrast with the generator the electric motor, Figure 18, is a device that converts the electric energy to a mechanical energy. On contrary of the Generator that had its power regulated by the ICE, this type of motor needs an ESC, Figure 17, to regulate the power that the motor will produce.



**Figure 17 - ESC Model**

The voltage and the load current are going to the ESC, and the current that it enters it is the same that gets out, but the voltage alters according to  $\delta_{ESC}$  and its internal resistance.

$$U_{ESC,EM,out} = \delta_{ESC} (U_{ESC,EM,in} - R_{ESC} I_{ESC,EM,out}) \quad (12)$$

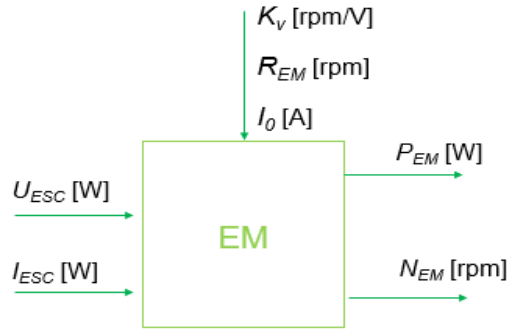


Figure 18 - EM Model

Electric motors are characterized by their weight, voltage, and maximum power output, but also by several other parameters that determine how the efficiency and the power vary with the rpm. There are three basic constants that can characterize the motor performance: the rpm, the torque and the  $K_v$ . These are the ones that are needed to calculate the power coming from the electric motor.  $K_v$  relates the motor speed ( $N_{EM}$ ) to the voltage applied, where  $U$  is the applied voltage,  $I$  the current and  $R$  the armature resistance (Equation 14).  $K_v$  is often specified for a particular motor, and due to the  $K_v$  and the  $K_t$  are related, only the  $K_v$  needs to be specified (Equation 13). The motor torque is related to the applied current (Equation 17) where the  $Q$  is the torque and  $I_o$  is the non-load current at the specified voltage [32].

$$K_t = \frac{1}{2\pi \cdot K_v} 60 \quad (13)$$

$$N_{EM} = K_v (U_{ESC} - I_{ESC} R_{EM}) \quad (14)$$

$$Q = K_t (I_{ESC} - I_o) \quad (15)$$

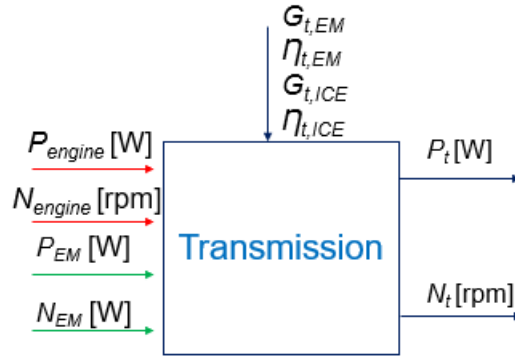
$$P_{EM} = Q N_{EM} \frac{2\pi}{60} \quad (16)$$

$$P_{in} = U_{ESC} I_{ESC} \quad (17)$$

$$\eta_{EM} = \frac{P_{EM}}{P_{in}} \quad (18)$$

### 3.2.7. Transmission subsystem

With different configurations there may be some small differences in the  $X_{input}$  but the process of knowing the outputs variables is the same. The parallel configuration is the only one that has the power supplied by the ICE and the EM using the same transmission.



**Figure 19 - Transmission Model**

In the case that the transmission, Figure 19, is only receiving energy from one of the power sources the other one is considered null. The ICE and EM rotational speed is the same so, like Equation 20 the rotational speed of the transmission is equal as the ICE or the EM.

With the  $X_{input}$  and the  $X_{data}$  the process of calculating the power and the rpm that the transmission emits is similar to the transmission belt of the generator. By using the efficiency,  $\eta_t$ , the power is calculated

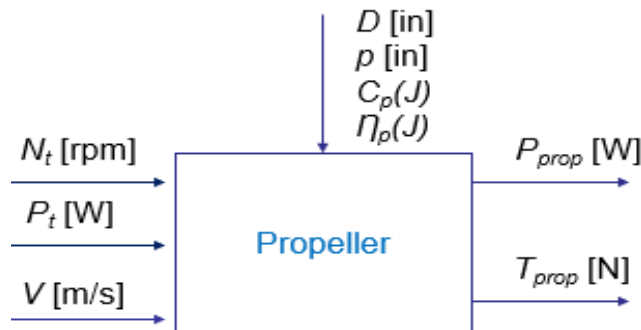
$$P_t = P_{EM} \eta_{t,EM} + P_{engine} \eta_{t,engine} \quad (19)$$

And with the gear ratio,  $G_t$ , the rotational speed is calculated so that both have the same value.

$$N_t = N_{EM} G_{t,EM} = N_{ICE} G_{t,engine} \quad (20)$$

### 3.2.8. Propeller subsystem

The power supply from the ICE and EM is going to be used as the propeller power. The performance of the propeller will reflect the performance of the whole hybrid system.



**Figure 20 - Propeller Model**

The Propeller uses two models to encompass all the dimensions of the blade. The output of a detailed model is a table of coefficient of power ( $C_p$ ) and efficiency ( $\eta$ ) vs the advance ratio.

## Energy model for propeller-powered aircraft hybrid propulsion system

The propeller rotational velocity is in cycles per second, and it can be expressed by

$$n = \frac{N_t}{60} \quad (21)$$

Advance ratio is the distance advanced by the propeller in one revolution, made dimensionless with propeller diameter. Therefore,  $J$  is expressed as

$$J = \frac{V}{nD} \quad (22)$$

In this work the value of the velocity,  $V$ , is converted to inch per second since the diameter is in inches, to make the advance ratio dimensionless.  $D$  is the diameter of the propeller.  $p$  is the pitch, often described in terms of units of distance that the propeller would move forward in one rotation.  $V$  is defined as relative wind speed.

The two models used describe the performance of the propeller, so that it could include different diameters and pitches. These mathematical models describe the performance of a two blades propeller. Through Table 4 the propulsive efficiency can be corrected from two blades to three and four blades.

For the first model with the dimension of  $D \in [7, 20]$ ,  $p \in [4, 15]$  and  $\frac{p}{D} \in [0.4, 1]$ . The analytical model consists of five equations (Eq. 23 to 29) [33].  $J_{max}$ ,  $C_{pro}$  and  $\eta_{rmax}$  are polynomial functions of  $D$  and  $p$  only in the form:

$$\begin{aligned} J_{max}(D, p) = & -1.099 + 0.1789D + 0.7614p - 0.001555D^2 - 0.1169Dp - \\ & 0.01523p^2 - 0.0005051D^3 + 0.005775D^2p + 0.003119Dp^2 - 0.0007585p^3 \\ & - 0.000004304D^3p - 0.000273D^2p^2 + 0.0001492Dp^3 - 0.00001965p^4 \end{aligned} \quad (23)$$

$$\begin{aligned} \eta_{rmax}(D, p) = & -0.3875 + 0.1077D + 0.05883p - 0.01285D^2 + 0.002117Dp - \\ & 0.1179p^2 + 0.0006309D^3 - 0.0001054D^2p - 0.00006636Dp^2 + \\ & 0.0009324p^3 - 0.00001161D^4 + 0.000005865D^3p - 0.00001089D^2p^2 + \\ & 0.0000178Dp^3 - 0.00003423p^4 \end{aligned} \quad (24)$$

$$\begin{aligned} C_{pro}(D, p) = & 0.0136 - 0.00469D + 0.005591p + 0.0004904D^2 - \\ & 0.0008541Dp + 0.0001986p^2 - 0.00001569D^3 + 0.00003468D^2p - \\ & 0.00001612Dp^2 + 0.000002577p^3 \end{aligned} \quad (25)$$

Equation 26 and Equation 27 are the quotient of the reduced power coefficient and the propulsive efficiency. With the reduced power coefficient, it must be divided by its value at  $J = 0$ , which is

## Energy model for propeller-powered aircraft hybrid propulsion system

called  $C_{pro}$ , and the  $\eta_r$  must be divided by its maximum value,  $\eta_{rmax}$ , and  $J$  is divided by  $J_{max}$ . Continuing the first model, it consists of the two set of equations for  $\frac{C_{pr}}{C_{pr0}}$  and  $\frac{\eta}{\eta_{rmax}}$ .

$$\begin{aligned} \frac{C_{pr}}{C_{pr0}} \left( \frac{J}{J_{max}}, \frac{p}{D} \right) = & \quad (26) \\ & 1 + 1.177 \left( \frac{J}{J_{max}} \right) + 0.004779 \left( \frac{p}{D} \right) - 5.287 \left( \frac{J}{J_{max}} \right)^2 - 1.654 \left( \frac{J}{J_{max}} \right) \left( \frac{p}{D} \right) + \\ & 8.743 \left( \frac{J}{J_{max}} \right)^3 + 6.371 \left( \frac{J}{J_{max}} \right)^2 \left( \frac{p}{D} \right) - 9.728 \left( \frac{J}{J_{max}} \right)^4 - 6.741 \left( \frac{J}{J_{max}} \right)^3 \left( \frac{p}{D} \right) + \\ & 4.49 \left( \frac{J}{J_{max}} \right)^5 + 1.812 \left( \frac{J}{J_{max}} \right)^4 \left( \frac{p}{D} \right) \end{aligned}$$

$$\begin{aligned} \frac{\eta}{\eta_{rmax}} \left( \frac{J}{J_{max}}, \frac{p}{D} \right) = & \quad (27) \\ & [5.702262681 \left( \frac{J}{J_{max}} \right) - 38.01485015 \left( \frac{J}{J_{max}} \right)^2 + 161.4243788 \left( \frac{J}{J_{max}} \right)^3 - \\ & 315.6039562 \left( \frac{J}{J_{max}} \right)^4 + 279.2845206 \left( \frac{J}{J_{max}} \right)^5 - 92.79235578 \left( \frac{J}{J_{max}} \right)^6] \frac{p}{D} \\ & [8.151725438 \left( \frac{J}{J_{max}} \right) - 116.4783213 \left( \frac{J}{J_{max}} \right)^2 + 533.0383366 \left( \frac{J}{J_{max}} \right)^3 - \\ & 1032.988581 \left( \frac{J}{J_{max}} \right)^4 + 891.0573894 \left( \frac{J}{J_{max}} \right)^5 - 282.7805492 \left( \frac{J}{J_{max}} \right)^6] + \left( \frac{p}{D} \right)^2 \\ & [5.427814965 \left( \frac{J}{J_{max}} \right) - 95.74279874 \left( \frac{J}{J_{max}} \right)^2 + 466.6603959 \left( \frac{J}{J_{max}} \right)^3 - \\ & 938.6448505 \left( \frac{J}{J_{max}} \right)^4 + 837.3278541 \left( \frac{J}{J_{max}} \right)^5 - 275.0284158 \left( \frac{J}{J_{max}} \right)^6] \end{aligned}$$

To get the estimated value of the  $C_p$  and the  $\eta_p$  it can be solved with the following two equations with four variables (advance ratio, propeller diameter, propeller pitch and the propeller rotational velocity):

$$\eta_p(J, D, p, N_t) = \frac{\eta}{\eta_{rmax}} \left( \frac{J}{J_{max}}, \frac{p}{D} \right) \eta_{rmax} \ln(N_t) \quad (28)$$

$$C_p(J, D, p, N_t) = \frac{C_{pr}}{C_{pr0}} \left( \frac{J}{J_{max}}, \frac{p}{D} \right) C_{pr0} \ln(N_t) \quad (29)$$

with  $0 \leq J \leq J_{max}$ .

For the second model, a polynomial representation data, is used with the dimensions in which works for  $D \in [11, 74]$ ,  $p \in [4, 101.4]$  and  $\frac{p}{D} \in [0.27, 1.68]$ . This also uses a polynomial approximation where  $C_{po}$  is the power coefficient at a null advance ratio,  $\eta_{max}$  the maximum propeller efficiency,  $J_{max}$  the maximum advance ratio [34].

## Energy model for propeller-powered aircraft hybrid propulsion system

$$\begin{aligned}
 J_{max}(D, p) = & 0.706462 - 0.0464051D + 0.0743501 p + 0.00106986D^2 - \\
 & 0.00166411D p - 0.000007715p^2 - 0.00000652096D^3 + \\
 & 0.00000868867D^2 p + 0.00000256353p^2 D - 0.000000703183p^3
 \end{aligned} \tag{30}$$

$$\begin{aligned}
 C_{p0}(D, p) = & 0.0509162 - 0.00551164D + 0.00748928 p + 0.000144156D^2 - \\
 & 0.000239091D p + 0.0000655092p^2 - 0.0000024073D^3 + \\
 & 0.00000554473D^2 p - 0.00000382407p^2 D + 0.000000875222p^3
 \end{aligned} \tag{31}$$

$$\begin{aligned}
 \eta_{max}(D, p) = & 0.375474 + 0.0133211D + 0.0148848p - 0.000358479D^2 + \\
 & 0.0000206271Dp - 0.000189967p^2 + 0.00000364483D^3 - \\
 & 0.00000404711D^2 p + 0.00000402876p^2 D - 0.000000467311p^3
 \end{aligned} \tag{32}$$

In this model the power coefficient ( $C_p$ ) and the propeller efficiency are dependent on  $J$ ,  $p$  and  $D$ . They are obtained by knowing the propeller maximum advance ratio, power coefficient for zero advance ratio and maximum efficiency [35].

$$\begin{aligned}
 C_p\left(\frac{J}{J_{max}}\right) = & C_{p0} \left[ 0.99982789 + 0.0084932171 \left(\frac{J}{J_{max}}\right) - 0.099077743 \left(\frac{J}{J_{max}}\right)^2 - \right. \\
 & \left. 0.68206222 \left(\frac{J}{J_{max}}\right)^3 + 0.061670035 \left(\frac{J}{J_{max}}\right)^4 \right]
 \end{aligned} \tag{33}$$

$$\begin{aligned}
 \eta_p\left(\frac{J}{J_{max}}\right) = & \eta_{max} \left[ 2.8444413 - 9.27724 \left(\frac{J}{J_{max}}\right) + 44.278398 \left(\frac{J}{J_{max}}\right)^2 - 103.461 \right. \\
 & \left. \left(\frac{J}{J_{max}}\right)^3 + 108.84369 \left(\frac{J}{J_{max}}\right)^4 - 43.202349 \left(\frac{J}{J_{max}}\right)^5 \right]
 \end{aligned} \tag{34}$$

With the value of  $\eta_{prop}$ , the  $X_{output}$  can be calculated but for that to happen the number of blades is needed to be considered. Table 4 demonstrates how the value of the  $\eta_p$  vary with different number of blades.

**Table 4 - Propeller Performance vs Blades, adapted [29]**

Performance	2 blades	3 blades	4 blades
Efficiency	$\eta_p$	$0.97\eta_p$	$0.94\eta_p$

Using the efficiency of the propeller and the power coming from the transmission, the power that the propeller is producing is calculated:

$$P_{prop} = \eta_p P_t \tag{35}$$

And the thrust associated

$$T_{prop} = \frac{\eta_p P_t}{V} \quad (36)$$

For a more accurate  $C_p$  value depending on the number of blades, a correction is applied. Both models are for a propeller with two blades and so Equation 37 is a correction for propellers with 2, 3 and 4 blades.  $C_p(\frac{J}{J_{max}})$  is divided by the number of blades of the models and then to know the actual value, the multiplication of the result by the number of blades ( $\beta$ ) allows it to know the real  $C_p$ .

$$C_p = \frac{C_p(\frac{J}{J_{max}})}{2} \beta \quad (37)$$

### 3.3. Full hybrid propulsion system

In the process of analyzing the power of the propulsion system, the subsystem models need to be coupled to provide an integrated converged solution. For that, in this section the combination of the combustion system and the electric system will be approached to see if they work together and to assure that the performance of one model is within the performance condition of the adjacent so that does not receive power that is not within their work performance limits.

With the internal conditions set, the performance of the whole aircraft still needs to be checked and Equations from 38 to 40 present the lift coefficient ( $C_L$ ) drag coefficient ( $C_D$ ) and the required power ( $P_{req}$ ). The Propeller and Transmission power must be the same value.

Equation 38 is the relation between the weight and the dynamic pressure times the wing area, where  $m_{aircraft}$  and  $m_{battery}$  are the aircraft and the battery mass, respectively.

$$C_L = \frac{(m_{aircraft} + m_{battery} + m_{fuel})g}{0.5\rho S V^2} \quad (38)$$

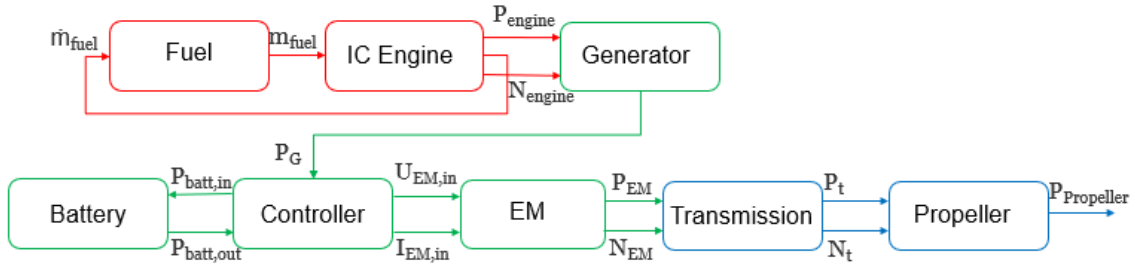
Equation 39 is a second-degree polynomial depending on the  $C_L$ .

$$C_D = 0.0295 - 0.0033C_L + 0.0303C_L^2 \quad (39)$$

Finally, after knowing  $C_L$  and  $C_D$ , the requirements for calculating  $P_{req}$  are acquired. With Equation 40, the condition that confirms if  $P_{req}$  and  $P_{prop}$  have the same value is computed.

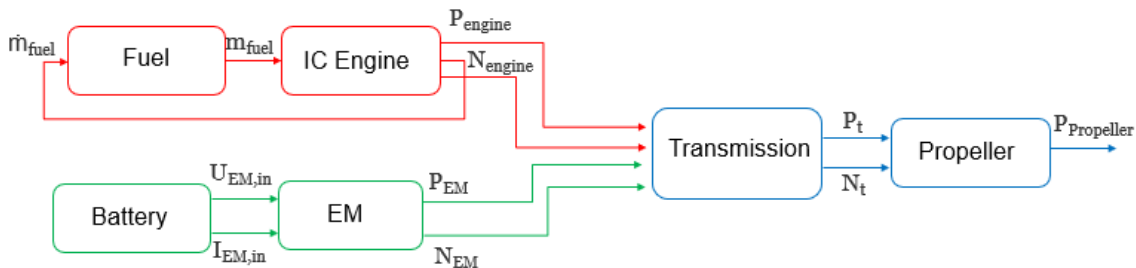
$$P_{req} = 0.5\rho V^3 S C_D \quad (40)$$

## Energy model for propeller-powered aircraft hybrid propulsion system



**Figure 21 - Series configuration: Connection between subsystems**

Figures 21 and 22 show the path for the energy from the power source to the propeller. Figure 21 is the representation of the power flow through the subsystems for the series configuration. The propeller is driven by the electrical motor and the power of the internal combustion engine is converted into electrical power by the generator. Since the electrical motor is providing the complete propulsion power alone, one way to attenuate the rotational speed of the EM is to use a gear ratio that makes the rotational speed of the transmission higher than in the EM. That way the motor is able to perform without compromising its limits. In the representation, the ESC is incorporated in the EM. To guarantee that it works, some conditions (Eq.38-40) were considered. The power of the Propeller and Transmission are the same, and the Propeller propulsive power and aircraft required power are the same. In the case of the series configuration, where only the motor is connected with the transmission, only  $P_{propeller}$  needs to have the same value as the  $P_{req}$  and  $P_t$ , respectively. By having the value of the power that the EM needs to work, the voltage and current from the battery and, the power and rotational speed that the ICE produces will be adjusted. For configurations with a Controller, in the input file it is decided how much the Generator will help, e.g., being 30% or 67% of what the Controller will need to send to the EM. Knowing the required power from the EM and how much the Generator is helping it can be determined power that the ICE is producing. Also, the Controller has the ability to charge the battery as presented in Figure 21, being optional if the user wants. Just like the Generator the voltage and the current for charging the battery is introduced in the input file.

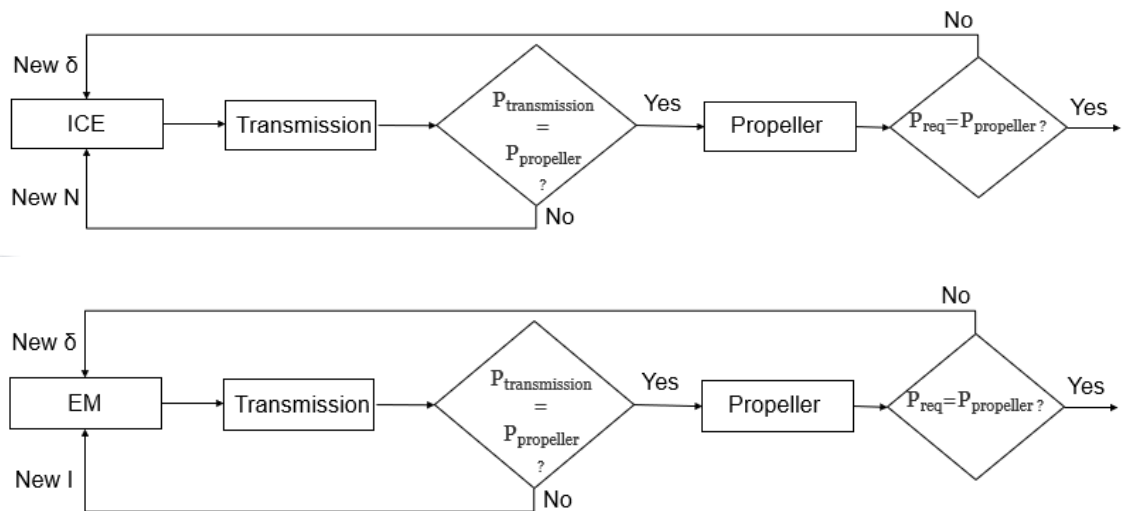


**Figure 22 - Parallel configuration: Connection between subsystems**

Figure 22 has a transmission that has the combustion and the electric subsystem connected. Going with the same principle on Figure 21, the  $P_{propeller}$  must have the same value as the  $P_{req}$  and  $P_t$ . With both subsystems connected to the same transmission the rotational speed there is going to be only one,  $N_t$ . As shown in Equation 20 the ICE subsystem and the EM subsystem with their

## Energy model for propeller-powered aircraft hybrid propulsion system

respective gear ratio will be working at the same rotational speed. Usually the EM needs a to have a gear that makes its value to be the same as the  $N_{engine}G_{t,ICE}$ . The gear ratio affects both, that is, for the combustion subsystem it can have a value e.g., 1, and for the electrical subsystem has another e.g., 2. With the rotational speed of the same value, the system adjusts the power being produced to equal the required power. The ICE will adjust the power setting so that the power being produced is what the system needs, the same happens to the EM. As needed  $\delta$  will be higher or lower so that the model can produce the right amount according to Equation 40 and Equation 38.

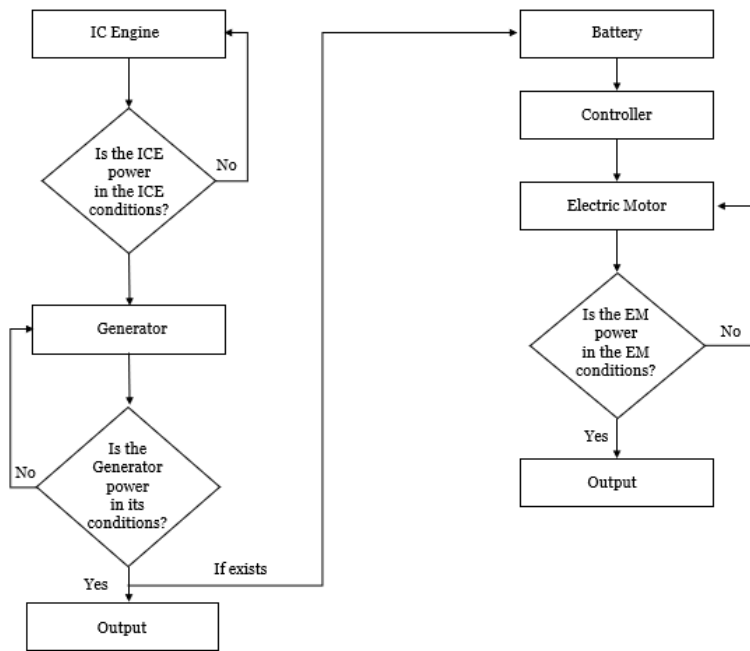


**Figure 23 – Subsystem validation for a flight condition. Part 1: Combustion validation; Part 2: Electrical validation**

With all these conditions to assure that the HEPS is working accordingly, there is one more thing that it must be verified, that being the work conditions of the subsystems. Figure 23 represents the process of validation for each subsystem. For a flight condition  $(V, \rho)$  the system will have a  $P_{req}$  and a  $P_t$  associated, and for Part 1 if the Transmission and Propeller power are not the same, a new  $N_{engine}$  will be placed until it has the same value, if the required power is not the same as the Propeller power it will have a new  $\delta$ . The same principle works for the electrical subsystem but if the power is not the same, what will change is the current because  $N_{EM}$  is influenced by the current as mentioned in EM model.

Each one of the models have a condition associated with which it can work and for that the code has conditions that limit, readjust and if necessary, informs that it is not compatible with the considered flight condition. Figure 24 illustrates the process of how the power flow goes.

## Energy model for propeller-powered aircraft hybrid propulsion system



**Figure 24 - Flowchart of the power vs conditions of work**

Figure 24 is portraying how the process of knowing if the power produced is within the equipment conditions of work. Each model has boundary conditions for which it works and ensuring that each one does not work beyond what is capable of without compromising the others. If a model does not comply with the work conditions the program informs and tries to correct it. Using the ICE model performance as an example, with the following specifications:

- $P_{engine}$ : 1756.9 W – 2253.1 W
- $N_{engine}$ : 6000 – 8800 rpm, used at 7500 rpm
- $sfc$ :  $0.0000153 \frac{kg}{W \cdot s}$
- $\rho$ :  $1.11 \frac{kg}{m^3}$
- $\rho_o$ :  $1.225 \frac{kg}{m^3}$
- $\delta$ : 0.6

The power produced is 1099.69 W which is below the minimum value of the power that the ICE can work and for that the program stops right there and informs and, if is possible, it will apply a correction. Just like the ICE, the other parts also have work conditions, and the process is similar. Figures 21 and 22 show the connection between the subsystems and finally Figure 24 presents the work conditions set in a flowchart so that it can show that the verification of performance (Figure 23) of each part is within its work capability. When the correction of a model or the whole system is not possible, or enter an infinite loop the program will stop, inform of the cause and, if it can, it will save the last data in a file.

## 3.4. Implementation

With the software JetBrains PyCharm Community Edition 2019.2.3 x64 that has Python 3.7, the program for the energy model of HEPS was elaborated. Having a program that can calculate the power of the hybrid propulsion system, it allows to save time and prevent human errors in the intermediate calculations as stated in the models. The models alone could not be enough to make the code, the implementation of functions and informatics knowledge of Python was necessary so it could perform for more than one condition, save in a file, and present graphs. However, if the user wants, he can use another software to make a graphic since he has the file with the output data.

### 3.4.1. Code

Energy Model is the name of the program that estimates the flow of energy of four HEPS configurations: series, parallel decoupled, parallel coupled and parallel. The program comes with a text file for the inputs (Input.txt) allowing an easier way of modifying the inputs whenever the user wants or because it is the continuation of the previous case study. Some inputs are not in the input file such as some conditions of flight like velocity and altitude and the initial rotation speed of the ICE. The code is made by functions that are equivalent of the models where each one of them has working conditions for the configuration in use. As can be seen in Figures 23 and 24, some functions have a loop cycle such as while and for, that helps to estimate the variables over time. ICE\_Fuel, EM\_ESC and Propeller have an internal function that lets divide the array in many parts so that it can be done for more than one flight condition (Figure 25), but it is not being used.

```
def mult_div(array, div, valores):
    time_inicial = []
    time_inicial.insert(0, time_final[:-1])
    time_inicial.insert(0, 0)
    i = 0
    CORTES = []
    divt = div + 1
    while i < divt:
        Cortes = [time_inicial[i], time_final[i]]
        CORTES.append(Cortes)
        i += 1
    Cortes = np.array(CORTES)
    n = 0
    for corte in Cortes:
        array[int(corte[0]):int(corte[1])] = array[int(corte[0]):int(corte[1])] * valores[n]
        n += 1
    return array
```

Figure 25 - Function to divide the array

The code is structured that initially it informs the user of the configurations it has and what types of case study it has, as choosing the power setting,  $\delta$ , for the ICE and the EM or only for one of them or none of them. After those conditions being established the program will start to calculate and if one of the models is not in the working conditions of the inputs and/or the iteration makes

## Energy model for propeller-powered aircraft hybrid propulsion system

it work higher or low of what it can then a warning is going to appear. If it is in the first iteration the code will stop and inform the user that he needs to change the inputs or the initial rotational speed of the ICE or the initial current of the EM, but if it passes the first iteration the warning may show up but automatically it will try to correct it but if it cannot do it, it will stop create a file with the latest value and will inform which model/function is presenting the error and what kind, Figure 26.

```
if np.any(p_ice < P_min) or np.any(p_ice > P_max):  
    print("The ICE power is not between the power minimum and maximum.")  
    sys.exit()
```

**Figure 26 - Restriction of power due to engine specifications (example)**

At the parallel coupled and parallel decoupled the program will calculate the combustion system first and after reaching at a solution it will do the electrical system. Those two parallels and the series configuration have the generator incorporated and in the file of the inputs there can be decided how much is the generator contributing to the EM. Table 6 demonstrates the generator producing 40% and the rest is obtained by the battery. Having two propellers on those three configurations where one system (electrical) is powered by two sources, a controller is needed to assure that excessive power is not going to the EM and so if the current or the voltage is higher than the maximum then what comes out is only the maximum values of the current and the voltage.

In the iteration process conditions are established so that the code works until it converges at the solution, such as the power that the propeller is producing is the same as the required power and the propulsion power of the propeller is the same as the transmission for any ratio. With the condition set there is also other conditions working at the same time. There is the number of cycles counter so that it does not get stuck in an infinite loop and there is a 3% relative margin error for the conditions of iteration. The number of cycles and the values of the convergence constant are iterating (current,  $\delta$  and rotation speed) are defined initially and when the variables are near the convergence point then the number of cycles rises and the value of the convergence constant lowers.

Series configuration has a peculiarity of having the electrical system working without the combustion. At the first look this configuration is only working by doing the simulation of the electrical system but when it converges to the solution, the combustion system will be done because in the Inputs there is a section where the percentage that the generator (combustion system) is contributing for the whole propulsion system. Parallel configuration besides the conditions of equality of the required power with the propeller power and the propulsion coefficient of the propeller with the transmission, this also needed another two conditions so that it would perform correctly, and so it needed to have the same speed and the same power in the transmission. The rotational speed and power are considered the ones that are entering to be converted to a new value according to the efficiency and ratio, respectively.

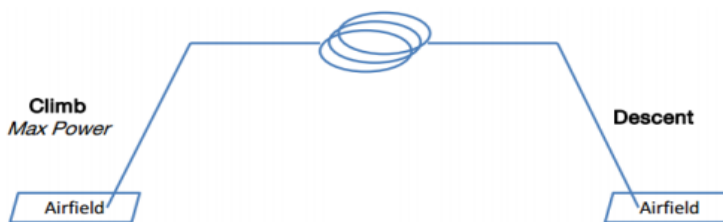
## Energy model for propeller-powered aircraft hybrid propulsion system

When the code finishes running it will automatically create a file with the output and make graphs of some variables. The name of the file where the output is going to be stored is assigned in the Input file with the others like the number of blades or the resistance of the EM. The Input file needs to be on the desktop so that the code can read it.

## 4. Results and discussion

With the implementation of the code presented in chapter 4, repeatedly for different situations were obtained the results presented in this chapter.

These results will be presented carefully, following a logic that allows the easy comparison between three configurations that will be used as an example. With most of the inputs similar, some particularities will be different to see how the system behave. The simulation will take place at three different points of the mission without stopping. Figure 27 is an example of a conventional surveillance mission.



**Figure 27 - Exemplary conventional surveillance mission with flight phases, adapted [36]**

The results are presented carefully in an easy manner of understanding which allow an easy comparison between three configurations: parallel, parallel coupled and series. For these configurations, only one of the external parameters (altitude and velocity) is varying, i.e., the altitude. For the three analyzed configurations,  $\delta$  will also be one of the variables that is going to vary.

In Table 5 it is presented the general characteristics of the HEPS and the aircraft. Table 5 has the inputs for all results that are going to be presented in this chapter.

**Table 5 - General Input values**

S [m <sup>2</sup> ]	0.91
m <sub>aircraft</sub> [kg]	23
sfc <sub>o</sub> [N/ (W s)]	5.94×10 <sup>-07</sup>
m <sub>fuel</sub> [kg]	3.38
a	0.3
C [A s]	180000
U <sub>batt</sub> [V]	42
R <sub>batt</sub> [Ω]	0.001
K <sub>v</sub> [rpm/V]	206
I <sub>o</sub> [A]	1.10
R <sub>EM</sub> [Ω]	0.055
D [inch]	18
p [inch]	12
V [m/s]	22
m <sub>battery</sub> [kg]	6.515
C <sub>L,max</sub>	1.32

#### 4.1. Study cases

This section presents, the study of performance depending on the transmission ratio, number of blades and altitude that the HEPS is operating.

With the modeling of each component of the HEPS and using the series and the coupled parallel configurations, the performance can be analyzed when they are together. By using those two configurations with different number of blades and one type of ratio of the transmission, Table 6 presents the power produced by their subsystems.

**Table 6 - Verification of the propulsion system power**

Number of Blades	Series			Coupled Parallel		
	2	3	4	2	3	4
ICE power [W]	317.8	361.7	402.6	532.8	558.6	591.6
Generator Power [W]	234.9	246.9	262.5	220.1	228.4	239.7
EM Power [W]	532.6	557.7	590.6	532.8	558.6	590.6
Propulsive Power [W]	409	408.3	408.4	409	409	408.3

Table 6 uses  $G_{t,ICE}=1$  and  $G_{t,EM}=1$  at sea level with the velocity at 20 m/s, making the rotational speed going through the transmission the same as the corresponding motor/engine. On both configurations the power from one model to another can be seen decreasing until it reaches the propeller, although the electric motor produces more power than the generator. For the electric subsystem, the generator is responsible for 40% of the power going to the electric motor and the 60% comes from the Battery.

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The graphs are composed by points of three configurations, with three different numbers of blades and different gear ratios. The graphs from Figure 28 to 48, show points from different conditions, but they are arranged in a way that if seen from left to right, every three points is for a number of blades, every nine points is for a gear ratio. Table 7 is a visual aid for the graphs. For all the results in this chapter the  $G_{t,ICE} = 1$  but for  $G_{t,EM}$  it goes from 1 to 3. Table 10 has 1:1 meaning the first number is the gear of the ICE and the second is the EM. The following points follow the same logic, from 1:1 to 1:3.

**Table 7 - Order of points of graphics, first 9 points**

1:1								
2 blades			3 blades			4 blades		
series	coupled	parallel	series	coupled	parallel	series	coupled	parallel

With several configurations in the study cases, Table 8 is a representation of a specific HEPS (Parallel configuration) with the same velocity at different altitudes, starting from the sea level, then going to 500 m and finishing at 20 m.

**Table 8 - Performance of parallel configuration**




Altitude [m]	0	500	20
Simulation Time [s]	28	3778	3903
$P_{ICE}$ [W]	279.3	542.3	269.8
$N_{engine}$ [rpm]	4877.8	4894.4	4846.3
$m_{fuel}$ [kg]	3.376	2.395	2.379
$\delta_{ICE}$	0.195	0.396	0.190
$U_{batt}$ [V]	41.84	-	41.16
$C_{batt}$ [A s]	155198	-	56324.62
$I$ [A]	24.70	-	24.02
$P_{EM}$ [W]	279.4	-	269.6
$N_{EM}$ [rpm]	2438.9	-	2423.1
$\delta_{EM}$	0.315	-	0.318
$\eta_{EM}$	85.71	-	85.79
$P_{propeller}$ [W]	409.14	397.7	393.9
$\eta_{Propeller}$	75.49	75.60	75.28
$C_p(J)$	0.04253	0.04286	0.04197
$J$	0.592	0.590	0.596
$C_L$	1.196	1.218	1.162
$C_D$	0.069	0.070	0.067
$\frac{CL}{CD}$	17.361	17.295	17.453

Three altitudes were considered for the comparison of the combustion system, the electrical system and the whole HEPS. Establishing the velocity at 22 m/s, the  $G_{t,EM} = 2$  and three blades for the propeller for all cases, the results of Table 8 were obtained. For the altitude of 500 m the electrical subsystem is not working due to the limitation of the battery endurance. As mentioned in the early chapters the electrical subsystem is mainly used for auxiliary performance such as take-off and landing. Since the ratio is  $G_{t,EM} = 2$ , the rotational speed of the EM is half of the ICE, helping the electrical system to perform within its normal operational conditions. Throughout the mission, the weight of the aircraft decreases due to the consumption of the fuel consequentially making the  $P_{req}$  lower than initially.

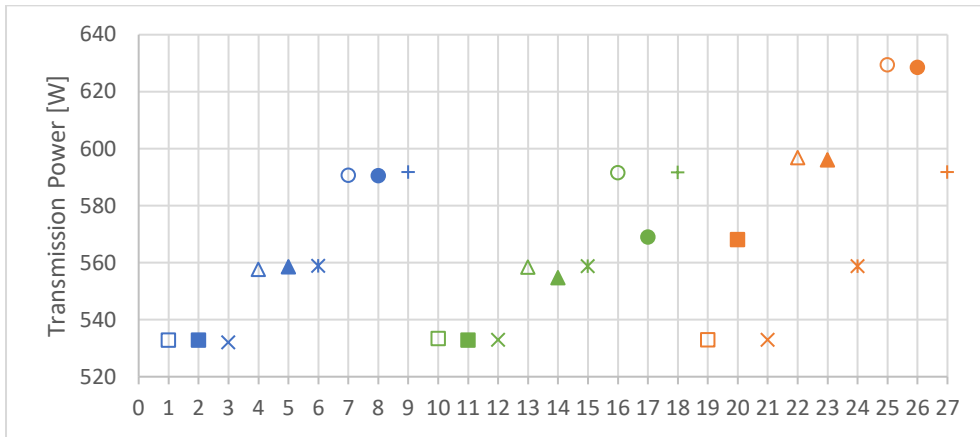
Using the values of Table 5 as inputs for the altitude at sea level, the performance for all three configurations will have the same  $C_L$ ,  $C_D$  and  $P_{req}$ , however, the internal variables do not have to have the same value. The program is used to do the simulation with the time frame of 28, 3778 and 3903 seconds with the velocity of 22 m/s. To assure that the configuration is working properly Equations 38 to 40 are conditions requirements. Equation 40 and  $P_{prop}$  must have the same value.

From Figure 28 to Figure 40 show the differences of some subsystems and it can be seen which produces or consumes or has a higher or lower value at the same conditions. Table 5 has the general inputs for all study cases only changing the value of the power source since it is a continuous mission like Figure 27.

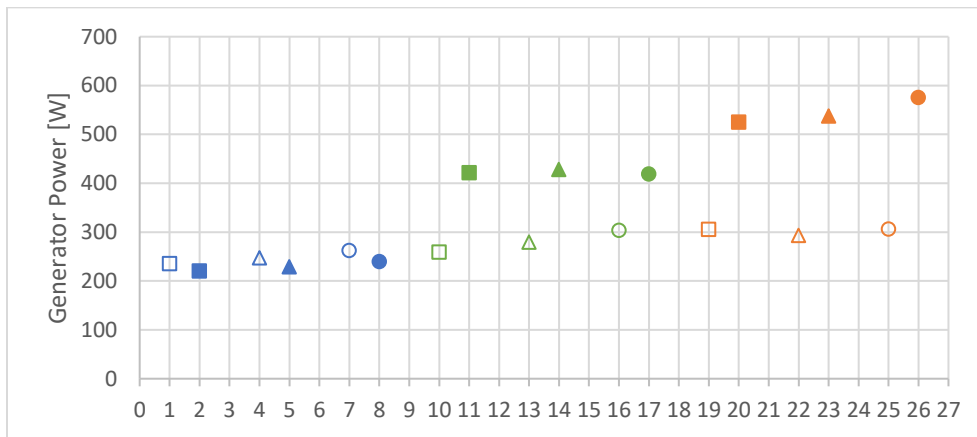
### 4.1.1. First case study: sea level

Figure 28 to Figure 32 show the results at a simulation instant of 28 seconds at sea level. The graphs have different kinds of points on display so that it can be easy to compare a specific one if needed. By using Table 7 as reference, blue represents  $G_{t,EM} = 1$ , green represents  $G_{t,EM} = 2$  and orange represents  $G_{t,EM} = 3$ . The figure  is for 2 blades,  is for 3 blades and  is for 4 blades. For the series configuration the figure is hollow, for the coupled the figure is filled and for the parallel it has a special character (for the 2 blades it is ×, for 3 blades is ✕, and for 4 blades it is +).

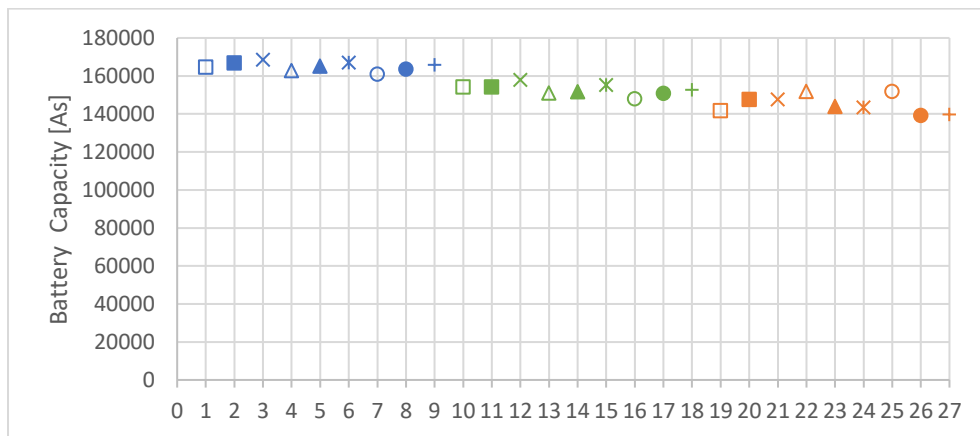
# Energy model for propeller-powered aircraft hybrid propulsion system



**Figure 28 - Transmission Power at sea level**



**Figure 29 - Generator Power at sea level**



**Figure 30 - Battery Capacity at sea level**

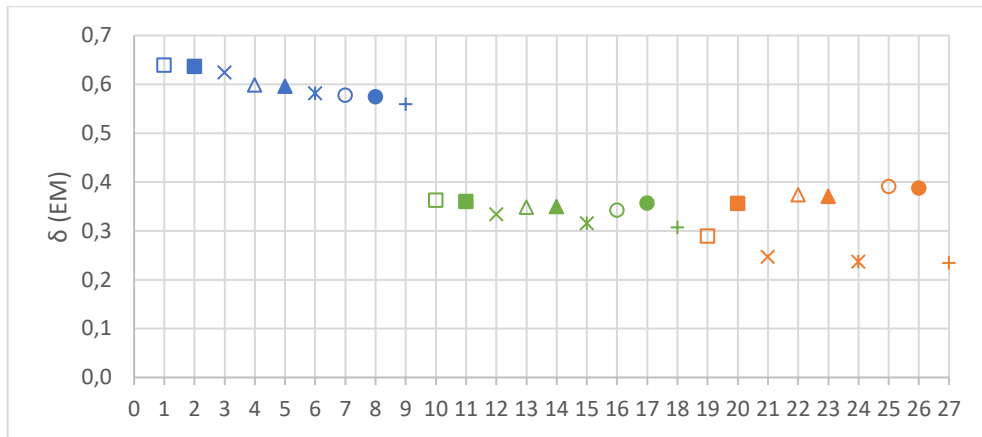


Figure 31 -  $\delta_{EM}$  at sea level

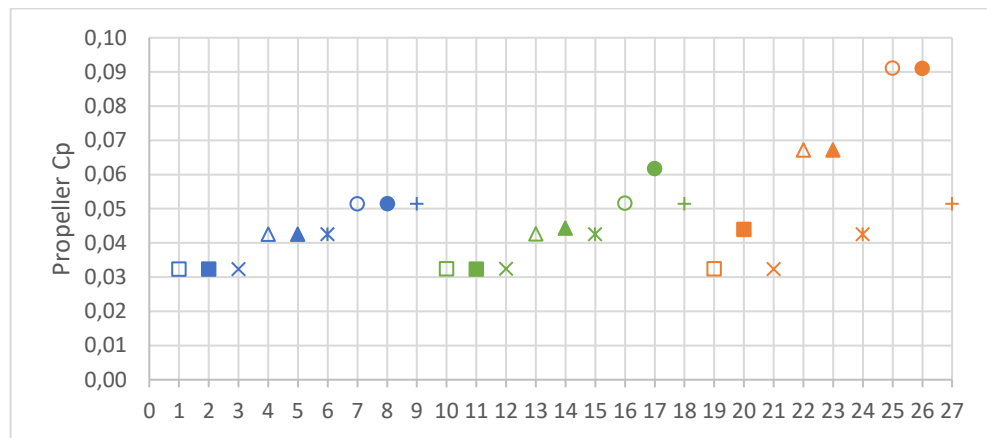


Figure 32 -  $C_{p,propeller}$  at sea level

Figure 29 only has two configurations since the parallel does not have a generator. It can be seen that for blue, the series produces more power, but for  $G_{t,EM} = 2$  (green) and  $G_{t,EM} = 3$  (orange) it is the opposite. Figure 30 show that, in the electrical subsystem, with 4 blades the Battery consumption is higher than the others and at the same time the EM produces more power (Figure 28) by having a lower  $\delta$  (Figure 31). Having the series configuration with one propeller the rotational speed of the generator is not fixed because the value attributed will depend on what the electrical subsystem will need. With the coupled parallel configuration, the combustion subsystem has a work point, and the transmission belt that connects the ICE with the Generator will make the Generator have the same speed as the ICE. By taking into account all these three configurations and seeing which is best depending on what type of mission the aircraft is doing, for example if the purpose is to use the one that consumes less energy, then the parallel with the ratio 1:1 and 2 blades is the best, but if the objective is to find out which as a higher  $C_p$  then the series and the coupled with  $G_{t,EM} = 3$ , with 2 and 3 blades are the ones to choose.

### 4.1.2. Second case study: 500 m

Reaching the altitude of 500 m the electrical subsystem stops working and only the combustion subsystem is working. Unlike the previous situation where the generator provided 40% of the required electrical power, in this condition it provides 100%.

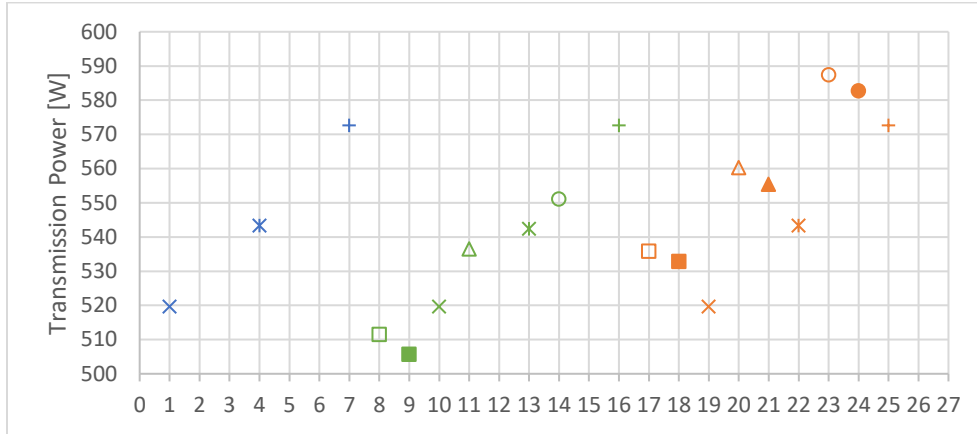


Figure 33 - Transmission Power at 500 m

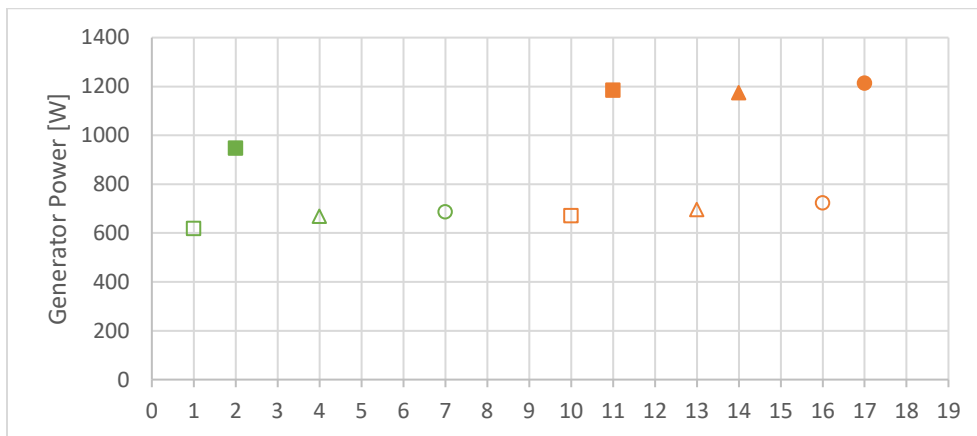


Figure 34 - Generator Power at 500 m

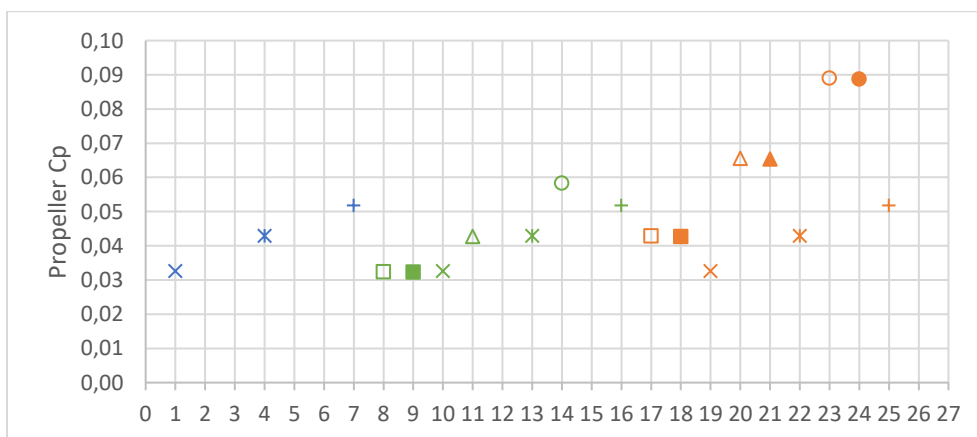


Figure 35 -  $C_{p,propeller}$  at 500 m

With the electrical system dependent of the generator (if it has) for some gear ratios it could not find a solution. For  $G_{t,EM} = 1$  both series and parallel coupled could not find a solution for any number of blade, and for  $G_{t,EM} = 2$  the same happens but to only the series configuration for propellers with three and four blades. Being at a higher altitude than the previous one, the power necessary to work is lower, Figure 33, but with the generator as a power source for the electrical system, the power being produced is higher than at sea level. Having two study cases, the evaluation of the performance will change since there were some that did not work at 500 m and, those who cannot and can be used only at sea level. With the power source being the combustion subsystem, the values of the power (Figure 33) are less dispersed than at sea level.

#### 4.1.3. Third case study: 20 m

At an altitude of 20 m for 125 s the generator goes back to contribute for 40% of the electric subsystem. From sea level to 500 m there were some configurations that did not go through, and from 500 m to 20 m it happened again. From the initial 27 points to 14 points on the graph. At 20 m, this one has five more that cannot find a solution in comparison with the second case study. For  $G_{t,EM} = 3$ , it is the parallel coupled with two and four blades. For  $G_{t,EM} = 1$ , it is the parallel with three and four blades. For  $G_{t,EM} = 2$ , it is parallel coupled with three and four blades, and the parallel with four blades.

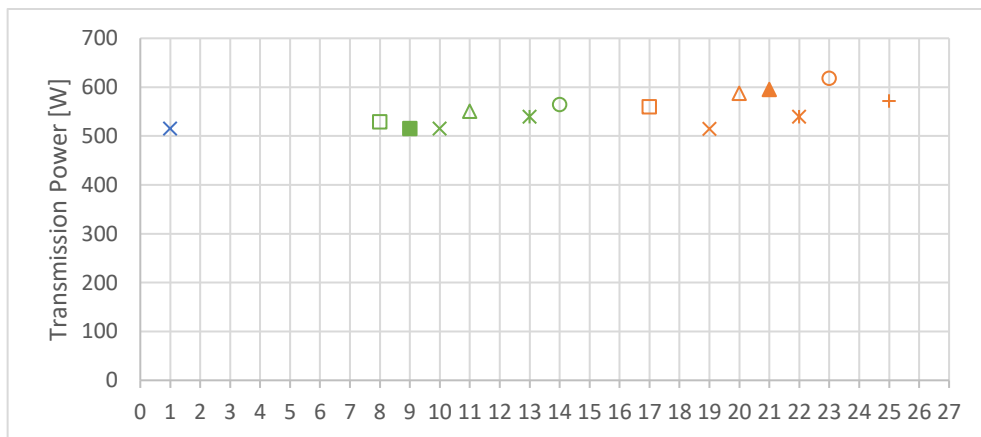


Figure 36 - Transmission Power at 20 m

## Energy model for propeller-powered aircraft hybrid propulsion system

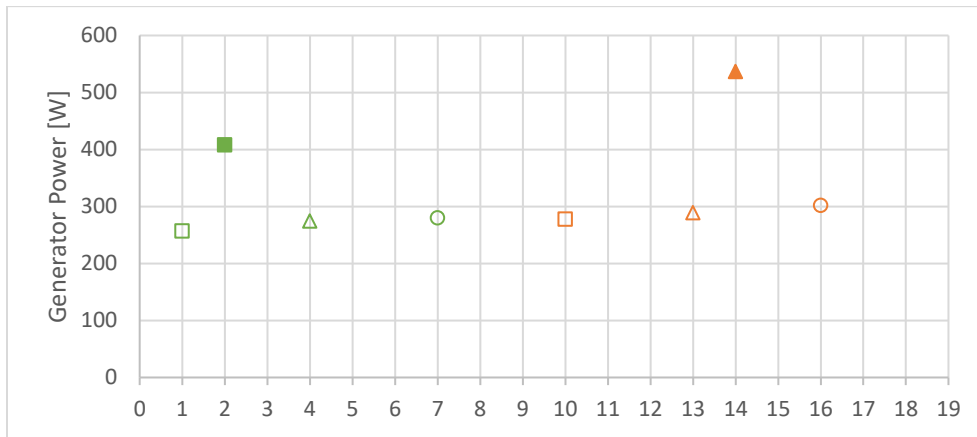


Figure 37 - Generator Power at 20 m

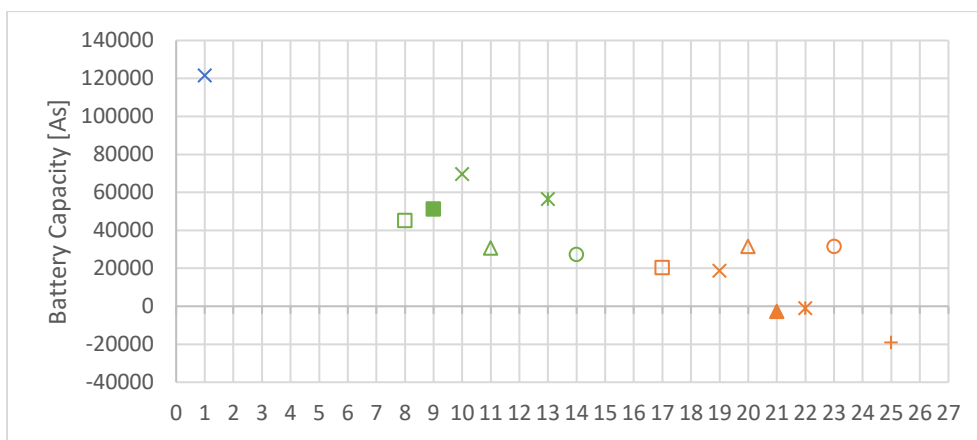


Figure 38 - Battery Capacity at 20 m

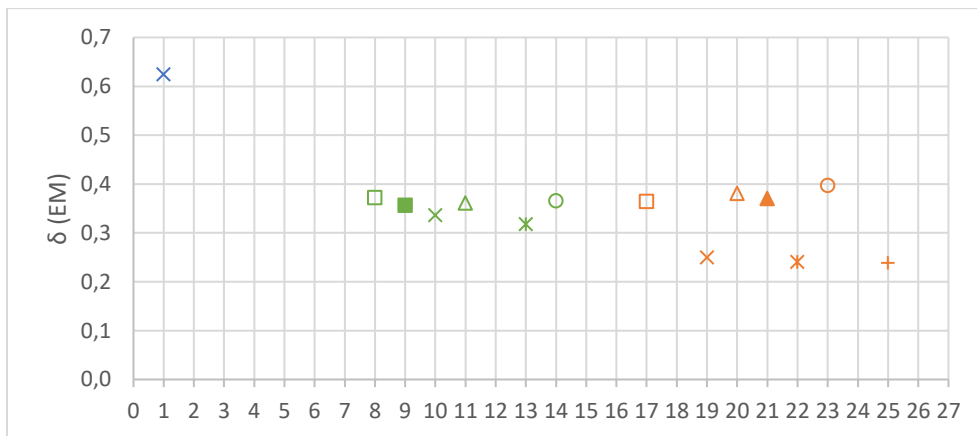


Figure 39 -  $\delta_{EM}$  at 20 m

## Energy model for propeller-powered aircraft hybrid propulsion system

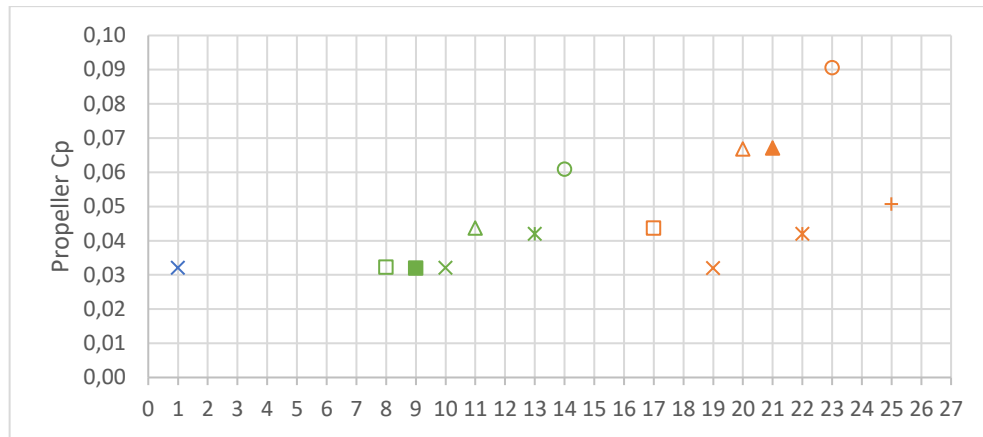


Figure 40 -  $C_{p, propeller}$  at 20 m

Figure 38 may be the one to catch the attention because the battery capacity for 3 configurations is below zero and so these conditions can be used without altering the battery and increase the help from the generator. Other options can be having a battery with a higher capacity without compromising the weight or recharging. In this last study case, there is two more configurations that did not have a solution for 20 m in comparison with 500 m, and so for the whole mission only the ones that are present in this last case are worth comparing and seeing which performs best for the mission that it has.

The results from the three different altitudes demonstrates that in the beginning there were more options than at the end. At sea level and 20 m the results were more disperse than at 500 m where it only had one power source, since the battery was not releasing power.

The fuel consumption at each study case was mostly the same. The program as seen can work for any condition and with an easy way of changing the velocity, it can easily make results for comparison. For this simulation, the components used were for a small aircraft.

## 5. Conclusion

The search for an electric system that can be applied to the commercial aviation is a long expected dream and some companies had breakthroughs, but for short distance flights. For the commercial aviation there are two options: the first is changing the energy storage by having a lighter battery with higher capacity or having a more suitable way of using fuel cell, and the second is using HEPS.

In this dissertation several studies were made to compare the performance of different HEPS and their subsystems. Considering four configurations (series, coupled, decoupled and parallel), their subsystems were modeled so that could analyze what was going on in each one. With mathematical models for each subsystem, it was established how they would work together as a whole HEPS, but in case one of them is not working within its condition the program will try to apply a correction and if it fails, a warning will appear to inform the cause of the problem. With Python, a program was made that incorporates all the models with conditions and cycles thus making into functions on Python.

The several study cases that were analyzed and compared, allowed to see the performance of the subsystems, see which one would consume more or which one would work better and even see if one of the components could be downsized to enhance the performance. The study cases have the same velocity but different altitudes and at 500 m the generator is providing 100% of the electrical power. The configurations had different number of blades and  $G_t$  but the Propeller works at the same power in each altitude.

Through the Energy Model program, one can observe the behavior of the HEPS and its subsystem. Observing how the whole propulsion system and its subsystems perform allows the user to change any component to improve the HEPS or to be more compatible with each other, such as Figure 22 demonstrates the connection between the parts, Table 8 presents the power that a configuration produces at different altitudes and Table 6 shows the performance of two different configurations. Depending on the type of mission, i.e., endurance and range, it influences the kind of parts that are going to be used in the whole system, such as Figure 38, where there are three configurations that have the Battery capacity below zero, saying that what should change is the Battery or the type of mission, e.g., endurance. Energy Model can simulate for propeller-power aircraft, and include small/light aircraft and UAV. The hybrid propulsion has more application in the field of UAV.

By using the program, it can provide a better planning of the components of the HEPS, a comparison of different types and conditions of work and the type of components that are part of the HEPS configuration.

### **5.1. Future work**

The work presented in this dissertation has limits of how it works, such as how many flight conditions it can do in one simulation, the fact that is only including the propulsion system and the Controller is not flexible depending on how the system is reacting.

The code already has a function that can work for several flight conditions, but the validation needs to be improved so that it can do several conditions in the same simulation. Making the Controller more flexible will be adding more conditions, so that without changing manually it can determinate the best action being charging the Battery or making the Generator provide more or less than it is already providing. An aircraft is consisted by diverse areas such as aerodynamics, structure, system and propulsion. In this work only the propulsion system is approached and to have a more realistic data, the other areas that make an aircraft, e.g., aerodynamics and structure, are necessary to consider.

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# Appendices

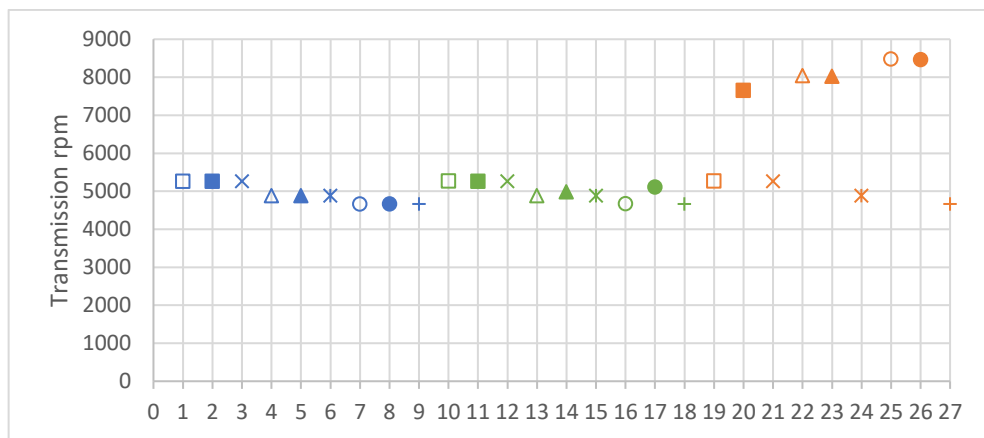
## Appendix A

In this appendix are shown graphs of the rotational speed and advance ratio. This can be useful to assess how much rotational speed the EM and the Transmission are working and see if using a gear is beneficial or not for the performance of the electric motor and the battery consumption, and to see what the advance ratio of the blade is. The graphs shown are from different study cases.

Table 9 is a visual aid for the graphs. For all the results in this chapter the  $G_{t,ICE} = 1$  but for  $G_{t,EM}$  it goes from 1 to 3. Table 10 has 1:1 meaning the first number is the gear of the ICE and the second is the EM. The following points follow the same logic, from 1:1 to 1:3. By using Table 9 as reference, blue represents  $G_{t,EM} = 1$ , green represents  $G_{t,EM} = 2$  and orange represents  $G_{t,EM} = 3$ . The figure ■ is for 2 blades, ▲ is for 3 blades and ● is for 4 blades. For the series configuration the figure is hollow, for the coupled the figure is filled and for the parallel it has a special character (for the 2 blades it is ×, for 3 blades is ✂ and for 4 blades it is +).

**Table 9 - Order of points of graphics, first 9 points**

1:1								
2 blades			3 blades			4 blades		
series	coupled	parallel	series	coupled	parallel	series	coupled	parallel



**Figure 41 - Transmission rpm at sea level**

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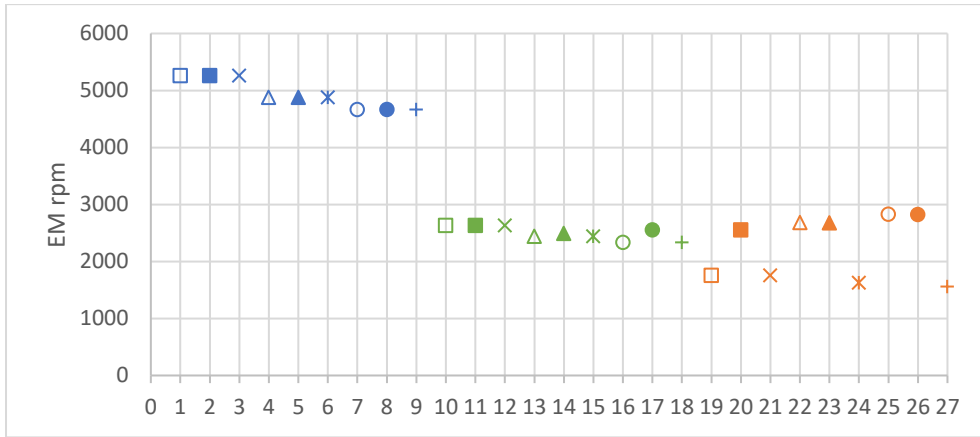


Figure 42 - EM rpm at sea level

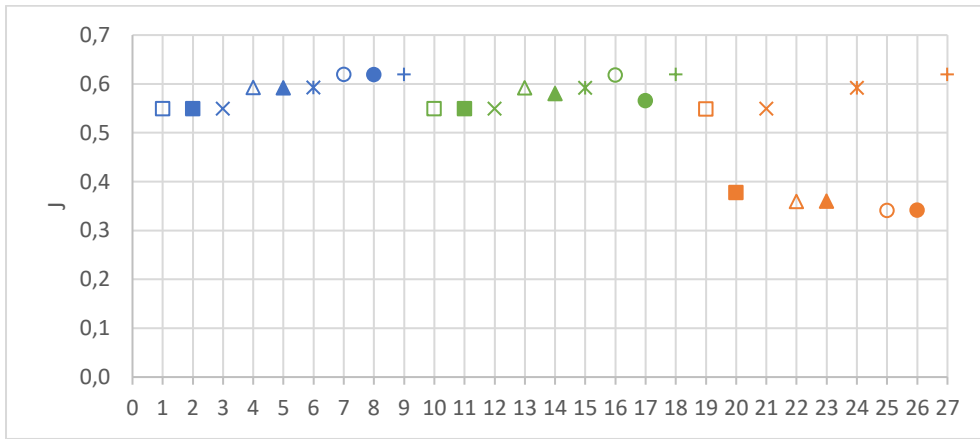


Figure 43 - J at sea level

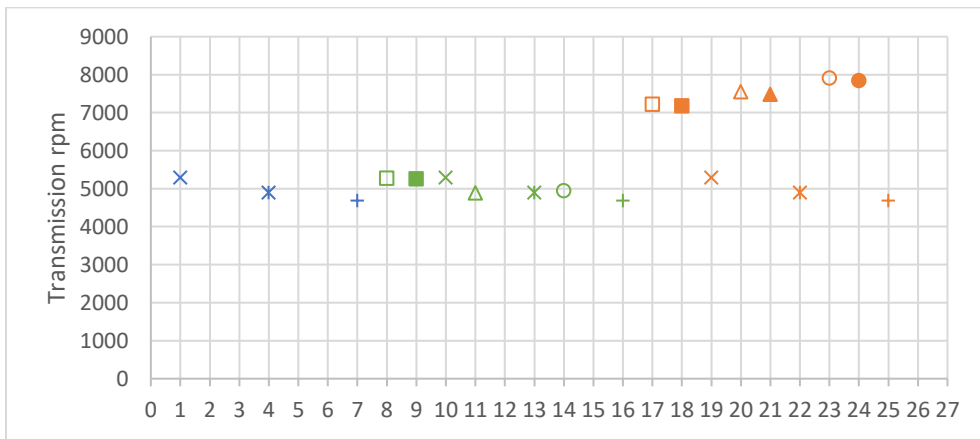


Figure 44 - Transmission rpm at 500 m

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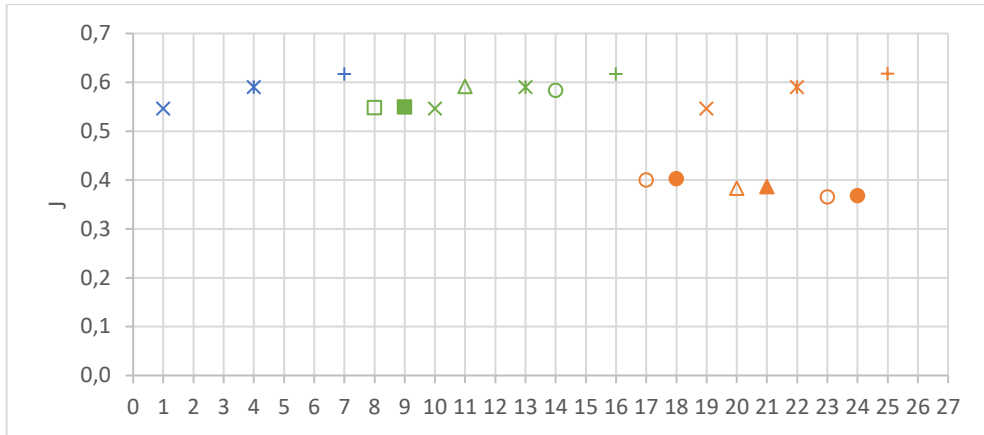


Figure 45 - J at 500 m

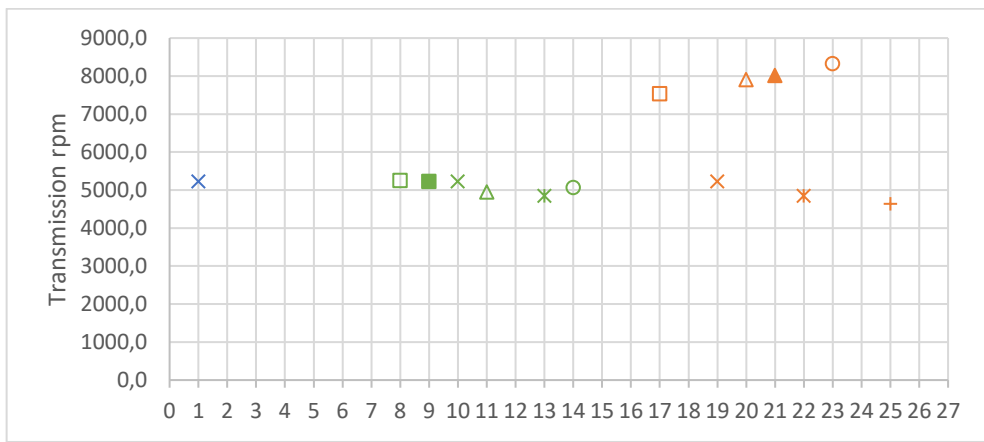


Figure 46 - Transmission rpm at 20 m

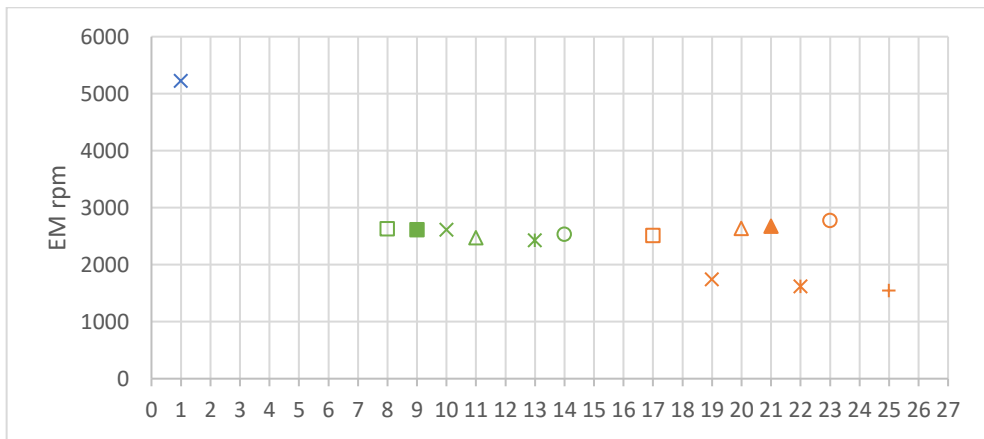


Figure 47 - EM rpm at 20 m

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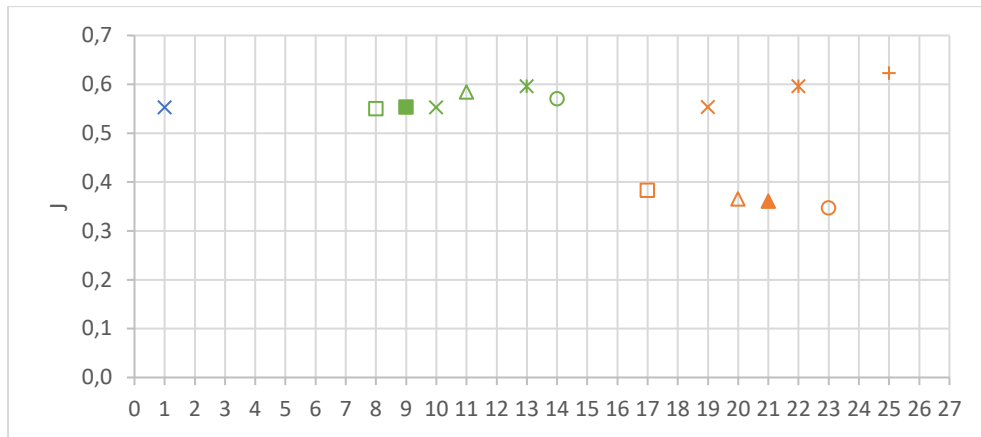


Figure 48 - J at 20 m