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DESIGN OF ALL ELECTRIC SECONDARY POWER SYSTEM FOR FUTURE ADVANCED MALE UAV

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Keywords: *fuel cell, all electric secondary power system, male uav, integrated simulation environment*

Abstract

SAvE (Systems for UAV Alternative Energy) is a research project funded in 2007 by Piemonte Regional Government, Italy, and assigned to Politecnico di Torino and Alenia Aeronautica. Aim of the project is the study of new, more efficient, more effective and more environmentally friendly on board systems for future advanced Unmanned Aerial Vehicles (UAV), particularly for future advanced MALE UAVs. The paper deals with the analysis and design of the all electric Secondary Power System of a future advanced MALE UAV, that we consider as "reference aircraft". After a thorough trade-off analysis of different configurations of the Secondary Power System, the hybrid configuration, characterized by generators (or better, starter/generators), fuel cells and traditional and innovative batteries, has been selected as the most promising. Detailed investigations to find the best way to apportion the supply of secondary power, considering the various power sources (generators or starter/generators, batteries and fuel cells) in the different modes of operations, have been performed thanks to an integrated simulation environment, where physical, functional and mission scenario simulations continuously exchange data and results.

1 Introduction

SAvE (Systems for UAV Alternative Energy) is a research project funded by Piemonte Regional Government and assigned to Politecnico di Torino and Alenia Aeronautica. Aim of the project is the study of new, more efficient, more effective and more environmentally friendly on board systems for future advanced Unmanned Aerial Vehicles (UAV). Figure 1 synthesizes Partners, topics and goals of the research project.

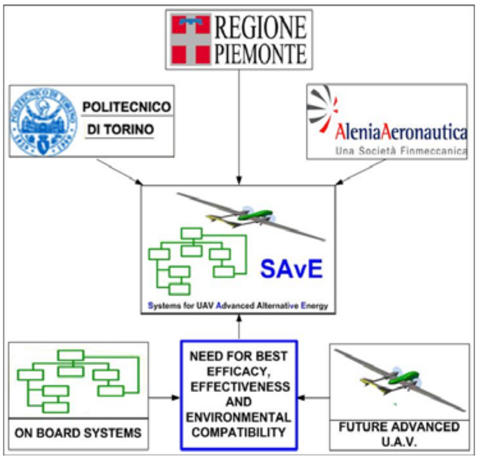


Fig. 1. Partners, topics and goals of "SAvE" research program.

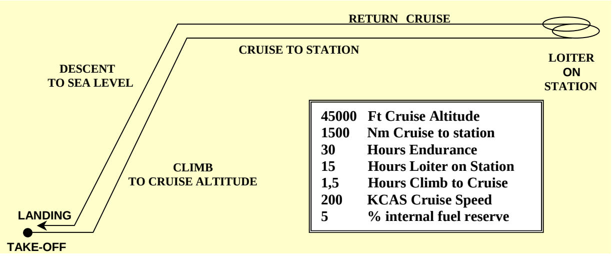
Both Alenia Aeronautica and Politecnico di Torino [1] are strongly involved in research programs on UAV topics. Other initiatives, closely related to the SAvE project, are in fact currently under way, dealing in particular with an Advanced Environmental Monitoring System. Moreover, it is worth remembering that Alenia Aeronautica has recently designed, manufactured and flight tested two UAV technological demonstrators: the Sky-X (see the bottom of Figure 2), which is a jet powered UAV for the future development of Unmanned Combat Aerial Vehicles UCAVs, and the Sky-Y (see the top of Figure 2), which is a propeller powered UAV for next generation MALE (Medium Altitude Long Endurance). Within the scope of the SAvE project it has been decided, to focus the attention specifically on the

Secondary Power System. The Secondary Power System, applying the all-electric philosophy, is thus the primary field of research of the SAvE project. However, Propulsion, Fuel, Anti-Ice and Environment Control System are also considered, because of their close connection with the Secondary Power System. Eventually the Aircraft Configuration, the Structural Layout, the Landing Gear, the Avionic System (both basic and mission) and the Flight Control System are not studied within the SAvE program, but they represent the interface context for the other systems, thus being a source of requirements and constraints.

Fig. 2. Alenia Aeronautica "Sky-Y" and "Sky-X".

2 Mission and reference aircraft

The reference mission profile is illustrated in Figure 3, while the reference aircraft configuration considered in the research program is depicted in Figure 4 and Figure 5 (3D CAD model and digital mock-up [3]).



45000	Ft Cruise Altitude
1500	Nm Cruise to station
30	Hours Endurance
15	Hours Loiter on Station
1,5	Hours Climb to Cruise
200	KCAS Cruise Speed
5	% internal fuel reserve

Fig. 3. SAvE reference mission profile.

Table 1 shows the main technical data of the reference aircraft and its mission avionics equipment, i.e. sensors and communication links to transmit images, video and data to the ground stations. SAvE reference aircraft [4] is powered by two 2400 cc Diesel (automotive derivative).

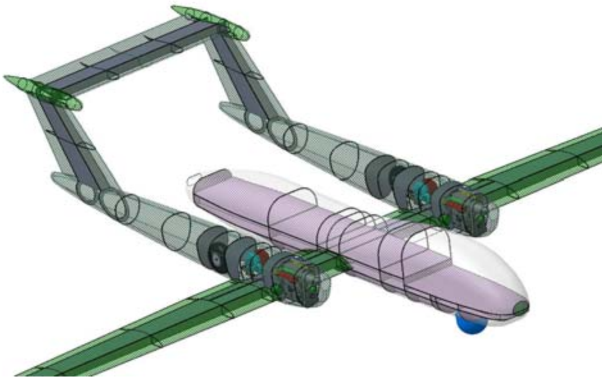


Fig. 4. SAvE reference aircraft: digital mock-up

Fig. 5. SAvE reference aircraft: digital mock-up side view.

Taking into account the different mission phases of the reference mission profile (engine start, taxing, take-off and first climb, climb 3000-7000 m, climb 7000-15000 m, cruise, descent 15000-7000 m, descent 7000-3000 m, approach and landing) and the various avionics equipment used in each mission phase, depending on the considered mode of operation, the electrical loads per each mission phase can be estimated. Figure 6 illustrates the electrical loads per each mission phase for different modes of operation: the normal and the emergency mode. In the normal mode of operation the planned mission (surveillance) is regularly performed, whereas in the emergency mode the planned mission is aborted and the aircraft starts immediately the descent. Main mission avionics equipment (for instance radar SAR and WBDL-SAT ADT) are in this case turned off, while EO/IR and WBDL-LOS ADT with processing equipment are still turned on (in particular the IR video-camera is switched on during approach and landing phases to have a better visibility), in order to find the right spot for landing.

Dimensions	
Length:	11.47 m
Wing Span:	25.00 m
Wing Area:	25.00 sqm
Aspect Ratio:	25
Weights	
O.E.W.:	2213 kg
Fuel Weight:	1200 kg
M.T.O.G.W.:	3763 kg
Performances	
Endurance:	30 h
Radius:	2500 NM
Operational Altitude, Z:	14000 m
Time of climb:	1,5 h
Cruise speed:	200 KCAS
TO and Landing lengths:	1800 m
Power	
2 x 230 HP (Z ≤ 10000 m)	
Mission avionics equipment	
▪ Radar SAR.	
▪ EO/IR Electro Optical Infra Red Sensor.	
▪ IR Video-camera for landing.	
▪ WBDL/LOS-ADT Wide Band DataLink/Line Of Sight-Air Data Terminal.	
▪ WBDL/SAT-ADT Wide Band DataLink/Satellite Air Data Terminal.	
▪ Datalink Computer.	

Table 1. Main technical data.

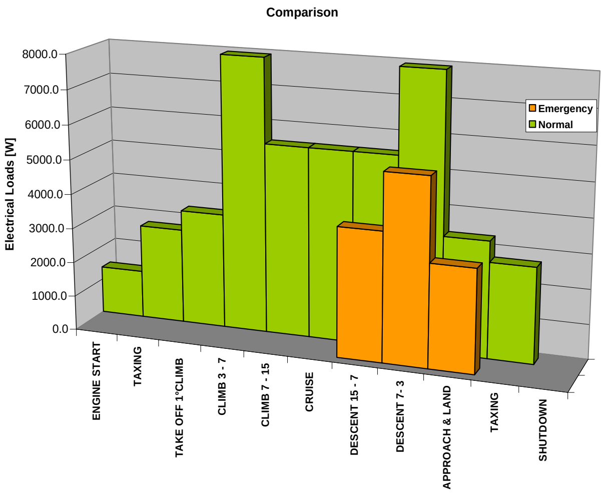


Fig. 6. Electrical loads per each mission phase for different modes of operation.

Moreover in emergency mode all transfer pumps are switched on (apart from 7000 to 3000 m of height when the anti-icing system is active) to empty the fuel tanks, in order to make the aircraft lighter and more maneuverable. This implies that the glide duration increases, thus extending the time available (about two hours have been estimated from the cruise height of about 15000 m) to choose the right spot and to make the aircraft land there safely, without damaging any people or infrastructures. As it can be noted from Figure 6, peaks of electric loads are expected during climb from 3000 to 7000 m and during descent from 7000 to 3000 m [5]. These peaks are mainly due to the possibility of using the electric anti-icing system for the Pitot Static System and the propellers, besides the Goodrich system for the wing anti-icing. Eventually comparing the graphs for the normal and the emergency modes, it can be highlighted that smaller electric loads are estimated for the emergency mode because some mission specific avionics equipment are turned off. Because of the high electric loads for quite a long time, the emergency is the crucial mode of operation of this aircraft and it has to be coped with innovative technologies.

Before describing the electrical power system, it is worth saying that the SAvE aircraft shall be designed with a cumulative probability to lose the system of $5*10^{-6}$ per flight hours or less [6]. The architecture of the electrical power system shall have an adequate level of redundancy to approach the safety design objective of $5*10^{-8}$ per flight hours.

3 Secondary power system configurations

Alternative configurations of the all electric Secondary Power System have been defined and preliminary sized. The most significant configurations, that have been analyzed, are:

- the Conventional configuration (see Figure 7) [7], with starters, generators and batteries (traditional and innovative batteries);
- the Only Fuel Cells configuration [8] with generators (or starter/generators), batteries and fuel cells for both the

normal and emergency mode of operation;

- the Fuel Cells Only for Emergency configuration [8] with generators (or starter/generators), batteries and fuel cells only for the emergency mode of operation;
- the Hybrid Fuel Cells configuration [8], with generators (or starter/generators), fuel cells and traditional and innovative batteries.

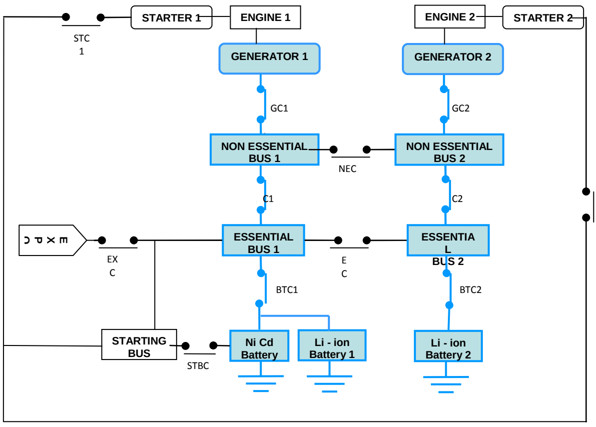


Fig. 7. Conventional configuration architecture – Normal mode of operation.

In the Only Fuel Cells configuration, the fuel cells supply all buses of the SAvE aircraft with the requested electric power during the entire mission. Figure 8 shows the architecture of the electrical system of the Only Fuel Cells configuration, where in blue are highlighted the fed components during the normal mode of operation. The Nickel Cadmium battery is used for starting the engines up and, together with the Lithium-ion polymer battery, the Nickel Cadmium supplies all users in case of power peaks in the normal mode of operation and the essential buses in the emergency mode of operation. The electrical loads of the non essential buses of the Conventional configuration have been transferred to the new shedding buses (see Figure 8). In case of failure of both starter/generators and one fuel cell, the electrical load of all buses is too big for the remaining fuel cell. The shedding buses are therefore cut off and the fuel cell, together with the batteries, supplies with electric power only the essential and the emergency buses. The electrical loads of the essential buses of the Conventional configuration have thus been split into the essential and emergency buses because, in case of fuel cells failure, the emergency buses, that contain the minimum avionic equipment to allow a partial control of the aircraft, can still be supplied with electric power by the batteries.

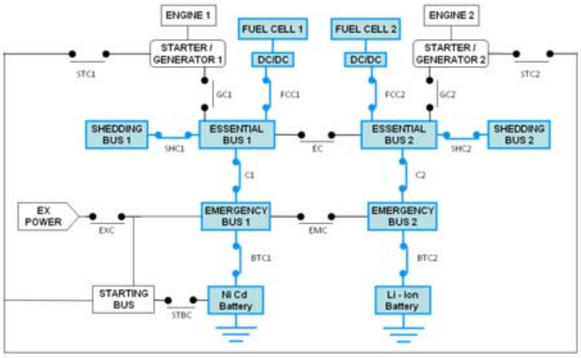


Fig. 8. Only Fuel Cells configuration architecture – Normal mode of operation.

In order to reduce the system weight, in particular the weight of the H_2 stored on board the aircraft, a configuration with fuel cells used only for the emergency mode of operation (Fuel Cells Only for Emergency configuration) has also been studied. As in the emergency mode of operation the system has to be supplied with lower electric power with respect to the normal mode of operation, the fuel cells selected for this configuration are small that those considered for the Only Fuel Cells configuration. Moreover, unlike the Only Fuel Cells configuration, the avionic equipment have again here been subdivided into non essential and essential buses, like in the Conventional configuration, as the difference between the Conventional and the Fuel Cells Only for Emergency configuration lies only in the emergency mode of operation, which in the former case is performed by the batteries whereas in the latter case is performed by the fuel cells. During the normal mode of operation the two starter/generators supply all users with the requested electric power. In case of failure of one starter/generator, the mission can continue because the remaining starter/generator can still supply all buses. The architecture of the Fuel Cells Only for Emergency configuration is shown in Figure 9.

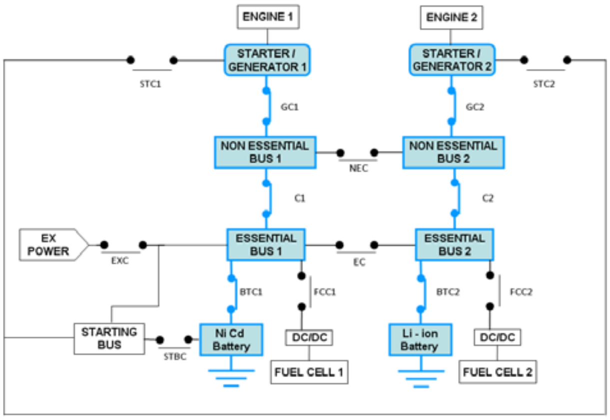
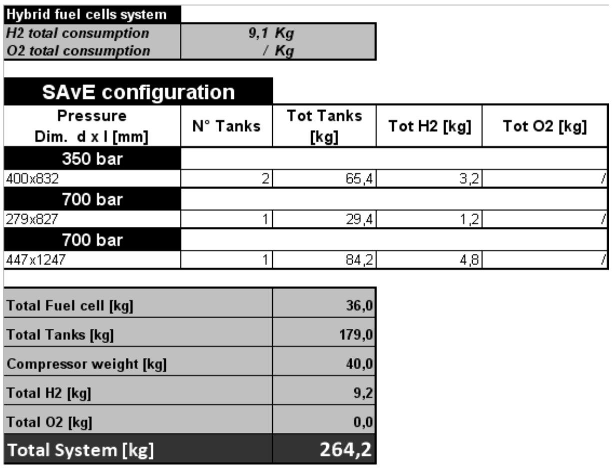


Fig. 9. Fuel Cells Only for Emergency configuration architecture - Normal mode of operation.

3.1 Hybrid Fuel Cells configuration

In order to reduce the H_2 consumption and therefore the amount of H_2 stored on board the aircraft to supply the fuel cells, the Hybrid Fuel Cells configuration has been studied. An elementary fuel cell of 4.5 kW has been chosen. This value of power has been scaled on the basis of the datasheet of the MES DEA 3.0 fuel cell [9].



Hybrid fuel cells system	
H2 total consumption	*9,1 Kg*
O2 total consumption	*/ Kg*

SAvE configuration

Pressure Dim. d x l [mm]	N° Tanks	Tot Tanks [kg]	Tot H2 [kg]	Tot O2 [kg]
350 bar				
400x832	2	65,4	3,2	/
700 bar				
279x827	1	29,4	1,2	/
700 bar				
447x1247	1	84,2	4,8	/

Total Fuel cell [kg]	36,0
Total Tanks [kg]	179,0
Compressor weight [kg]	40,0
Total H2 [kg]	9,2
Total O2 [kg]	0,0
Total System [kg]	**264,2**

Fig. 10. Tanks data for Hybrid Fuel Cells Configuration.

In the normal mode of operation both the fuel cells and the starter/generators supply all aircraft buses with the electric power. During the normal mode of operation the required mean electric power is about 5.5 kW, while it is about 3.7 kW during the emergency mode of operation. Taking into account the free room inside the aircraft, it is possible to store a set of tanks, as reported in Figure 10.

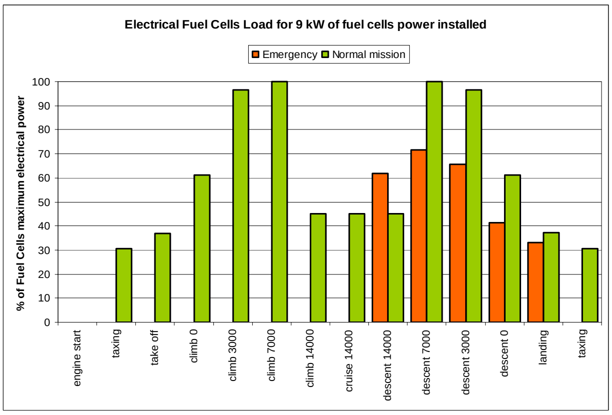


Fig. 11. Fuel cell mission profile for Hybrid configuration.

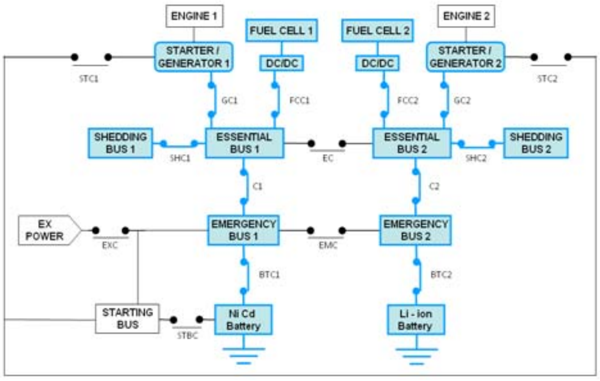
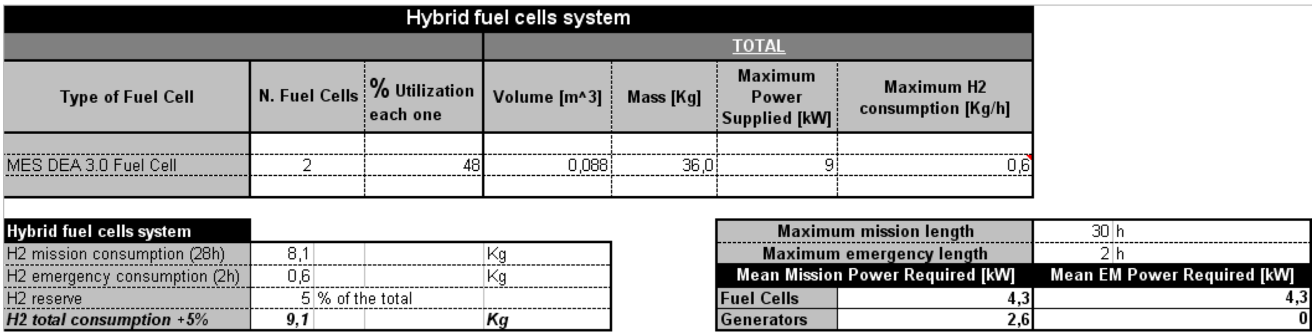


Fig. 12. Hybrid fuel cells configuration architecture – Normal mode of operation.

These tanks may be used to store both H_2 and O_2 (if necessary). Making the hypothesis that all tanks are used to store H_2, in the normal mode of operation the electrical power provided by the fuel cells is about 45% of their maximum power during the cruise mission phase, while during the climb and the descent mission phases the fuel cells supply all aircraft buses (see Figure 11). In the normal mode of operation if the aircraft buses have to be supplied with an amount of electric power higher than the power provided by the fuel cells, the starter/generators supply the system with the remaining amount of electric power. Unlike the normal mode of operation, in the emergency mode of operation the fuel cells supply all users with the total amount of electric power. The batteries, like for the Only Fuel Cells configuration, are used for the engines start-up and to absorb power peaks.



Hybrid fuel cells system

Type of Fuel Cell	N. Fuel Cells	% Utilization each one	TOTAL Volume [m^3]	TOTAL Mass [Kg]	TOTAL Maximum Power Supplied [kW]	TOTAL Maximum H2 consumption [Kg/h]
MES DEA 3.0 Fuel Cell	2	48	0,088	36,0	9	0,6

Hybrid fuel cells system			
H2 mission consumption (28h)	8,1		Kg
H2 emergency consumption (2h)	0,6		Kg
H2 reserve	5	% of the total	
H2 total consumption +5%	*9,1*		*Kg*

Maximum mission length		30 h
Maximum emergency length		2 h
	Mean Mission Power Required [kW]	Mean EM Power Required [kW]
Fuel Cells	4,3	4,3
Generators	2,6	0

Fig. 13. H_2 consumption assessment (Hybrid Fuel Cells configuration).

Since the fuel cells work in parallel with the starter/generators to provide the aircraft with the entire electric power, the electrical loads have been split into essential, shedding and emergency buses like the Only Fuel Cells configuration and unlike the Conventional and the Fuel Cells Only for Emergency configurations. The architecture of the Hybrid Fuel Cells configuration is shown in Figure 12. Figure 13 shows a sizing of H_2 consumption both in normal and in emergency mode of operation. The total amount of H_2 has been calculated considering the worst case scenario, with a mission phase that lasts 28 hours and an emergency descent of 2 hours. After choosing the fuel cells working percentage (in order to use the maximum quantity of H_2 that is possible to store on board the aircraft; see Figure 14), the amount of electric power, that the compressor has to be supplied with, has been calculated. It is worth remembering that the compressor is used to give the fuel cells the correct air flow rate at high altitude where the air density decreases. The compressor input electric power equals the 33% of the power provided by the fuel cells during the cruise mission phase and decreases linearly during the climb and descent mission phases, as the altitude diminishes. The compressor input electric power has to be added to the net mean electric power required by the aircraft buses, which varies according to the mode of operation. Since the gross mean electrical power is higher than that provided by the fuel cells, also the starter/generators supply the system with a certain amount of electric power (see Figure 13). Please note that the power required during the normal and the emergency mode of operations, as reported in Figure 13, are a mean value of the electrical load in the different flight phases.

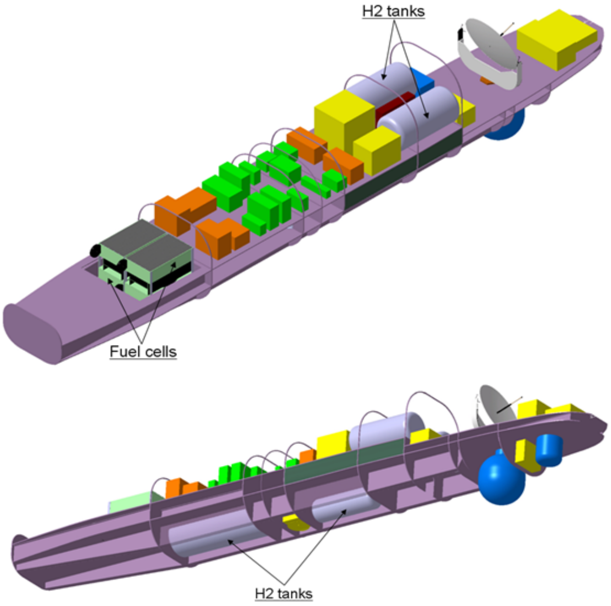


Fig. 14. Installation of fuel cells with upper and lower H_2 tanks.

4 Integrated simulation environment

For modern engineering systems modeling has become a fundamental design tool, as it allows to investigate dynamic systems behaviours, without the utilization of physical models, thus saving both money and time. Within the SAvE project several Matlab/Simulink models have been used, as reported in the following list:

- the SAvE Aircraft Model: this model simulates the dynamic behaviour of the whole aircraft (with the exception of subsystems that will be integrated afterwards) and allows to simulate a typical aircraft mission.
- Actuators: this model simulates the electric actuators dynamic response with particular attention to the values of electrical power, current intensity and current voltage.
- Thermal Model: this model allows to dynamically estimate the superficial temperature of the avionic equipment, that are installed on board the aircraft, and the mean temperature inside the aircraft, throughout the mission.
- Mean Value Electrical Model: this model allows to estimate the electrical power consumption of the systems and subsystems, that are installed on board the aircraft, and the mean power generation by means of generators and fuel cells.
- Electrical Sources Detailed Models: these models allow to simulate the dynamic behaviour of the components for the electric power generation. Because of their dynamic response, the simulation step has be very small (about 0.00001 sec), in order to study the most severe conditions and transient phenomena.

After developing and testing these single models, the aim of the work is the creation of an Integrated Simulation Environment to simulate a complete 30 hours mission of the aircraft, either with the Secondary Power System Conventional configuration or with the Secondary Power System Hybrid Fuel Cells configuration. The Integrated Simulation Environment integrates the SAvE Aircraft Model, the Thermal Model and the Mean Value Electrical Model. The Electrical Sources Detailed Models are not part of the Integrated Simulation Environment, as they are used to analyse in particular the timely limited dynamic behaviours of critical components. The Integrated Simulation Environment takes into account the variation with time of weights and electrical loads and it allows to investigate how these variations affect the aircraft performance and, particularly, to estimate the impact of the various Secondary Power System configurations in terms of environment (fuel consumption) and performance. Moreover, thanks to the Integrated Simulation Environment, it is possible to size more accurately the Secondary Power System components (electric machines, fuel cells, batteries, etc.) and the consumables (H_2, diesel), that have to be stored on board. The simulation of the system dynamics is useful to estimate the electric power consumption of the actuators, driven by the Flight Control System (also in case of turbulence and gusts). This estimation is extremely relevant in emergency mode of operation, when knowing the correct amount of energy to store on board is crucial to terminate the flight safely. Apart from the actuators, the simulation of the system dynamics is also important to calculate more into the details the electric power consumption of the compressor, that supplies the fuel cells. It is worth remembering that the electric power consumption of the compressor varies with the altitude and on its turn the vertical speed greatly varies with the increase of altitude itself.

4.1 SAvE Aircraft Model

The forces acting on the aircraft can be divided into four categories:

- Aerodynamic forces.
- Propulsion forces.
- Gravitational forces.
- Forces of interaction with ground.

The External Environment block gives the variables needed to calculate the forces acting on the aircraft (gravitational acceleration WGS84, atmospheric parameters, turbulence gusts, etc.). The forces are calculated in dedicated blocks from aerodynamic and propulsion data-set. The heart of the model airplane is the block that implements forces and moments, using the equations of motion (six degrees of freedom kinematics of a rigid body) to get the dynamic evolution of the airplane. The flight control computer, that has been modeled in the simulator, is essential to make the airplane fly in an automatic way for long simulation sessions.

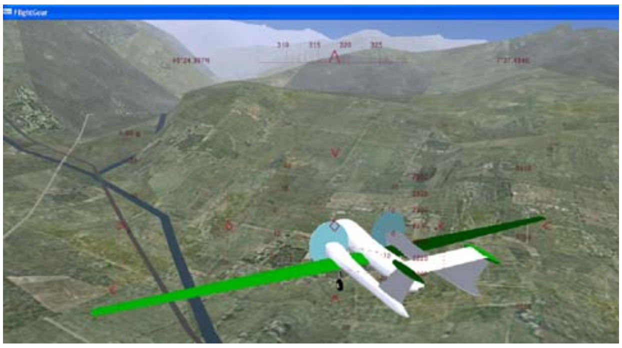


Fig. 15. Flight visualizer.

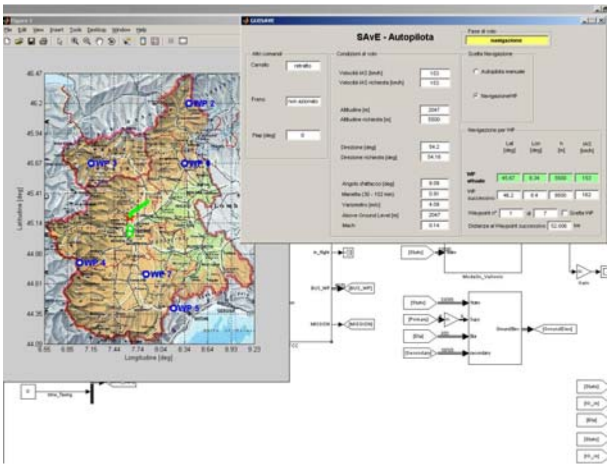


Fig. 16. Aircraft model, Graphical User Interface.

An enhanced flight animation has also been carried out, using "Flightgear" software (open source software). The Flightgear animation has turned out to be quite useful, as it allows to perform analyses, that are less specific but more representative of the general behavior of the airplane model (Figure 15). A Graphical User Interface to command the aircraft in manual or automatic way (Figure 16) has also been implemented.

4.2 Thermal Model

In order to estimate the superficial temperature of the avionic elements (Figure 17), installed on board the aircraft, and the mean temperature inside the different fuselage sections, a thermal analysis has been made, considering natural or forced convection and conduction within the plates where the avionic components are installed, taking also into account the effects of thermal radiation.

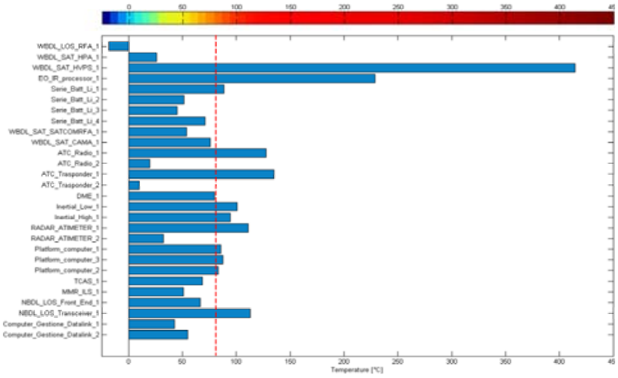


Fig. 17. Avionic equipment temperature during the flight.

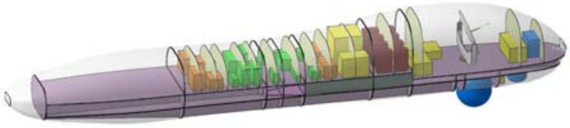


Fig. 18. SAvE fuselage divided into different sections.

The aircraft 3D CAD model (Figure 18) has make it possible to estimate the view factor (thermal radiation). As a consequence also the calculation of the thermal radiation between different avionic elements and between the avionic elements and the fuselage has been possible. The heat conduction analysis has been developed using the Electrical Analogy (inside a conductor the flow of electricity is driven by a potential difference; likewise the flow of heat is driven by a difference in temperature). Eventually it is worth remembering that the developed Thermal Model is suitable for the SAvE aircraft but it can also be applied to other avionics displacement.

4.3 Mean Value Electrical Model

A Mean Value Electric Model has been developed for each studied Secondary Power System configurations (Figure 19), in order to estimate the electric power consumption in terms of fuel (power generation by means of starter-generators) and hydrogen consumption (power generation by means of fuel cells).

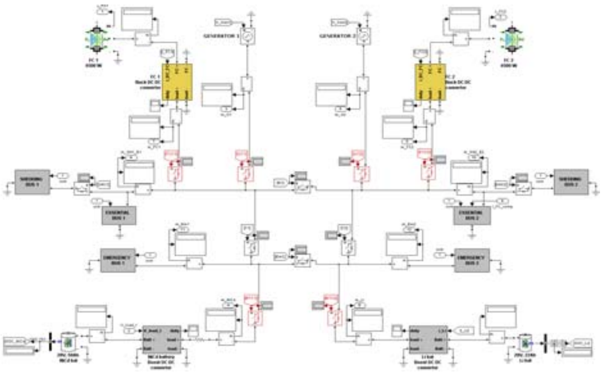


Fig. 19. Mean Value Electric Model (Hybrid Fuel Cells configuration).

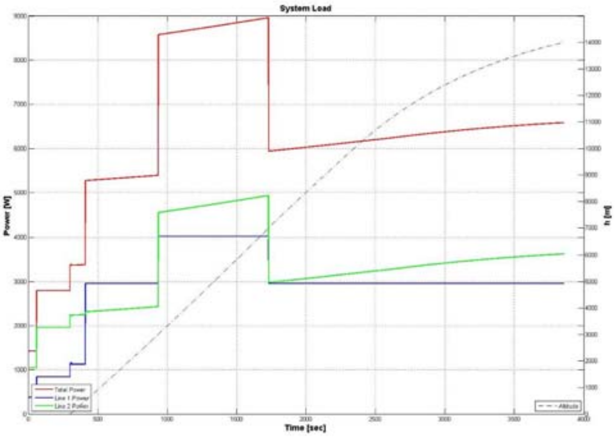


Fig. 20. Example of electrical system loads during climb.

The air consumption has also been considered in order to calculate the electric power consumption of the compressor, that has to be installed on board the aircraft to feed the fuel cells with the demanded quantity of air. The batteries and the fuel cells need a DC-DC converter to link up with the rest of the system for different reasons: the Lithium battery needs to control and to limit the maximum charge and discharge current, whereas the Nickel-Cadmium battery and the fuel cells use the DC-DC converter to control the output voltage, setting it to the reference value (28 V). The electrical loads are modeled like a resistance ($R = V^2 / P$).

As an example of the results obtained, Figure 20 shows the typical electrical load during climb (Power vs. Time): the red line is the total power, while the blue and green lines represent respectively the power consumption of the first and second line of the Electric System. The dot line represents the altitude vs. the time of climb.

4.4 Detailed Electrical Sources Models

Both the Conventional and the Non Conventional detailed electrical models are going to be developed in the project in the next future. In the Conventional model the electrical machine is a synchronous alternator only for electrical generation, whereas in the Non Conventional model it is a permanent magnet synchronous machine, that performs both the starter and generator (starter–generator) functions. Different machines imply different architecture and different components.

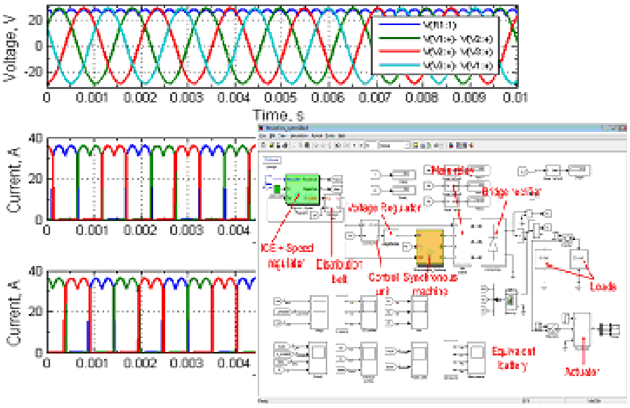


Fig. 21. Example of Detailed Electrical Sources Model and results. Detailed conventional power generation.

These models simulate the dynamic behaviour of the components (Figure 21), that are involved in the electric power generation, like:

- Electric machine.
- Voltage controller.
- Bridge rectifier.

- Control unit.
- Voltage regulator.
- Main relay.

These models represent a great tool for the design and optimization of the control logic.

5 Conclusions

After a thorough trade-off analysis [10] of the various configurations of the Secondary Power System, the Hybrid Fuel Cells configuration has been selected as the most promising. Results of preliminary studies on the Hybrid Fuel Cells configuration have shown that in the normal mode of operation at high altitude during the cruise mission phase the generators (or starter/generators) supply the aircraft with almost all secondary power, whereas at lower altitude during the climb and the descent mission phases the fuel cells supply the aircraft with almost all secondary power. In the emergency mode of operation, innovative batteries supply the aircraft with almost all secondary power, when the aircraft has just started gliding but, as the it descends to lower altitude, the contribution of the fuel cells steadily increases. More detailed investigations to find out the best way to apportion the supply of secondary power, considering the various suppliers (generators or starter/generators, batteries and fuel cells) in the different modes of operations, are now under way, thanks to the Integrated Simulation Environment, where physical, functional and mission scenario simulations continuously exchange data and results. It is worth remembering that all studied Secondary Power System configurations consider fuel cells working at their nominal efficiency at high altitude (low pressure and temperature) with a partial air compression. Further studies on the impact of the fuel cells performance at low pressure and temperature (without air compressor) on the envisaged Secondary Power System configurations have just started but still need dedicated experimental tests.

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