UNICO I+D Project
6G-INTEGRATION-4

E11-6G-INTEGRATION-4

Simulation of the energy loads of the 5G system as part of the energy system

Abstract

This deliverable includes the simulation of the energy loads of the 5G system, as well as information about typical generation and storage systems in an aircraft, along with details about the architectures of hybrid energy management systems. It defines the main aircraft loads and their required energy level, followed by the sizing of energy generation and storage systems to meet the entire power demand of the load. Finally, simulations are conducted for energy sources separately and together with the loads.

Document properties

Document number	E11-6G-INTEGRATION-4
Document title	Simulation of the energy loads of the 5G system as part of the Energy System
Document responsible	Eduardo Cano Corral (Edair Technologies)
Document editor	David Gualpa
Editorial team	Alfonso Torrelo
Target dissemination level	Public
Status of the document	Edition
Version	1.0

Production properties

Reviewers	Eduardo Arca Ramirez (Edair Technologies) Eduardo Cano Corral (Edair Technologies) Daniel Segovia Vargas (Universidad Carlos III)

Disclaimer

All information in this document is provided "as is" and no guarantee or warranty is given that the information is fit for any particular purpose. The user thereof uses the information at its sole risk and liability.

Contents

List of Figures

List of Tables

List of Equations

List of Acronyms

APU - Auxiliary Power Unit

AC - Alternating Current

ANN - Artificial Neural Network

DC - Direct Current

EMS - Energy Management System

ESS - Energy Storage Systems

FLC - Fuzzy Logic Control

GEN-GENERATOR

GPU-Ground Power Unit

HESS - Hybrid Energy Storage Systems

MEA - More Electrical Aircraft

MF- Membership Function

PEM - Proton Exchange Membrane

PEMFC - Proton Exchange Membrane Fuel Cell

PI- Proportional Integral

PV- Photovoltaic

PWM-Pulse Width Modulation

RAT - Ram Air Turbine

RBC- Rule Based Control

RES - Renewable Energy Sources

SOC - State of Charge

MF - Membership Functions

'

Executive Summary

This deliverable provides detailed information about typical generation and storage systems used in aircraft, while also addressing the architectures of hybrid energy management systems. It identifies and describes the main loads in both conventional and solar aircraft, assessing their required energy levels. Additionally, the sizing of energy generation and storage systems is carried out to fully meet the power demand of the load. Independent simulations of generation and storage systems connected to variable loads are conducted to analyze their performance under various scenarios.

Furthermore, the generation and storage systems are fully integrated, connected to a variable load, and controlled by an energy management algorithm. This comprehensive approach offers a complete understanding of how these systems work together and adapt to changing energy needs.

1. Introduction

An aircraft's electrical system consists of a set of electrical and electronic devices designed for the generation, control, and distribution of electrical power under normal or emergency conditions to all components that require it, in accordance with the margins established by regulations and standards.

In the following diagram, you can observe the conventional electrical diagram of an aircraft, which can be divided into the generation system and the distribution system. [1]
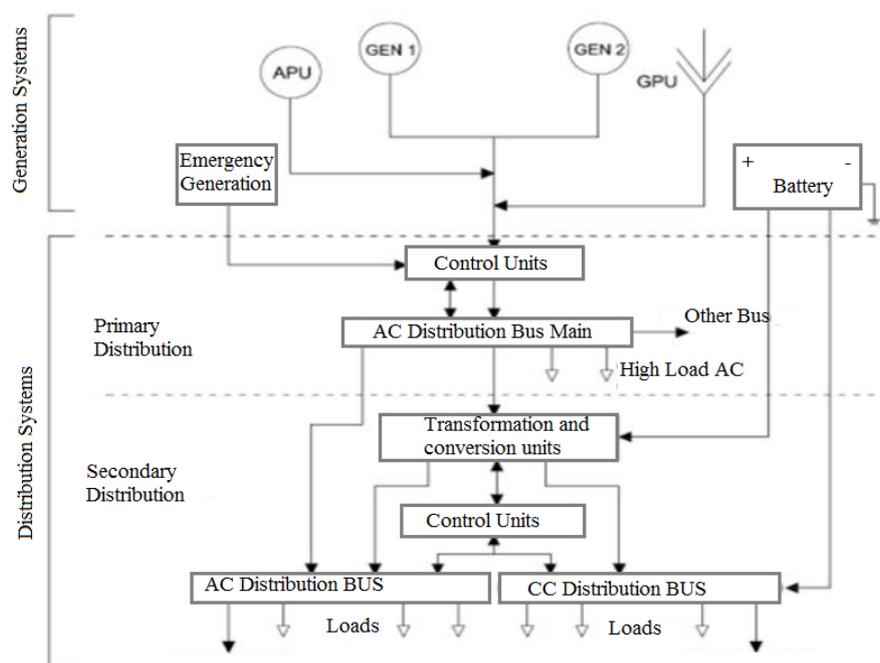
FIGURE 1-1: AIRCRAFT'S ELECTRICAL SYSTEM

Generation Systems: In an aircraft, the generation system is carried out by various units, such as the main generators, auxiliary generators, and auxiliary power units. Batteries also serve as components that generate power in case of failures in the other primary systems.

Distribution Systems: This system can be divided into two blocks: primary distribution and secondary distribution. In the primary distribution, high-consumption loads are found, and from this distribution, power is supplied to the secondary distribution, which in turn provides energy to busbars, protection devices, and load switching elements. Subsequently, the secondary distribution branches out to distribution bars and, subsequently, to lower-power circuits. [1]

2. Technical Characteristics

2.1. State of the Art of Embedded Generation and Storage Systems

2.1.1. Generation

2.1.1.1. Fuel cells

Fuel cells are highly efficient energy-generating devices that enable the conversion of chemical energy into electrical energy. These cells use the characteristics of oxidation-reduction reactions, allowing for the direct extraction of electricity through controlled electron movement.

When hydrogen and oxygen are separated by an electrolyte (electrolytic membrane), the protons from hydrogen atoms migrate through the membrane, while electrons cannot. These electrons attempt to move to the other side of the membrane to reach a stable state. [2]

By connecting an electrical circuit between the two electrodes, the electrons travel through it, and this movement of electrons through the external electrical circuit is controlled to generate electrical energy. In the electrochemical process, the overall reaction is divided into two smaller reactions: one is an oxidation reaction, and the other is a reduction reaction. The oxidation reaction begins with the dissociation of hydrogen atoms into protons and electrons and occurs at the anode.

There are various types of fuel cells based on their configurations, applications, or the type of fuel they use, but the most commonly used one is the PEM or PEMFC. [2]

2.1.1.2. Solar panels

Solar panels have a vital role in the conversion of solar energy into electricity. This process is based on the photovoltaic effect, which involves the generation of electrical current when sunlight strikes specific semiconductor materials. These panels are primarily composed of semiconductor materials, such as crystalline or amorphous silicon, which have the ability to release electrons when stimulated by sunlight. Solar cells, which are the basic energy conversion units, make up the solar panels and generate direct current when exposed to sunlight. This current can be used directly or converted into alternating current using an inverter for use in homes or the electrical grid. [3]

The efficiency of a photovoltaic panel is crucial in selecting solar technology, as it determines the amount of solar energy that can be converted into electricity. Modern solar panels typically have efficiencies ranging from 15% to 22%. To maximize energy generation, it is essential to install the panels in locations with adequate sun exposure and optimal orientation to receive maximum sunlight during the day. Additionally, in standalone photovoltaic systems or in areas with frequent

power interruptions, energy storage systems, such as batteries, are employed to store the electricity generated during the day and use it when sunlight is scarce.

An important characteristic of solar panels is their sustainability, as they represent a renewable and clean energy source that does not emit pollutants or greenhouse gases during operation. This significantly contributes to reducing dependence on fossil energy sources and mitigating climate change. [3]

2.1.2. Storage Systems

2.1.2.1. Batteries as Energy Storage Systems

Batteries are energy storage devices that utilize electrochemical processes and have the capacity to subsequently release that energy, almost in its entirety, in a cycle that can be repeated a certain number of times. The basic unit of a battery is called a "cell," and a group of cells connected in series or in parallel is referred to as a battery. [4]

The cell is composed of the following components: cathode (+) and anode (-) electrodes, the electrolyte, which is the substance containing ions that freely move within it, enabling it to act as an electrical conductor, and isolator that keep the components inside separated. Electrical energy is stored or released through electrochemical reactions that transport electrons between the electrodes, which are internally connected by an electrolyte (liquid solutions, solid conductive polymers, gel), to carry out specific reduction/oxidation reactions. Catalysts are often used to accelerate reaction rates to acceptable levels. The operation principle of a battery is essentially based on a reversible process called reduction-oxidation, where one component is oxidized (loses electrons), and the other component is reduced (gains electrons). Therefore, it is a process in which the components are not consumed but only change their oxidation state; these components can return to their original state under the right circumstances. These circumstances include closing the external circuit during the discharge process and applying an external current during the charging process. [4]

The capacity of a cell is the total amount of electricity produced in the electrochemical reaction, usually measured in ampere-hours (Ah). The theoretical capacity is defined as the product of the number of moles involved in the complete discharge reaction (x), the number of electrons involved in the reaction (n), and the Faraday constant. However, the actual capacity of the battery is always lower than the theoretical capacity because the utilization of active materials never reaches 100%. In practice, the capacity of a battery is calculated by discharging the cell at a specified current until it reaches a specified terminal voltage value known as the cutoff voltage. In this way, the capacity value is the product of that discharge current (A) and the discharge duration (hours). For this reason, battery capacity is measured in milliampere-hours (mAh) or ampere-hours (Ah). [4]

2.1.2.2. Supercapacitors

Supercapacitors, also known as double-layer electric capacitors, are energy storage systems recognized for their ability to store and release energy extremely rapidly. Their main characteristic is high capacitance, which allows for the storage of large amounts of electrical charge. This is achieved through the formation of a double electric layer at the interface between the electrodes and the internal electrolyte of the supercapacitor. While they may not store as much energy as chemical batteries, supercapacitors possess high energy density and long life cycles, making them valuable in applications requiring quick energy bursts, such as regenerative braking in electric vehicles. [5]

The high speed of charging and discharging of supercapacitors is one of their key advantages, making them ideal solutions for situations that demand immediate energy delivery. Moreover, these devices can endure a large number of charge and discharge cycles without significant degradation, ensuring an extended lifespan compared to some batteries. Despite their relatively low nominal voltage, supercapacitors can be connected in series to obtain higher voltages. To fully leverage their benefits, they are often combined with batteries in applications that necessitate both long-term storage and rapid responsiveness.

Supercapacitors find diverse applications in fields such as electric vehicles, intermittent energy storage, backup systems, consumer electronics, and more. Their versatility lies in their ability to provide energy quickly while maintaining a long lifespan. This combination of features makes them an attractive technology for addressing energy storage challenges in a variety of industries. [5]

2.2. State of the art of Hybrid Energy Management Systems Architectures and Isolated Smartgrids

In the past decade, concerns about the environmental effects of electricity generation have led to a transition towards RES to meet global energy demand. Combining RES with ESS can reduce the reliance on energy from traditional sources like diesel fuel. [6]

Each ESS has limitations that significantly restrict its utility. Many systems require high power and high energy, and the ESSs are constrained by these factors. This is why it is necessary to use two or more ESSs to create HESS.

A hybrid system combination involves using both batteries and supercapacitors together to leverage their unique characteristics. For instance, batteries have features like low specific power, high specific energy, shorter lifespan, lower self-discharge capacity, and lower cost per watt-hour.

'

On the other hand, supercapacitors exhibit lower specific energy, higher specific power, rapid charging, longer lifespan, and high self-discharge capacity. Thus, the combination of batteries and supercapacitors utilize the complementary properties of each other and become a system that offer wide availability, low cost, and perfect complementarity. [6]

2.2.1. Systems Topologies

Interconnection topologies can be classified as passive, semi-active, and active. The choice of topology significantly varies depending the system requirements and the functions of the energy management system.

2.2.1.1. Passive Topology

This topology is the most commonly used due to its simplicity and the low number of components required for its implementation. Other advantages include reduced cost, weight, and system volume. However, its disadvantages are uncontrolled current flow and limited use of the supercapacitor.

In the passive hybrid topology, the battery bank and the supercapacitor are directly connected in parallel to the DC-link connection, which means they are required to have the same voltage level. The contribution of energy from each energy source to meet the load demand is defined by the internal resistance of the storage devices. [7]

In this passive topology of batteries and supercapacitors, high-power pulses are absorbed by the supercapacitors due to their low impedance, which makes supercacitors function similarly to a low-pass filter. Furthermore, the charge and discharge characteristics vary considerably, resulting in poor voltage and charge regulation. [7]

In the following figure, this topology can be seen with its respective elements. [7]
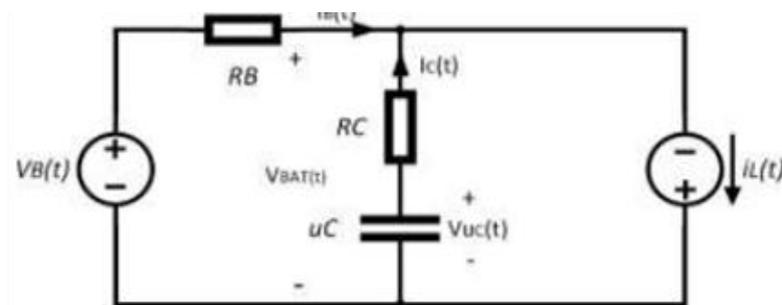
Figure 2.2.1.1.1-1: Passive Topology

'

2.2.1.2.   Semi-Active Topology

This semi-active topology is an improved version of the passive topology and has the significant advantage of being able to maintain the load at its nominal voltage thanks to the DC-DC converter, which is the element added value with respect to the passive topology. This topology retains the characteristic that the battery supplies part of the dynamic component of the load current, and the charge stored by the capacitor is still limited. There are three possible configurations for the semi-active topology, which are the parallel topology, the battery series topology, and the supercapacitor series topology.

The parallel semi-active topology involves placing a DC-DC converter between the parallel branch of the battery and the supercapacitor, as shown in the following figure. [7]
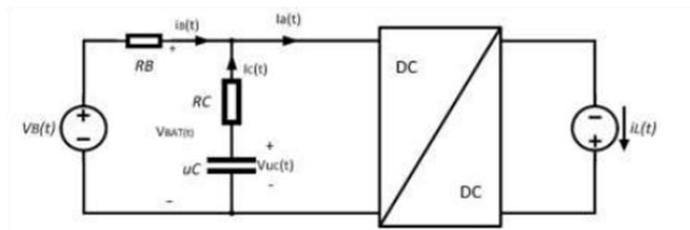
FIGURE 2.2.1.2.2-1: PARALLEL SEMI-ACTIVE TOPOLOGY

The semi-active supercapacitor series topology, widely used in regenerative braking, involves connecting a DC-DC controller between the supercapacitor and the DC-Link.

The semi-active battery series topology consists of using a DC-DC converter and connecting it between the battery and the DC-Link connection point. Both topologies can be seen in the following diagram. [7]

(a)   (b)
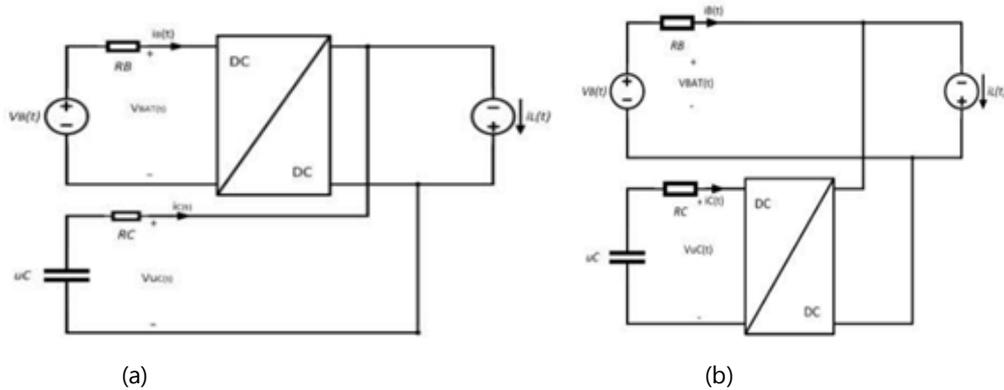
Figure 2.2.1.2.2-2: (a) Semi-Active Battery (b) Semi-Active Supercapacitor Series Topology

2.2.1.3. Active Topology

This topology is an improved version of the previous ones as it addresses the issue of load voltage variations and the integration of storage technologies. Its main drawback lies in the increased complexity of the topology due to the addition of a converter sized for the maximum load power, resulting in reduced efficiency and a higher system cost. There are three possible configurations for the active hybrid topology: active capacitor series, active battery series, and active parallel. [7]

The active parallel topology involves connecting a DC-DC converter in parallel for each of the storage devices, as shown in the following diagram. [7]
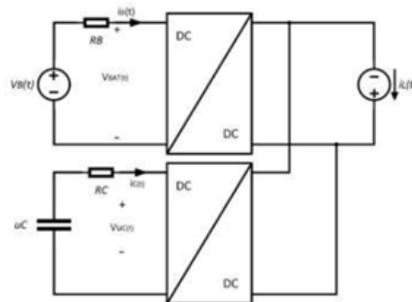
FIGURE 2.2.1.3.3-1: ACTIVE PARALLEL TOPOLOGY

The active battery series topology is an improvement on the semi-active topology, as it can address issues with voltage fluctuations in the supercapacitors by placing a DC-DC converter between this storage device and the load. However, the inclusion of an additional converter initially makes this topology more costly. The diagram of this topology is as follows: [7]
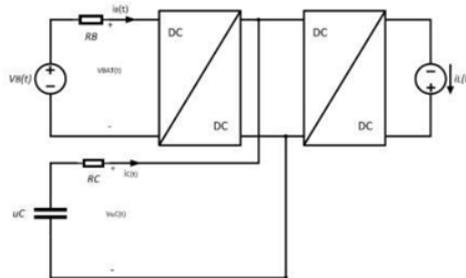
FIGURE 2.2.1.3.3-2: ACTIVE BATTERY SERIES TOPOLOGY

The capacitor series topology is established as an enhancement of the semi-active topologies, in this case, the semi-active capacitor series topology, where the disadvantages of battery voltage reduction are addressed through the inclusion of a DC-DC converter, which is located between the battery and the load, as seen in the following figure: [7]
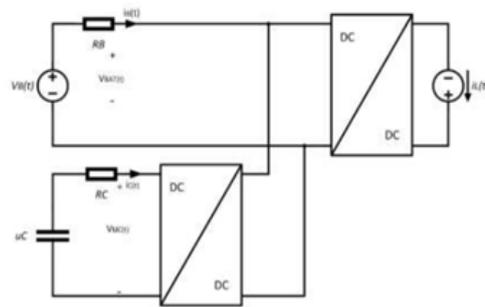
FIGURE 2.2.1.3.3-3: ACTIVE CAPACITOR SERIES TOPOLOGY

2.2.2. Techniques and algorithms of control systems

There are several parameters for selecting a HESS control technique, among which the extension of the lifespan of storage system components, power quality, reduction of power intermittency, hybridization structure, controller response time, and controller cost.

EMS has various functions, including voltage and frequency regulation, power oscillation damping, ramp rate control, generator start/stop, and optimization of generation, load, discharge, etc. Through these functions, profitability of the system is increased, efficiency is enhanced, and generator operation is optimized in terms of the required response and quality as needed by the operator. [8]

The diagram that best illustrates the operation of the EMS is the following, where dashed lines represent connections to the EMS.

The EMS monitors the status of network components by measuring the values of all their working variables (voltage, current, temperature, etc.) through sensors, stores the information in its database, and executes the necessary commands to coordinate the overall system based on the results obtained from its optimization algorithms. This system allows for intelligent network control. [8]
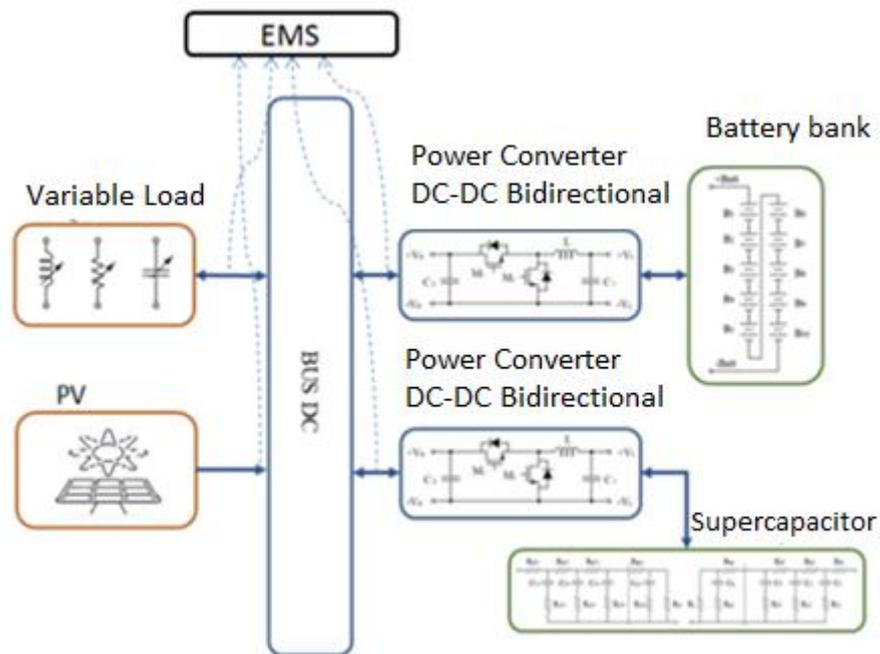
FIGURE 2.2.2-1: EMS DIAGRAM

There are several techniques for the HESS control algorithm, which can be divided into two groups: intelligent techniques and classical techniques. Among the classical techniques are Filtration-based control, Rule-based control, Dead-beat control, Droop control, and Sliding mode control.

Among the intelligent techniques are Model Predictive Control, ANN, FLC, Optimization-based control, Unified control, Hierarchical control, Supervisory control, Feedforward control, and Robust control. [6]
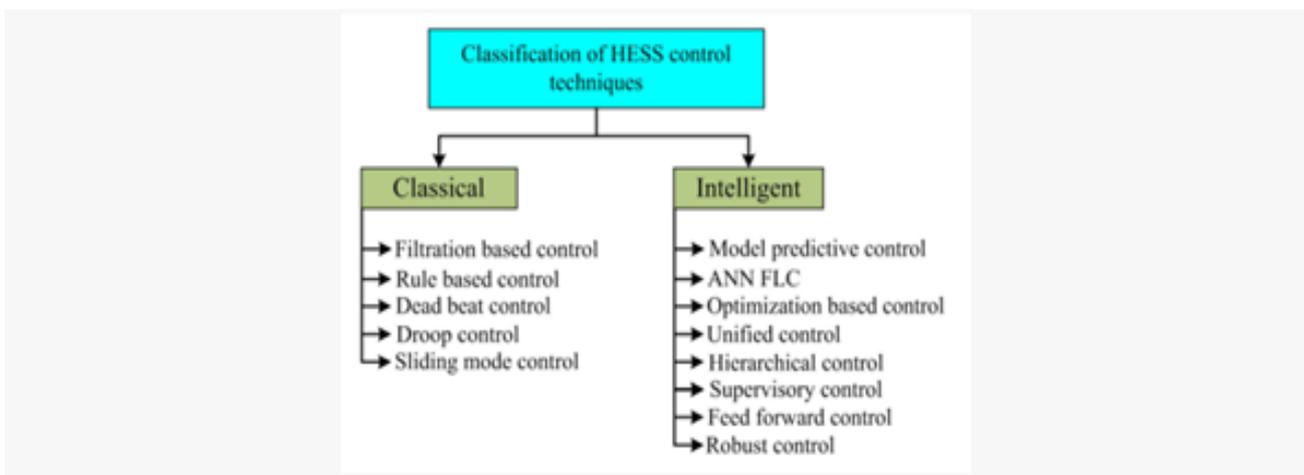
FIGURE 2.2.2-2: CLASSIFICATION OF HESS CONTROL TECHNIQUES

2.2.2.1.   Filtration Based Control Techniques

Filtration Based Control Technique refers to a control strategy or technique that uses filtering methods for control purposes. This technique is often used in systems where it's essential to filter out noise or unwanted signals from the measurements or control signals.

In many control systems, sensors and actuators provide measurements and control signals that may contain noise or unwanted disturbances. Filtering-based control techniques involve the use of filters, such as low-pass filters, high-pass filters, or band-pass filters, to process the measured signals or control signals before they are used in the control algorithm. [6]

This technique separates the energy demand into low and high-frequency components using a filter circuit, leading to the regularization of battery current variations. A low-pass or high-pass filter (LPF) is used to control battery charge levels. The controller is implemented to improve battery lifespan, achieve faster dynamic response, and minimize computational load.

The following diagram illustrates the implementation of this low-pass filter. [6]

The average grid voltage (Vo) is compared with the reference voltage (V ref) and passed through a PI controller. The controller provides the total current that must be supplied from the Hybrid Energy Storage System (HESS). This total current (Itot_ref) is divided into a dynamic power component and an average power component. The average power component exits the low-pass filter (fLPF) and is provided as a reference (IB ref) to the battery current control loop, while the dynamic power component is provided as a reference (IS ref) to the SC current control loop.
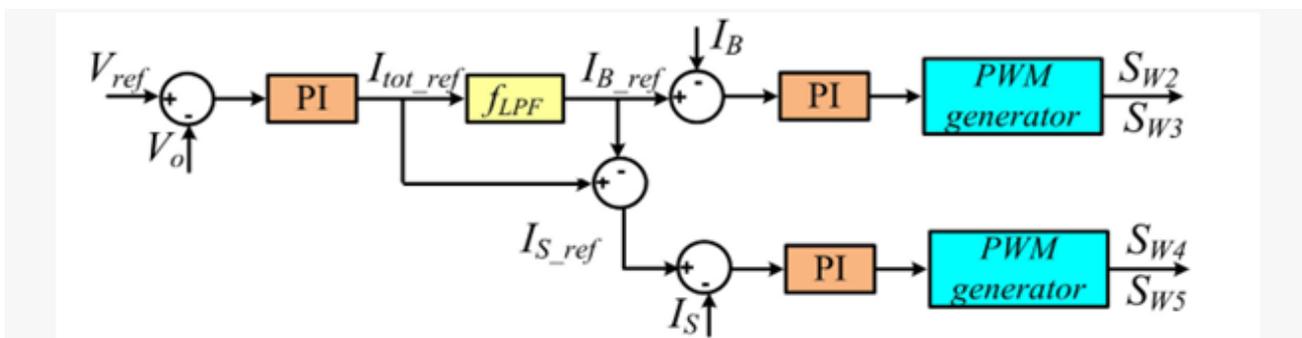
FIGURE 2.2.2.1-3: FILTRATION BASED CONTROL

2.2.2.2.   Rule based control techniques

This Rule-Based Control Techniques is a very simple control technique for storage systems that involves sequential decision-making based on rules defined by experts or mathematical models. A straightforward RBC approach is the use of thermostats that limit high-energy storage according to SOC limits. In a recent study, an improved method based on state machine control was introduced,

allowing for the inclusion of numerous rules designed based on expert experience. This approach was used to combine fuel cells and batteries in a system, dividing the operation into regions to achieve effective control. Rule-Based Control Techniques are popular due to their lower computational load and ease of implementation. However, it is noted that in real-world practice, the suppression of fluctuations such as wind speed and solar radiation may be limited. [6]

2.2.2.3. Dead beat control

This control technique is based on the system model to generate the duty cycle relationship for minimizing error regulation in a control cycle. In this way, state variable errors are kept under control, and the power distribution among ESS is effective. Fast dynamic response and high control precision are additional features of the deadbeat controller. Furthermore, it also acquires the characteristics of conventional controllers such as simple implementation and an easy tuning process. The following diagram illustrates this control technique. [6]

The supercapacitor current and the battery current are used to determine the HESS current (Ihess). This current, along with the bus voltage (Vbus) and the bus reference voltage (V*bus), enter a block that calculates the final reference current of the HESS (I*hess), considering the energy losses of each component. This current is divided into two currents: the reference current for the battery (I*bat) and the reference current for the supercapacitor (I*sc), which will supply the average power demand and the transient power demand, respectively. To calculate the battery's reference current, a low-pass filter (LPF) is used.

Once the reference currents for the battery and the supercapacitor are obtained, along with the bus voltage data for the battery and the supercapacitor voltage, the duty cycles of the battery and the supercapacitor are calculated by comparing them with saw signals.
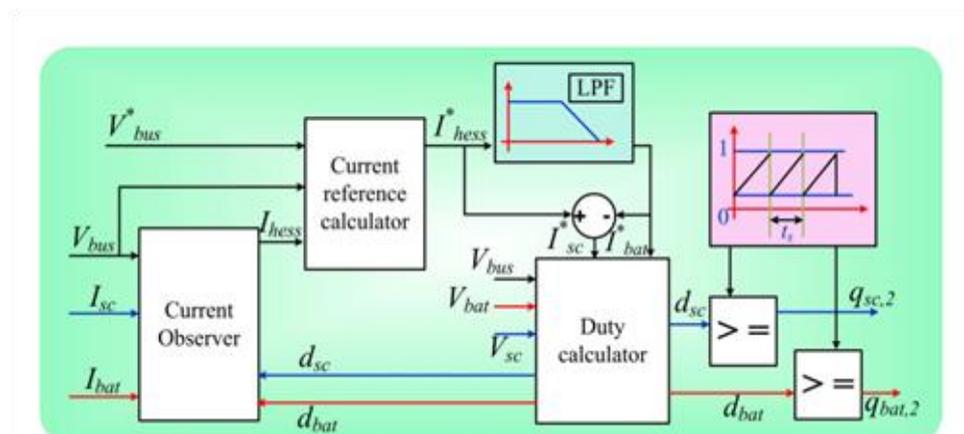
FIGURE 2.2.2.3-4: DEAD BEAT CONTROL

2.2.2.4.   Model Predictive Controller (MPC)

This technique is new and efficient, especially for solving multivariable control problems, based on the prediction of future control decisions for the state of the machine. MPC also benefits by achieving optimization in current processes and preserving future processes. MPC can predict future control inputs and future system responses as well. [6]

The model of this control technique is as shown in the following figure. [6]

The system is based on a feedback model that utilizes the voltages and currents of the energy storage elements, calculating the reference currents for these elements using a hysteresis block. The feedback model employs a PI controller block that takes the bus voltages (Vbus) and the bus reference voltage (Vref) as inputs. The output signal is then combined with the load current (Iload) to generate the bus reference current (Ibusref).
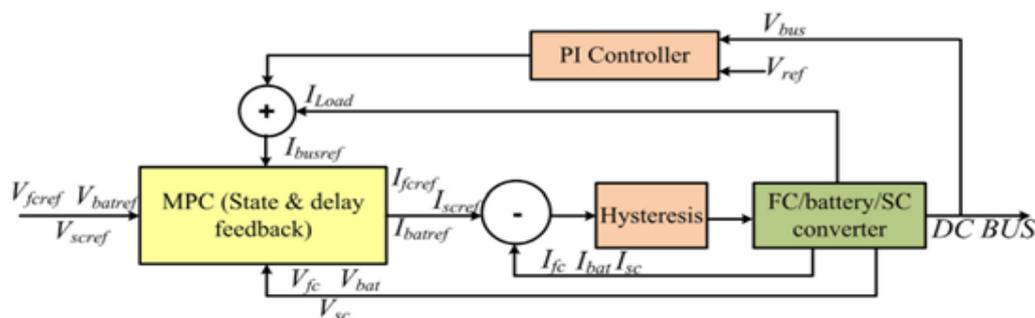
FIGURE 2.2.2.4-5: MODEL PREDICTIVE CONTROLLER

2.2.2.5.   Neural Network and Fuzzy Logic

ANN and FLC are effective methods for real-time energy management system control compared to conventional methods.

Intelligent control strategies can enhance the dynamic behavior of the system without requiring the exact system model, but the drawback is that they do not guarantee optimal performance. ANN is suitable for use in control systems; however, due to its 'black box' nature, it lacks rules for defining its structure, such as the number of cells or layers. Another disadvantage of ANN is that the learning and adjustment process requires historical data. [6]

One way to use ANN in energy storage system control is through feedback loops to learn from new data and experiences. This approach's primary analysis factor is computational complexity, which depends on the amount of data used for ANN training.

In contrast to ANN, the FLC stands out for its comprehensibility and resistance to parameter variations. An additional advantage is that FLC does not depend on an accurate system model or a specific training method. The FLC algorithm is based on rules and MF. [6]

A drawback of this FLC controller is that as the number of variables increases, the process of optimizing membership values becomes much more complex. One way to overcome this issue is to use a multi-mode fuzzy logic-based controller, which can operate in both short-term and long-term scenarios.

In the short term, it enhances performance on the alternating current side, and in the long term, it improves battery aging and efficiency issues. [6]

2.3. Definition of electrical loads of the different equipment

For the design and analysis of the electrical system of an aircraft, it is necessary to know what the system loads are, and based on this data, determine which power sources should be designed and installed on the aircraft to provide proper power supply during flight.

The electrical design of an aircraft can be understood as a microgrid. In the following figure, the model of a MEA, based on the B-787 aircraft model, can be seen, which features a main 230V alternating current bar with a nominal frequency of 400 Hz and a 270V DC bar. Both the AC bar and the DC bar are connected to resistive loads and their respective filters or rectifiers. [1]
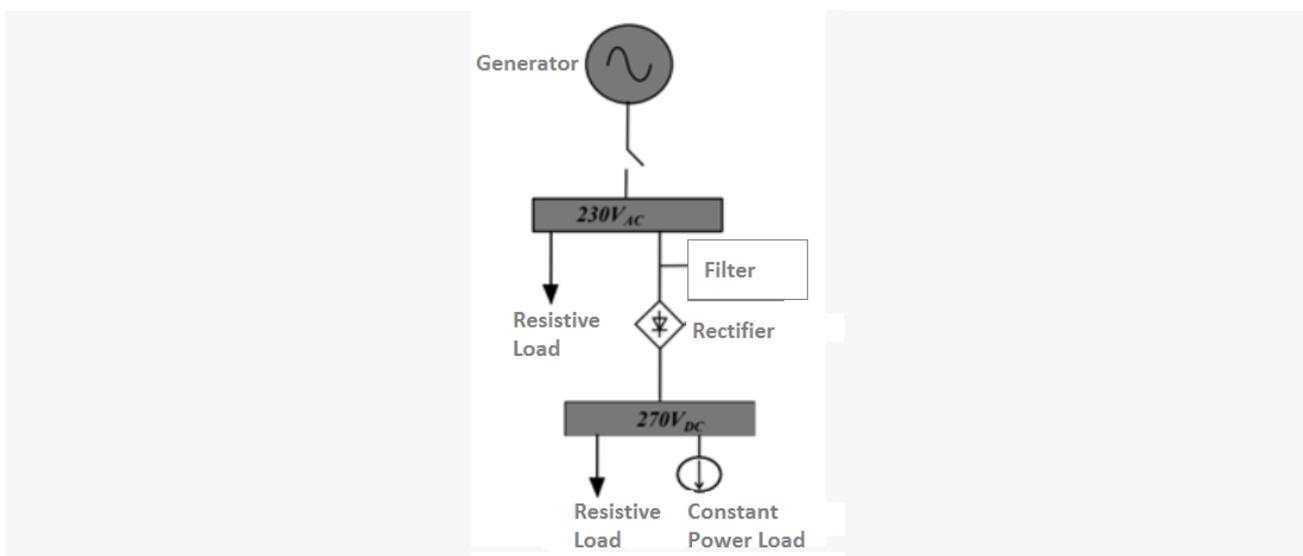

FIGURE 2.3-1: ELECTRICAL DESIGN OF AN AIRCRAFT

2.3.1. Type of load on an aircraft

In aviation, the quantity of loads and circuits is quite extensive, and the significance of each one depends on its role within the system. Loads on an aircraft, similar to other non-land vehicles, can be categorized into three categories: vital loads, essential loads, and non-essential loads, depending on whether a load is critical to the aircraft's flight or if the temporary or prolonged loss of the load does not jeopardize the flight. [1]

- Non-Essential Services: These are systems that can be left without power without affecting flight safety in order to reduce the load in case of an emergency or abnormal situation. These loads are connected to buses that, depending on the manufacturer, may be referred to as main buses, load buses, or generator buses, and they receive power directly from the generators. Both AC and DC buses of this type provide electrical power to services such as the galley services, passenger entertainment services, or reading lights.
- Essential Services: These are loads necessary to ensure safe flight in an emergency situation and are connected to buses referred to as essential buses, always powered by at least one generator (main generators, APU, or emergency RAT generator) or from the aircraft's batteries. Typically, all aircraft have essential buses in both AC and DC.
- Vital Services: These loads are indispensable on an aircraft and are used for emergency landing. These systems are connected to buses known as hot buses, reserve buses, or emergency buses. Within this group, there are loads such as cabin and crew emergency lighting, radio systems, fuel control systems, or fire protection systems. [1]

2.3.2. Principals loads of a Solar Aircraft

The loads on a conventional aircraft are well-known, but there are crucial differences between the loads on a conventional aircraft and a solar aircraft that are decisive in sizing the mechanical and electrical design. Among the main loads found on a solar aircraft are: [9]

- Solar Panels: The primary load on a solar aircraft is its array of solar panels, which capture energy from the sun and convert it into electricity to power the electric motor or propel the aircraft. These panels occupy a significant portion of the aircraft's surface.
- Servomotor: The solar aircraft rely on the generation of solar energy through their solar panels. Servomotors are used to track the sun's position and adjust the solar panels to maximize the capture of solar energy.
- Electric Motor: An electric motor is necessary to convert the electric energy generated by the solar panels into motion and, thus, propel the aircraft. The electric motor and its components are an essential load.

- Instruments and Control Equipment: As with any aircraft, instruments and control equipment are required to operate the aircraft. These may include navigation systems, communication equipment, energy monitoring systems, safety systems, and more.
- Specific Payload: Depending on the aircraft's purpose, it may carry a specific payload. For example, scientific instruments, cameras, sensors, or other specialized equipment if it is a research mission.
- Optional Payload: In some cases, solar aircraft may carry additional payload, such as supplies or research equipment, depending on their specific missions. [9]

2.3.3. Equation of the loads

2.3.3.1. Antenna 5G

Analyzing the power that an electrical antenna can consume depends on many factors such as its technology, configuration and use.

That is why it is possible to analyze in general the system of radio reception and transmission, in which three main components are considered:

- Idle Power Consumption (P_idle): This is the energy consumed when the antenna is not transmitting or receiving data but remains operational to maintain connectivity and network monitoring.

- Power Transmission Consumption (P_transmit): This is the energy consumed when the antenna is transmitting 5G signals to mobile devices or other antennas.

- Power Reception Consumption (P_receive): This is the energy consumed when the antenna is receiving signals from mobile devices or other antennas. [10]

So, a simplified representation of the total energy consumption (P_total) of a 5G antenna could be:

$$Ptotal = Pidle + Ptransmit + Preceive$$

Equation 2.3.3.1- 1: Antenna reception and transmission system power

Each of these components (P_idle, P_transmit, and P_receive) will depend on specific factors such as antenna technology, operating frequency, traffic density, and other parameters. In practice, a series of measurements and detailed technical data would be required to accurately calculate these values. [10]

It's important to note that energy consumption can also vary based on network load and how energy is managed within the 5G infrastructure. Efficient energy management systems can reduce energy consumption during periods of low demand and increase it when necessary to maintain adequate quality of service.

To obtain the power required for the radio transmission and reception system, the following equation would be used: [10]

$$Energy = efficiency * Power * Time$$

Equation 2.3.3.1- 2: Antenna reception and transmission system energy

2.3.3.2. Electric Motor

- Electrical Circuit Equation: This equation describes the relationship between the applied voltage to the motor, the electric current flowing through the motor, and the electrical characteristics of the motor, such as its resistance and inductance. For a DC motor, the circuit equation is known as Ohm's Law and is expressed as: [11]

$$V = I * R + L * \frac{di}{dt}$$

Equation 2.3.3.2- 3: Electrical Circuit Voltage

Where:

V: is the voltage applied to the motor.

I: is the current through the motor.

R: is the resistance of the motor.

L: is the inductance of the motor.

di/dt: represents the rate of change of current with respect to time.

- Motor Torque Equation: This equation describes the relationship between the motor's produced torque and the current flowing through it. For direct current motors, this relationship can be expressed as: [11]

$$T = Kt * T * I$$

Equation 2.3.3.2- 4: Electrical Circuit Motor Torque

Where:

I: is the current of the electric motor

T: is the motor torque (measured in Newton-meters, Nm).

Kt: is the motor's torque constant, which relates current to motor torque. [11]

- Velocity and Position Equations: These equations describe how the angular velocity and position of the motor change based on the applied torque. For direct current motors, the relationship between torque (T), angular velocity (ω), and motor inertia (J) can be expressed as: [11]

$$T = J * w$$

Equation 2.3.3.2- 5: Electrical Circuit Velocity and Position

This equation can be combined with motion equations to describe how angular position changes over time. [11]

These equations form the basis of a basic mathematical-physical model for an electric motor. However, complexity increases significantly in more advanced motors or specific applications.

Based on more comprehensive aerodynamic studies, it was determined that the engines to be used are 28.9 kW.

2.3.3.3.   Compressor

The equation to calculate the energy required to operate a ballonet compressor would be

$$E = P * t$$

Equation 2.3.3.3- 6: Energy of compressor

Where:

- E is the required energy in joules (J) or watt-seconds (W·s).

- P is the power required for the compressor in watts (W).

- t is the operating time of the compressor in seconds (s). [12]

The power required for the compressor depends on various factors, including the size and design of the ballonets, the amount of gas that needs to be moved, changes in altitude, temperature, and the efficiency of the compressor. Therefore, the required power should be determined based on specific design and operational considerations of the ballonets.

2.3.3.4.   Condenser

A fuel cell is an electrochemical device that converts the chemical energy of a fuel (typically hydrogen) and an oxidizing agent (usually oxygen from the air) directly into electrical energy.

In a fuel cell, water is produced as a byproduct of the chemical reaction between hydrogen and oxygen to form water. To ensure that the recirculated hydrogen is clean and dry, a condenser or water separator system is used to remove and collect the water produced during the reaction. This component helps ensure the purity of the hydrogen before it re-enters the fuel cell system. The presence of unwanted water could affect the performance and durability of the fuel cell. [13]

One aspect of the condenser to be analyzed is its heat which is calculated with the following equation

$$Q = m * C * (T2 - T1)$$

Equation 2.3.3.4- 7:Heat of the condenser

Where

"Q":is the amount of heat released in the condenser.

"m": is the mass of circulating refrigerant.

"C" :is the heat capacity of the refrigerant.

"T1": is the temperature of the refrigerant before entering the condenser.

"T2": is the temperature of the refrigerant after leaving the condenser. [12]

2.3.3.5. Servomotor

The fundamental equation in a servo motor is the position control law, which relates the desired position (reference) and the actual position of the motor. A controller (such as a PID) is used to adjust the voltage to the motor to minimize the position error. The position control equation looks like this: [11]

$$u(t) = K_P * e(t) + \frac{K_P}{T_i} \int_0^T e(t)dt + K_P * T_d * \frac{de(t)}{dt}$$

Equation 2.3.3.5- 8: Control position of the servomotor

Where

u(t):is the signal control

Kp: is the coefficient of the proportional controller

Ti: Time integral

Td: Time derivative

e(t): is the position error

$\int_0^T e(t)dt$: is the integral of the error over time

$\frac{de(t)}{dt}$: is the derivative of the error over time

2.3.4. Time of load

The time of each load which is in operation is also a key factor in determining the energy needed for each load to function correctly. The following table shows if the loads are running continuously or if they operate intermittently.

Table 2.3.4-1: Time of each Load

Element	Number of units	Power source	Power	Consumption Time
Antenna 5G	1	DC	20Kw	halftime
Electric motor	2	DC	100kw	continuously
Compressor	1	DC	2kw	intermittent
Servomotor	1	DC	VARIABLE	intermittent
Navigation Systems	1	DC	1KW	continuously
Condenser	1	DC	VARIABLE	intermittent

2.4. Sizing of generation and accumulation systems to cover power profiles

2.4.1. System topology

To design the distribution and storage system, an active topology was chosen because it addresses the problems associated with other topologies, such as voltage fluctuations on the load and optimal control of the power supplied by the sources to the load.

Its main drawback lies in the increased complexity of the topology, due to the addition of a converter sized for the maximum load power and the consequent reduction in efficiency, accompanied by an increase in the system's price.
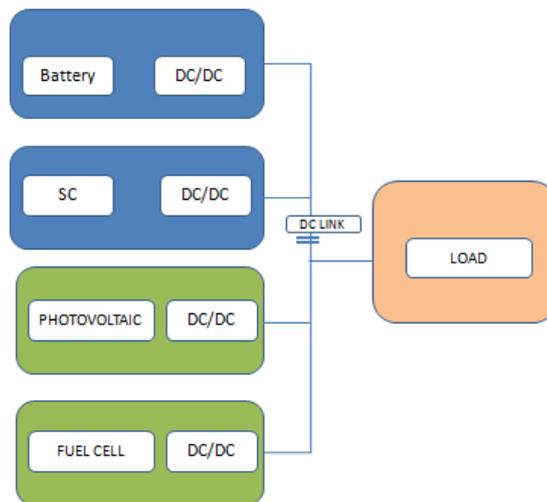
'

FIGURE 2.4.1-1: SYSTEM TOPOLOGY

2.4.2. Energy storage management algorithm

To control the energy storage system, the Rule-Based Control technique was employed, which involves defining sequential decisions based on rules.

The energy management algorithm is based on the following decisions:

It determines whether the load power is greater or less than the source power. If the load power is greater, then power needs to be extracted from the battery. If it is lower, then that power is used to charge the battery.

In both cases, if there is a sudden change in the load, the supercapacitor comes into operation to provide a power peak for both absorption and supply. The power of the supercapacitor is limited to a specific value of 5 kW and operates for a short duration. After this time, only the battery is engaged.

2.4.3. Sizing of energy sources

Starting with the data of the system loads, the sizing of the aircraft's power generation system is carried out.

The primary source of generation is the solar panels, which extract energy during the day while the aircraft is in operation. The secondary power source is the fuel cells, with hydrogen as the combustion element.

As energy storage systems, there are batteries and supercapacitors. Batteries will function as another energy source since solar panels do not provide the maximum power of 100 kW required for all systems. Their main role will be during the night or when none of the generation systems is operational. Supercapacitors will be used when the aircraft needs to accelerate its movement or when sudden load changes are detected.

The sizing of storage and generation systems has been carried out based on the sizing of loads. The main objective is for the energy management system to be capable of keeping the platform operational 24 hours a day. To perform the sizing, it is necessary to know the total consumption of the aircraft during the 24 hours of operation. Since consumption is not constant over time, operation profiles are defined to determine the engine power based on the speed achieved. Two profiles will be calculated, one for daytime flight with an 8-hour interval (8 solar production hours) and another for nighttime flight with a 16-hour interval. Nighttime flight will have a lighter workload, with the aircraft experiencing lower average consumption compared to daytime, benefiting from solar panel power supply.

Table 2.4.3-1:Flight Mode Profiles

Flight Mode Profiles					
Flight speed	10 km/h	60 km/h	100 km/h	0 km/h	Operating hours
Daytime flight percentage	20%	20%	10%	50%	8
Nighttime flight percentage	20%	5%	2%	73%	16
Power requirements for each velocity [kW]	10,00	25,00	100,00	0	

With these approximate flight profiles, we have a coverage for 24 hours of flight with representative speeds sufficient for calculating the aircraft's average energy consumption.
'

The assumptions made for this calculation are as follows:

- The solar generation system must be capable of supplying the energy to be consumed throughout the day, generating an excess on average that will be stored in the batteries to cover nighttime demand.
- The battery will be sized to cover the nighttime energy demand in conjunction with the supercapacitors.
- Supercapacitors will handle power spikes during accelerations as a support to the battery.
- The fuel cell will be used in case of an emergency if the stored and generated energy is not sufficient to meet the demand, but it will not be used within the aircraft's daily energy mix.

The calculations for the supercapacitor module required for installation start by determining the largest power step needed to transition from the previous speed to the next. In this case, we are taking 75 kW as the power required to transition from 60 to 100 km/h. This will be an instantaneous power output for 1 second. We will consider a step time of 5 seconds. With this, the maximum power the module should be capable of delivering will be 375 kW in 1 second, but it will be limited by the power electronics to a maximum of 75 kW.

For the battery, calculations are based on the energy consumption of the loads during nighttime and daytime flights according to the operational profiles. During daytime flight, it is assumed that all systems function normally, including servomotors, navigation systems, and antennas, maintaining 100% of their consumption and operation. Flight systems like the compressor will only be active for 30% of the flight, referring to the moments involved in inflating and deflating the ballonets.

With these considerations in mind, the average daytime consumption will be:

$$E_{Daytime} = Daytime\ flight\ hours(P_{Day\ motors} + P_{servomotors} + P_{Nav} + 0.3 * P_{Sist} + P_{antenna})$$

<div align="center">Equation 2.4.3- 1:Daytime Consumption</div>

This will result in an average consumption of 42.5 kW and a total consumption of 340 kW during the day.

During nighttime flight, the motor profile is less demanding. Similarly, the ballonets are assumed to operate at 10%, and the antenna will be used at 50% to conserve energy, while the rest of the systems will remain at 100% as they are critical for the control and manoeuvrability of the aircraft.

$$E_{Nighttime} = Nighttime\ flight\ hours\ (P_{Night\ motors} + P_{servomotors} + P_{Nav} + 0.1 * P_{Sist} + 0.5 * P_{antenna})$$

Equation 2.4.3- 2: Nightime flight

With this, there will be an average consumption of 18 kW and a total consumption of 287 kW during the night.

The total power consumed is set at 627 kW, which will need to be stored during the 8 daylight hours, leaving a solar plant requirement of 80 kW.

The battery should be able to supply the 448 kW throughout the night, sizing the battery to store 448 kWh, and limiting the power to 100 kW, which will be the maximum needed to cover a nighttime flight profile without issues.

Finally, the fuel cell will be sized to maintain the navigation systems and store energy for performing a landing manoeuvre if necessary or supporting the energy storage system. For this purpose, a 5 kW model has been chosen, which adequately meets the power requirements.

The power ratings for each of the energy sources and a description of their application are shown in the following table.

Table 2.4.3-2: Application of the load

Element	Type	Power	Application
Batteries	Accumulation	100 kW / 448 kWh	Energy storage and power supply during the night
Supercapacitors	Accumulation	75 kW	Energy storage and power supply during load changes
Fuel cell	Source	5 kW	Secondary or emergency power source
Photovoltaic panels	Source	80 kW	Supply power during the day

2.5. Storage and generation simulation results (separately and individually)

2.5.1. Storage and generation with load

These graphs show simulations of individual sources connected to different loads

2.5.1.1.   Battery with load

This simulation solely focuses on an energy storage system, in this case, a battery, connected to a variable load. The graph shows how the voltage decreases as the battery delivers power, in contrast to the current, which increases in value as it provides power. Additionally, in the lower graph, both the battery power and the reference power required by the load are represented. The power delivered by the battery (blue graph) follows the power curve demanded by the load (orange graph).
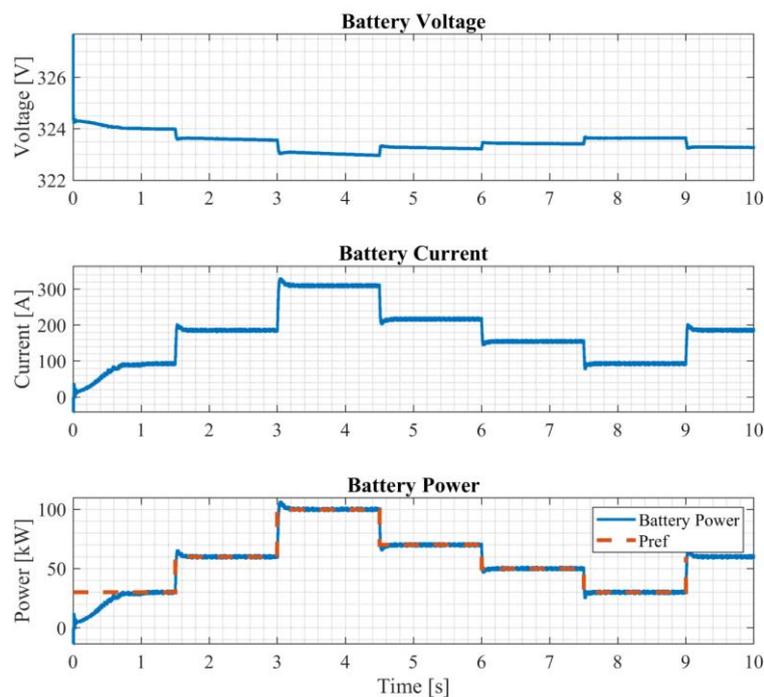

Figure 2.5.1.1-1: Voltage, Current and Battery Power

2.5.1.2. Supercapacitor with load

This simulation focuses on the supercapacitor connected to a variable load. The supercapacitor exhibits nearly the same behaviour as the battery, with the key distinction that its voltage decreases more rapidly as it delivers power. The current graph also demonstrates the supercapacitor's quick response to sudden load changes. Furthermore, in the lower graph, both the supercapacitor's power and the reference power required by the load are represented. The power supplied by the supercapacitor (blue graph) closely follows the power curve demanded by the load (orange graph), albeit with slightly more ripple compared to the battery graph.
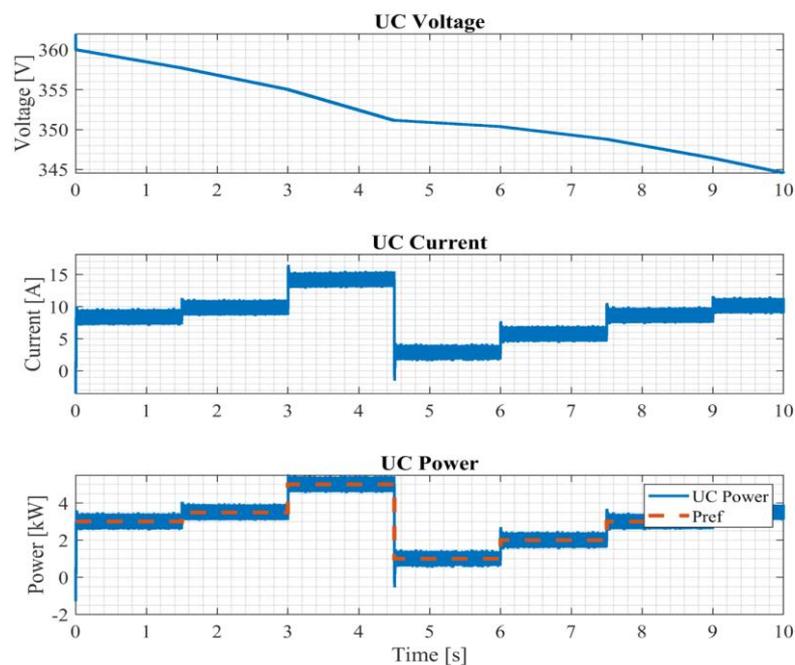

Figure 2.5.1.2-1: Voltage, Current and Supercapacitor Power

2.5.1.3. Photovoltaic Panel

The photovoltaic panel has a power-voltage curve, as shown in the following figure. For the simulation of the photovoltaic panel, an MPPT (Maximum Power Point Tracking) algorithm was designed to keep the voltage between 260-280V to ensure that the solar panel operates at its maximum efficiency and produces power close to 80 kW.
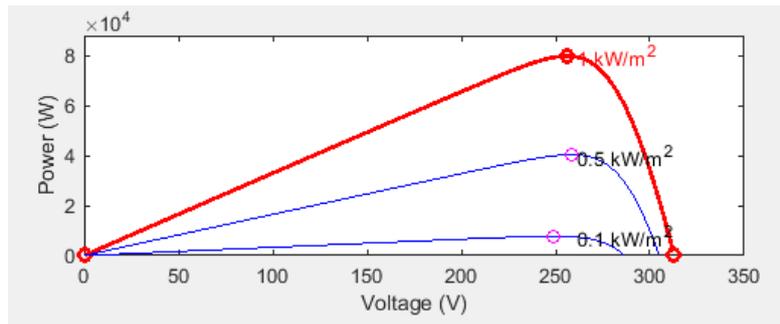
FIGURE 2.5.1.3-1: POWER-VOLTAGE CURVE

As seen in the figure, the voltage remains close to 260V, and the current increases or decreases as the load value changes, but it stays within the range of 250 to 300. Regarding the PV (Photovoltaic) power, the curve aims to maintain its optimal power value of 80 kW, even if the load demands less. This is because neither the battery nor the supercapacitor is connected, so the surplus power can be directed to one of the two energy storage elements.
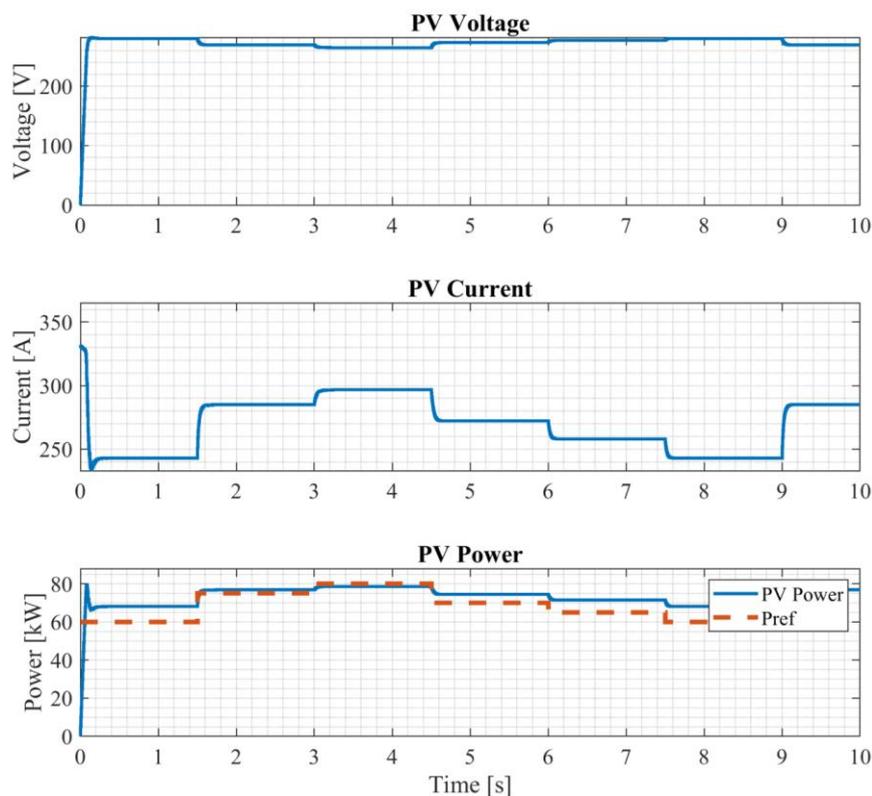

Figure 2.5.1.3-2: Voltage, Current and Photovoltaic Panel Power

2.5.1.4.   Fuel Cell

For the fuel cell simulation, a fuel cell was designed to generate power close to 5 kW. In the graph, it can be observed that the power output is constant and independent of the load's power demand. The power demanded by the load (shown in the orange graph) varies between 3 and 5 kW, while the fuel cell's power output remains a constant 4 kW.
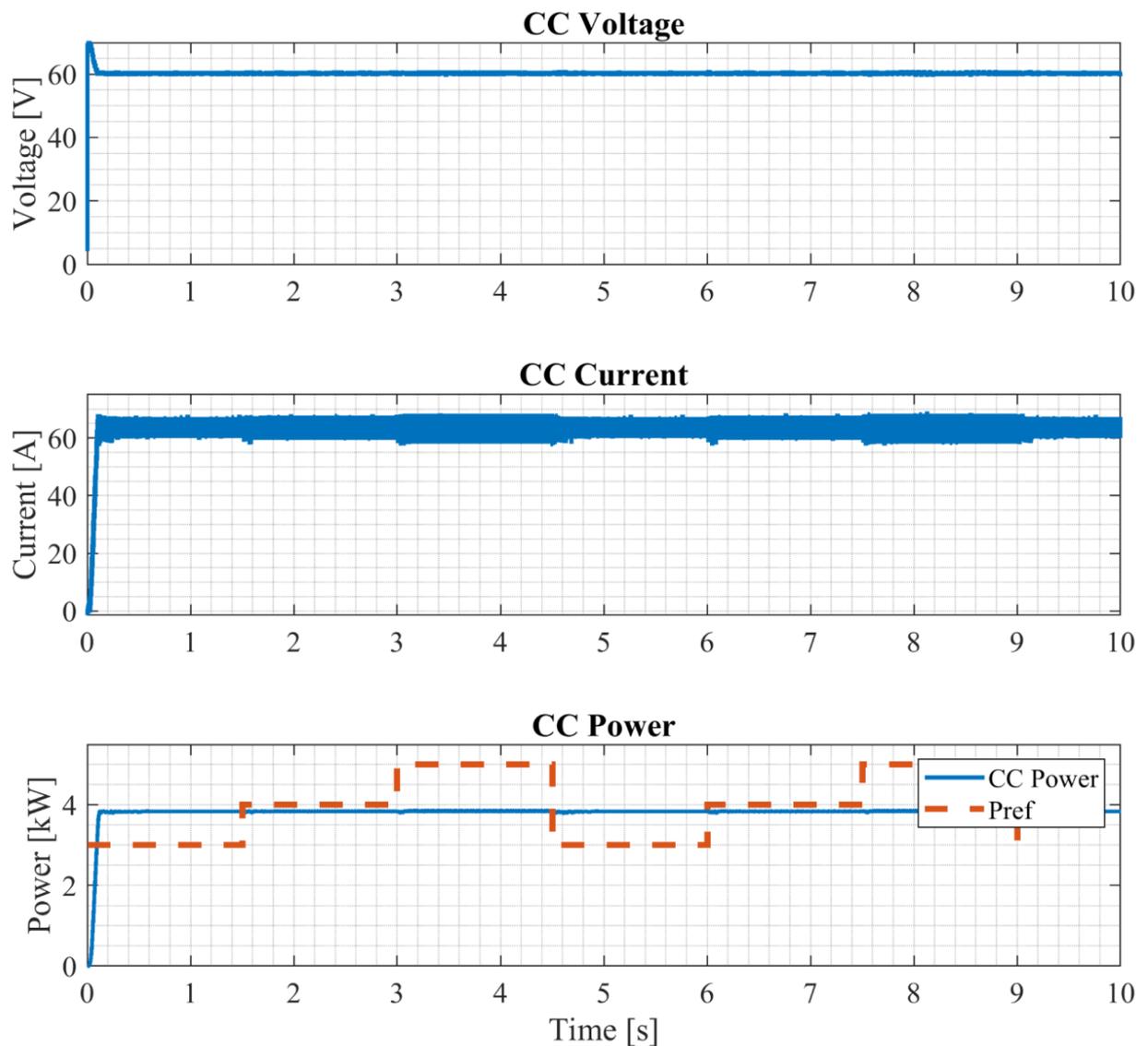

Figure 2.5.1.4-1: Voltage, Current and Fuel Cell Power

2.5.2. Integration of storage and generation systems

Once the simulation of each energy source connected to variable loads is completed, all energy sources and storage systems, such as batteries and supercapacitors, are integrated with the variable load.

Each of the energy generation and storage elements has its own voltage converter to ensure that the DC bus voltage remains close to 1000V. The input parameter for these storage elements is the reference power, and this parameter is controlled by the power control algorithm to ensure that the elements provide or absorb energy as needed.
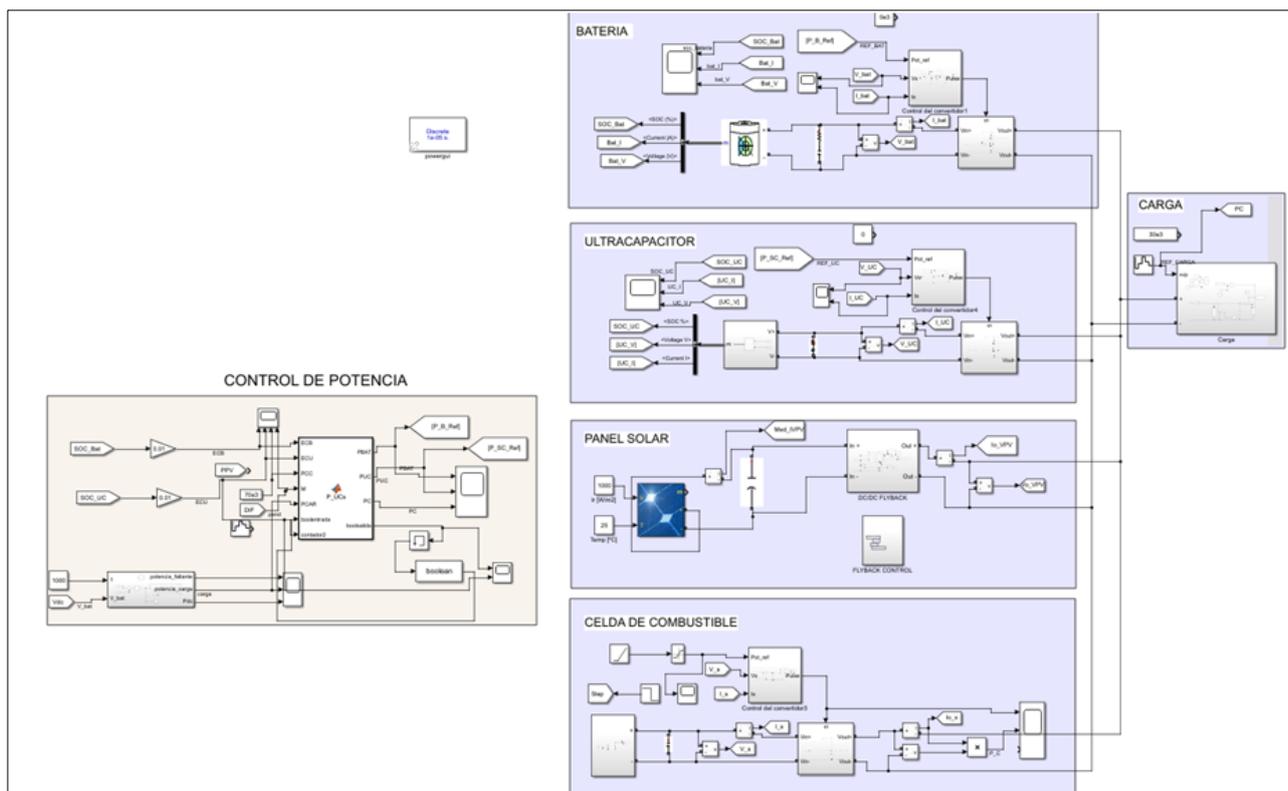

Figure 2.5.2-1: Storage and Generation Systems

To perform the simulation of the entire integrated system, a variable load ranging from 30 kW to 100 kW at different time instances was used, as shown in the following table.

Table 2.5.2-1:Energy required by the load

Energy required by the load	Start time
30e3	0s-1.5s
60e3	1.5s-3s
100e3	3s-4.5s

70e3	4.5s-6s
50e3	6s-7.5s

Regarding the energy sources, the solar panel will strive to operate at its maximum efficiency, aiming to provide the maximum available power. Figure 2.5.2-2 shows the current, voltage and power of the panel power. The current and voltage curves are similar to the ones when the source is connected to a variable load, varying within a range of values to allow the power output to be as high as possible. The power graph (PV Power) shows the relationship between the power from the photovoltaic panel (blue) and the variable load (in orange), indicating that even when the load is less or greater than the efficient power of the photovoltaic panel, the panel's power output attempts to remain constant.
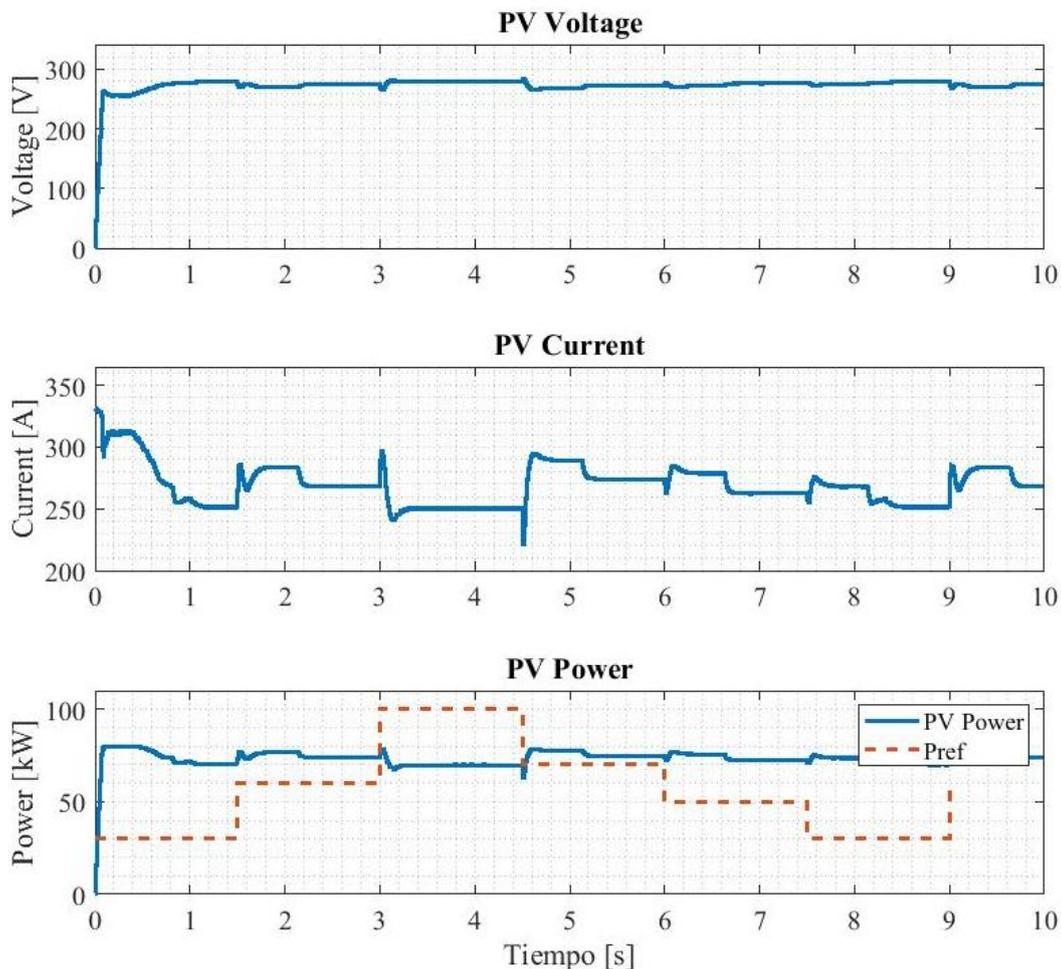

Figure 2.5.2-2: Voltage, Current and Photovoltaic Panel Power in the System

The fuel cell operates similarly to when it was connected to a single load. In the figure 2.5.2-3 shows the voltage, current and power of the Cell Power. The values of power, voltage, and current

remain constant regardless of the load connected. In the third graph (Cell fuel Power) can be observed that the power supplied by the fuel cell is much lower than what the load requires, but it functions well as secondary energy for the storage systems.
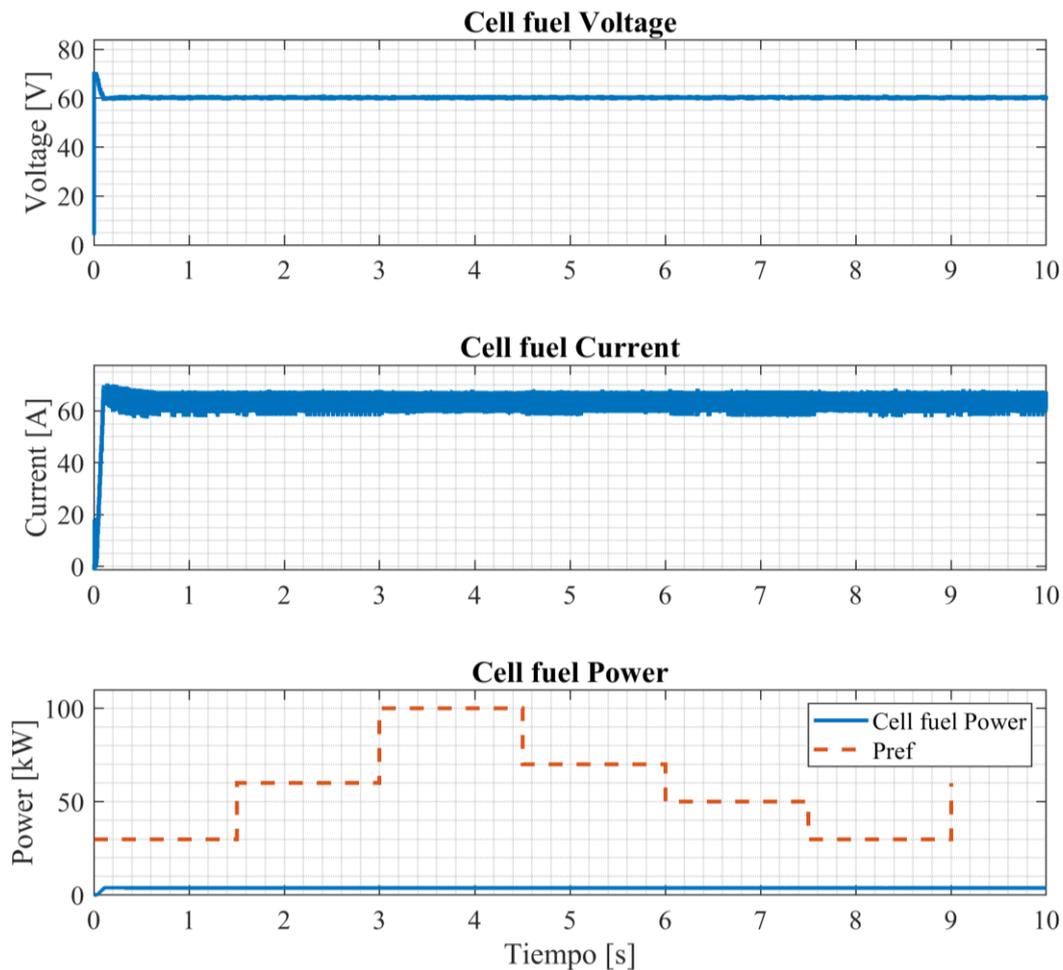

Figure 2.5.2-3: Voltage, Current and Fuel Cell Power in the System

Figure 2.5.2-4 shows the curves of voltage, current and power of the Storage systems. The graph (Load voltage) shows the voltage of the load is close to 1000v. The simulations that were made were of loads of 30kw, 60kw, 100kw, 70kw and 50kw. In the graph (Load Power) it can be seen that the power measured in the load is the same as the demand.

Between the two sources of generation which are the fuel cell and the solar panel, there is approximately 80 kW of power, which serves as a reference for the control algorithm. When a load consumes less power than this reference, the excess power is distributed to the battery and the

supercapacitor. Conversely, when the load demands more power than the total power available, the energy is drawn from these energy storage elements. It can be seen in the graphs Battery Power and UC Power. If the power is supplied by the energy storage elements, the power is positive, and if, on the other hand, power is absorbed by the energy storage elements, the power is negative.
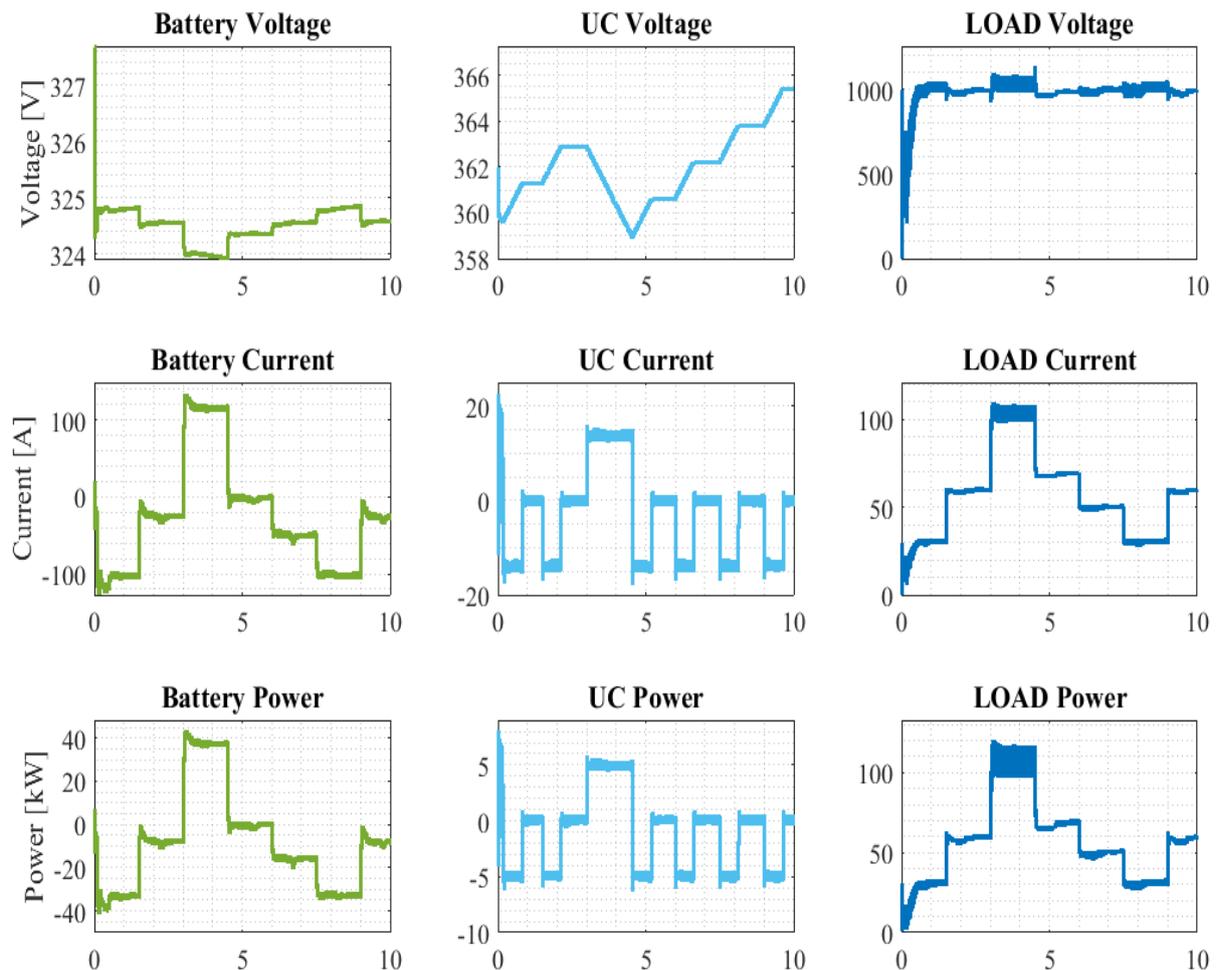

Figure 2.5.2-4: Curves of Energy Storage Systems

The Figure 2.5.2-5 shows the references for each of the generation elements and energy measured at the output of the storage elements. The references for the energy sources are based on the initial requirements, the solar panel should generate 80 kW and the fuel cell 5 kW.

The references for the energy storage systems are calculated by the energy distribution algorithm based on the load value and the total available energy.

In the first graph (Battery Power), the reference power for the battery (violet graph) is compared with the power measured at the battery's output (green). The battery generates the power that the energy management algorithm delivers as a reference.

The measurement at the battery output follows the reference power control signal.

In the second graph on the left (UC Power) the reference power for the supercapacitor (gray) is compared with the power measured at the supercapacitor's output (blue). The supercapacitor generates the power that the energy management algorithm delivers as a reference.

The measurement at the supercapacitor output follows the reference power control signal. The algorithm was designed so that the supercapacitor only operate for a short time.

The reference for the load is the power simulated using a variable resistance, and it is compared with the actual power delivered to the load. From this graph it can be interpreted that the power measured at the load is the same as the power demanded by the load.

The first graph on the right (FV) shows the theoretical power value of 80 kW that the photovoltaic panel (green graph) should have in comparison to the value measured at the output of the photovoltaic panel (Turquoise graph) once the entire generation and storage system is connected to the loads.

The second graph on the right (CC) shows the theoretical power that the fuel cell (red graph) should have in comparison to the power measured at the cell's output(green), which remains close to 4 kW.

The bottom graph on the right (PV+PUC+PFV+PCC) shows the total power generated by the generation sources and storage systems. This graph is similar to the power curve that reaches the load, meaning that it fulfills the load's power requirements if they are met.
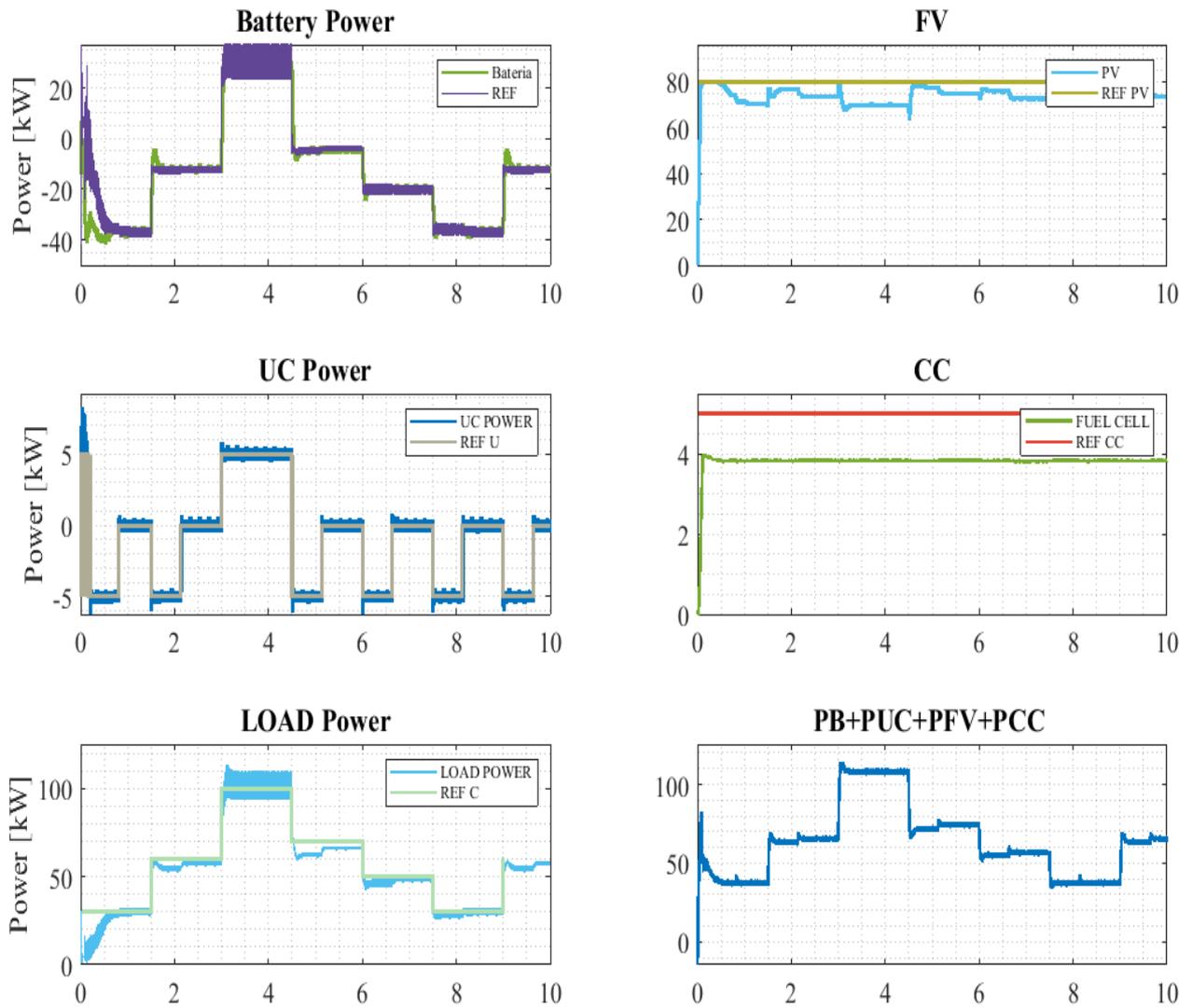
Figure 2.5.2-5 Curves of Generation Systems with Reference

3. Summary and conclusions

In summary, after conducting an analysis of the various systems involved, models have been implemented in a simulation environment to replicate the desired behaviour. This activity served as a foundation, along with the theoretical study and system dimensioning, to construct a virtual system that closely mimics the energy management system's operation.

With this system, the necessary algorithms have been implemented for its operation in accordance with design specifications and decisions made during the study. Therefore, the objective of creating a digital twin of the energy storage system has been successfully achieved.

The simulation of various storage sources has been carried out to gain a better understanding of the profiles that each one can cover, which is crucial when relating them to the 5G load.

Once the behaviour of the systems is validated separately, simulations of the combined systems are performed by combining different loads into a single demand profile, thereby validating the system's performance as a whole. This system, despite showing some voltage and current ripple levels, falls within acceptable ranges for the system, especially as they will be reduced once the dimensioning and filtering connections are made to each of the system components.

4. References

[1]   G. M. G. Buron, "Sistema Eléctrico de los aviones," 06 2016. [Online]. Available: https://uvadoc.uva.es/bitstream/handle/10324/18103/TFG-P-380.pdf?sequence=1. [Accessed 10 2023].

[2]   M. Molina and F. Olsen, "Design of improve fuel cell controller for distributed generation systems," *ScienceDirect*, pp. 1-3, 20 01 2010.

[3]   C. M. Herrera and F. Hernandez Sanchez, "Hindawi," 08 10 2015. [Online]. Available: https://cicy.repositorioinstitucional.mx/jspui/bitstream/1003/1596/1/id36108_Carlos_Morcillo.pdf.

[4]   A. Hernandez, "Análisis económico de un sistema de almacenamiento," 10 08 2022. [Online]. Available: https://biblus.us.es/bibing/proyectos/abreproy/70692/fichero/10+Baterias+para+Almacenamiento+de+Energ%C3%ADa.pdf.

[5]   D. Rodriguez, "Evaluacion de supercondensadores como sistema de almacenamiento para microredes," 10 03 2020. [Online]. Available: https://dspace.ups.edu.ec/bitstream/123456789/18565/1/UPS%20-%20ST004494.pdf.

[6]   T. S. BABU and R. V. KRISHNAKUMAR, "A comprehensive Review of Hybrid Energy Storage Systems:Converter Topologies,Control Strategies," pp. 4-6.

[7]   L. C. Hernandez and J. S. Rojas, "Simulacion de sistemas Híbridos de almacenamiento de energía aplicados en microredes," pp. 25-30.

[8]   G. A. Ramos and R. Costa, "Energy Management Strategies for Hybrid Energy Storage," *Researchgate,* 20 05 2022.

[9]   B. Piccard and A. Borschberg, Solar Impulse:The solar Airplane-Flying around the World without Fuel, Solar Impulse, 2017.

[10]   C. A. Balanis, Antenna Theory:Analysis and Design, Edition 3: Wiley, 2016.

[11]   B. S. Guru and H. Hiziroglu, Electric Machinery and Transformers, Oxford University Press, 2000.

[12]   A.J.Stepanoff, Centrifugal and Axial Flow Pumps:Theory,Design, and Application, Jhon Wiley and Sons, 1984.

[13]   R. O. Hayre and S.-W. Cha, Fuel Cell Fundamentals, Jhon Wiley and Sons, 2006.