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# Designing Hybrid Energy Source System for Long Endurance Electric UAV

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**Abstract.** The article presents the conceptual design of Hybrid Energy Source System (HESS) for Long Endurance Electric UAV. During the design, the MBD method was used to analyze energy consumption during various UAV operational states as well as the entire mission for different HESS concepts. Such analysis at an early stage of the concept allows you to choose the optimal HESS set for a given UAV and expected mission parameters. The design method is based on a simulation computer model of subsystems and flight phenomena affecting the energy consumption during the flight. The modular construction of the simulation model allows the use of various details of simulation models for different stages of project development. The use of the HESS solution as well as the method of its design makes it possible to overcome the basic inconvenience of using electric drives in all types of vehicles, ie reconciling sufficient temporary operational parameters of the drive and long-term operation. In addition to the description of the method itself and the details of the simulation model, the article also presents a case study for the popular UAV class.

**Keywords.** Hybrid Energy Source System, Model-Based Design, Unmanned Aerial Vehicle

## Introduction

Electric drives are gaining popularity, also among airplanes and UAVs. The basic problem regarding the use of electric drives is to ensure the required flight duration. Limited energy resources among technically available energy sources do not allow obtaining the required flight duration for the given functions of the flying object. On the basis of experience related to the design of energy-efficient land vehicles for which, by systematically reducing energy consumption, it is possible to design vehicles that achieving energy consumption by dozens times smaller than those used previously [1], the use of analogous methods for flying objects has been proposed. Achieving such a significant reduction in energy consumption is obtained through the consistent application of Model-based Design (MBD) and Model-Based Optimization (MBO) methods [2-6] from the first stages of vehicle design, investigating the impact of design features and optimizing technical solutions in terms of reducing energy consumption. The necessary condition of these methodology is building and developing, during the

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design of a vehicle, a simulation computer model not only of the vehicle itself but also of environmental elements having an impact on energy consumption. This second part of the model is simpler in the case of UAV because it includes phenomena related to flight mechanics and aerodynamics of a flying object for given flight conditions. In the case of a flying object, the number of operational states analyzed is very limited compared to land vehicles. It is sufficient for the flying vehicle to analyze the conditions of take-off, climb, descent, landing, and taxiing, and determine the optimum parameters of these operating conditions. Despite significant differences in the simulation model itself, the methodology used is the same for a flying and ground vehicle.

The challenge for a flying vehicle is therefore to design an appropriate source of energy to ensure proper operational parameters of the aircraft. At the current stage of development of energy sources, there are no sources available that ensure high instantaneous power and high energy density. A solution for achieving temporary operational parameters and a long flight durability is the use of several energy sources that at the same time ensure high instantaneous power and high energy density, ie the use of so-called Hybrid Energy Source System. Among the available sources of electricity in the proposed solution, both energy sources and energy storage subsystems are taken into account, i.e. different types of batteries, supercapacitors, hydrogen tanks, photovoltaic cells, fuel cell stacks with particular reference to hydrogen fuel cell stacks. In addition, the possibility of equipping the vehicle with a hydrogen production and storage station is also being analyzed. The study of the energy balance of the whole flight mission and the instantaneous operational states allows calculating of a hybrid source of energy for a given UAV application and parameters in a quantitative way at the concept stage. On the basis of such a simulation model, it is possible to further optimize specific solution concepts and the size and detailed operational and technical parameters for individual subsystems.

## 1. Methods of analysis of energy-efficient systems

Analysis of energy efficiency is connected with optimization of an analysed system. In pure or hybrid electric driving systems the analysis allows to maximize range of the vehicle, which in turn enables to optimize the power consumption [7]. Suitably high energy efficiency allows an UAV to reach the assumed range and endurance.

One of the methods of increasing energy efficiency is using appropriate power management systems and in the case of hybrid drive - various HEPS (Hybrid-Electric Propulsion System) control systems are used. The other methods are based on Fuzzy Logic or Neutral Networks and two types are distinguished: active and passive. In passive management system the simulation shows the behaviour of particular power sources and is the adequate system for the overall flight envelope, but the active management system has better system safety and ensures more efficient power distribution than the passive one [5].

Type of power management system depends on the used driving system in a UAV. This system improves energy efficiency and reliability of UAV and consists of battery and supercapacitor storage, electric starter or generator, specialized controller and electronic power converters. In case of solar-powered UAVs the system mainly consists of battery management, the power conversion stages and the maximum power point tracking [8]. To improve the performance of electric motor some optimization methods and algorithms are used. We distinguish the following kinds of analysis methods: analytical, magnetic circuit and finite elements method. In an analytical model the performance indicator of the electric motor like torque, output power, cogging torque is calculated. The second method is like the uniform principle used to describe magnetostatics and it could be a computational aid in the design of an electrical machine. The conception of magnetic reluctance is used in this model to establish an equivalent circuit. In FEM there are field analysis in electrical or electromagnetic machines. This is an approximate analysis used to analyse static magnetic field in an electric motor. The last method is now widely used [9].

In an electric motor, two basic factors for optimisation are distinguished: efficiency and power losses. The losses in power mainly consists of the core loss, copper loss stray loss and mechanical loss. The last two can be estimated on the basis of empirical data. The efficiency could be computed based on these losses [10, 11]. As optimization algorithms the following are used: evolutionary algorithms (EAs)- and its four subclasses: genetic algorithm (GA), differential evolution algorithms (DEAs), evolution strategy and evolution programming, estimation of distribution algorithms (EDAs), particle swarm optimization (PSO), ant colony algorithm and immune algorithm. The most popular types of optimization strategies or methods are:

- direct and indirect optimization method;
- sequential and multi-level optimization method;
- space mapping method [11].

Also the weather conditions are very important for energy consumption of UAVs. The two main factors are wind and temperature, which along with air density are linked with the battery drain and capacity. Likewise, the payload has an influence on the UAVs' energy consumption. Based on all the factors, which influence the energy consumption, different energy models could be proposed [12]. To obtain an energy-efficient UAV it is very important to prepare an aerodynamics optimization. Properly designed shape of the UAV could partially save energy. Here, it would be suitable to use finite element method. The next issue, which affects energy efficiency, is the location of the solar cells on the UAV. Placing them on the fuselage, as well as on the wings, can significantly increase power obtained from the solar cells.

## 2. Concept model for analysis of energy consumption of UAV

The concept model of subsystems of a UAV and accompanying phenomena, which influence the energy consumption during UAV mission was created in Simulink (Figure 1). The model is a modification of the model which describes hybrid power system in most electric aircraft.

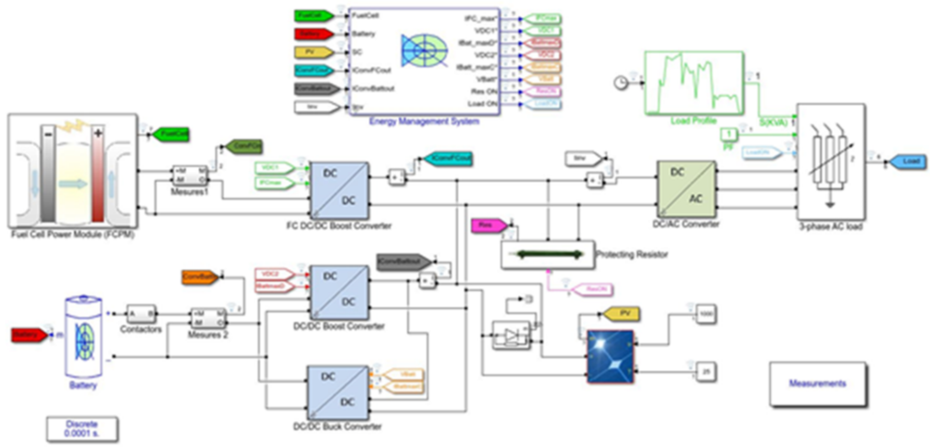


**Figure 1.** PVFC model

In this model there are two sources of energy - fuel cells and solar cells. Additionally, solar cells charge batteries, so even when the solar radiantion is equal to zero, the batteries could support fuel cells.

This model required the creation of a few subsystems:

1. Fuel cell stack power module (Figure 2),
2. 3-phase AC load (Figure 3),
3. Protecting resistor (Figure 4),

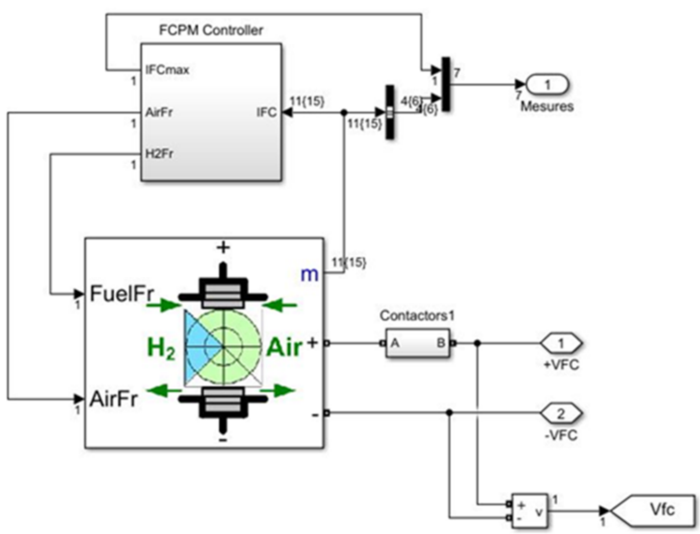


**Figure 2.** Fuel Cell Power Module.

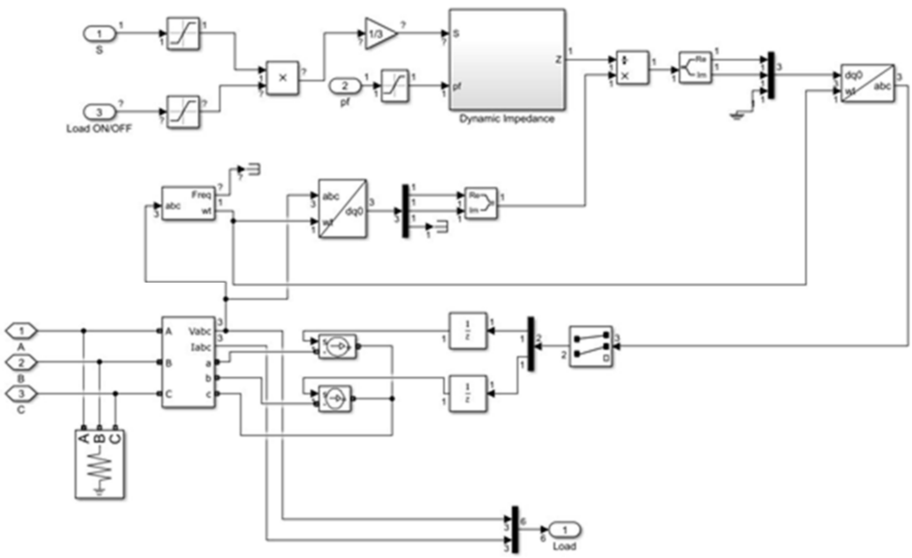


**Figure 3.** 3-phase AC load.

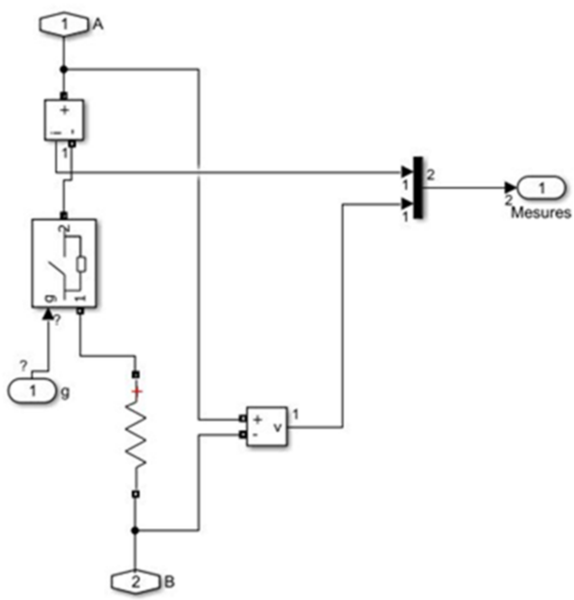


**Figure 4.** Protecting resistor.

Preliminary analysis of the UAV's energy consumption showed that for take-off and climbing with a constant speed equal 70 km/h it requires about 800 W, for cruising speed - about 680 W, and for flyight with maximum speed it would be need 1602 W.

When the radiation equals 1000 W/m$^2$ the maximum power coming from 1 m$^2$ of the PV cells is 349.59 W (I = 8.13 A, U = 43 V), so from 2 m$^2$ solar cells the power is equal to about 748 W. For the UAV PEM (Polymer Electrolyte Membrane) a fuel cell stack with nominal power equal to 1260 W (nominal I = 52 A, nominal U = 24.23 V) was chosen. The power of the fuel cell stack is regulated by the low hydrogen pressure control valve.

## 3. Case study – energy-efficient UAV

### *3.1. Assumptions for energy-efficient UAV*

The assumptions were prepared after conducting some research of UAVs available on the market. Among them, two of the most interesting UAVs were chosen: SITARIA-E [13] and Penguin B [14]. Both are classified as medium UAVs. The following assumptions are based on thorough investigation of the two UAVs mentioned above:

- empty weight: 30 kg;
- MTOW: 36 kg;
- wingspan: 4 m;
- length: 3 m;
- cruising speed: 80 km/h;
- max speed: 120 km/h;
- take-off speed: 70 km/h;
- wing area: 2m$^2$;
- stalling speed: 65 km/h;
- max climbing capacity: 2.5 m/s;
- max range: 300 km;
- practical ceiling: 3,500 m;
- take-off and landing runway: 200 m;
- propulsion system: fuel cells combined with batteries powered by solar cells;
- endurance: 10+ hours.

### *3.2. Concept of hybrid power source system*

As was previously mentioned in the assumptions the propulsion system would consist of fuel cells and batteries powered by solar cells (Figure 5).

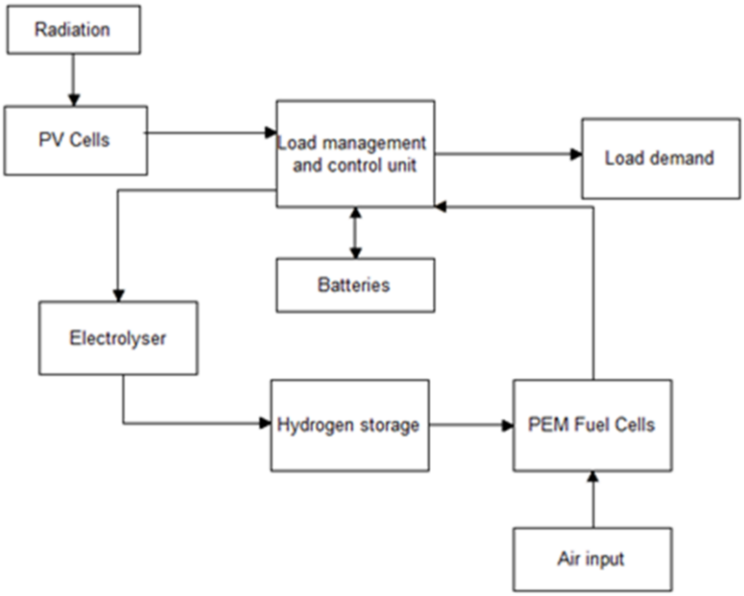


**Figure 5.** Diagram of hybrid propulsion system.

In this concept of the hybrid propulsion system, the electricity comes from solar and hydrogen fuel cells. When the radiation is high enough, the UAV could sustain flight powered only by the solar cells, but when the energy demand is bigger the control will start delivering hydrogen to the fuel cells.

### *3.3. Analysis of energy consumption in various operational states*

From the model simulation the following data for different flight phases were obtained (Table 1).

**Table 1.** Energy consumption for different phases of flight for the UAV model.

| Flight phase | UAV model |
|---|---|
| Take-off and climbing with constant speed 70 km/h | 800 W |
| Flying with cruise speed 80 km/h | 680 W |
| Flying with maximum speed 120 km/h | 1602 W |

During take-off and climbing with a constant speed of 70 km/h, the solar cells provide almost all required energy.

During this phase of flight, all required power comes from the solar cells. Excess power produced by solar cells would be used to charge the battery.

During flying with maximum speed, electric motor would be powered by solar cells and fuel cells. As can be seen, another source of energy would be needed only during take-off, climbing and flying with maximum speed, especially when the radiation would be different or the flight would take place at night. The energy balance in determined states of the movement allows for planning nominal parameters of individual energy sources. The energy balance for the whole mission is much more difficult to interpret, especially that deviations from the planned scenarios are possible. Analyzing probable scenarios allows to determine the necessary resources in exceptional energy storage.

## 4. Conclusions

The calculations made for the selected case study indicate the possibility of combining HESS with satisfactory power parameters of the instantaneous source of energy and ensuring at the same time the required flight durability. It should be realized that aircraft design is the art of compromise and the best results are not only while optimizing the designed object, its parameters and technical solutions, but also the adaptation of the mission itself, the operation of the flying object to the available technical possibilities. Then it is possible to develop a solution that is not only technically satisfying, but also economically and functionally justified. In subsequent activities, it is planned to develop a detailed simulation model for specific, proposed technical solutions in the technical design phase of subsystems. Mass and geometrical constraints are a very important limitation for seeking new solutions. In addition, methods for generalizing the simulation of the computer model will be sought so that it can be used in HESS design for other types of vehicles.

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