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HYBRID MOTOGENERATOR SYSTEM FOR ELECTRICAL PROPULSION OF UNMANNED AERIAL VEHICLES

Petar Getsov[1,2], Ruslan Yanev[2], Wang Bo[1], Georgi Sotirov[2], Pavlin Gramatikov[2]

[1]Ningbo University of Technology – China
[2]Space Research and Technology Institute – Bulgarian Academy of Sciences
e-mail: director@space.bas.bg; bo305@hotmail.com

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Abstract: *It's examined the possibility of increasing the flight duration of electrically powered UAVs by mounting on their board of a hybrid motogenerator system. Variants of such systems driven by an internal combustion engine and a hydrogen fuel cell have been studied.*

Introduction

In the world, the use of UAVs for military and civilian purposes is growing at an increasing rates. It is expected that by 2022, the total volume of the market for complete UAV systems will reach $ 21.3 billion, with an average annual growth rate of 20 %. The UAV market for civilian use in 2015 is $ 0.5 billion. The market forecasts are that: by 2022 it will reach 1.9 billion; its share to grow from 11 % in 2015 to 15 % by 2022; the tendency of increasing demand in favor of small UAVs (weighing up to 150 kg) will intensify. At the end of 2012, almost 98% of the world's most commonly used UAVs are heavier than air, 68% are with fixed wing, and 27 % have a rotating wing. The share of lighter-than-air aircraft is below 1 %.

At the end of the last century it became possible to use electrical energy to create moving and lifting thrust in aviation. Brushless electric motors with high specific power and efficiency were developed. It became possible to supply them with electricity from lithium-polymer, lithium-sulphide and other batteries with high specific energy and low relative volume. Precise control of the parameters of these motors was achieved by light, fast-acting controllers. Initially, they were used in model aircraf and micro - UAV with a fixed wing. Later, multicopter flying platforms were developed with lifting characteristic, maneuverability, controllability, automation and robotization capabilities that are unthinkable when the propulsuion is with traditional aviation thermal engines. The development of this type of aircraft has wide perspectives. According to the latest data, in the small class of UAVs, the preferences are: 94% for multicopters, versus 6% for airplanes.

At present, a common problem for all electrically driven UAVs is their limited flight endurance with real payload on board.

Main components in electric propulsion of UAVs

Batteries

The drive power is provided by rechargeable batteries - Table 1. The most important parameters that determine the performance of the batteries are:

- specific energy – C_pE_c(Wh/kg);
- specific volume– C_pE_v(Wh/l);
- modes and rates of charge-discharge;
- number of cycles charge – discharge;
- operating temperature range.

Table 1

Battery / Parameter	Ni-Cd	NiMH	Li-ion	Li-Po	Li-S
Specific energy (Wh/kg)	45 - 80	60 - 120	90 - 200	150 - 300	250 - 400
Specific volume (Wh/l)	100 - 220	200 - 350	300 - 420	300 - 450	350 - 500
Number of cycles	1500	1500	1000	1000	200
Nominal voltage (V)	1.25	1.25	3.3 - 3.8	3.7	2.1

Currently, the lithium-polymer (LiPo) batteries are the most suitable for propulsion of UAVs. In the last generations of these batteries, C_pE_c reaches 300 Wh/kg, with a theoretical maximum of 400 Wh/kg. They hold up to 1000 charge - discharge cycles. As the number of cycles increases, their capacity decreases. They work in the temperature range of $80^0 – 120^0$C. They do not have the "memory effect". Allow accelerated modes charge - discharge. They also have drawbacks, the main one of which is their sensitivity to overcharging and overdischarging when uncontrolled temperature runaway occures. Very often this is related to self-ignition of the batteries. To be avoided, in real-life conditions, batteries are discharged to (25–30) % and charged to (70–75) % of their maximum capacity. This means that they actually work with about half of the maximum specific energy announced by the manufacturers - ie. 150 Wh/kg instead of C_pE_c – 300 Wh/kg.

The next generation in lithium batteries development are lithium-sulphide and lithium-air. It is expected their C_pE_c to reach (600–1000) Wh/kg. Now on the market there are available Li-S batteries with C_pE_c – 380 Wh/kg. However, they quickly lose their capacity and still have a small number of charge-discharge cycles.

- Electric motors

Modern UAVs are powered by brushless electric motors with an efficiency of 95–98 % and specific power 3.0–4.0 kW/kg.

- Controllers - ESC (Electronic speed controller)

They control the operation of electric motors. They have an efficiency of about 95 % and a specific weight of 0.15 kg/kW.

- Propellers

Most often, they are directly mounted on the shaft of the electric motor. They are made of modern composite materials. Have high *lift-to-drag ratio* and a specific thrust, reaching 19,0 kg/kW.

With the specified parameters of the electric propulsion of UAVs, the maximum duration of the multicomputer flight hardly reaches 1 hour, and for airplanes – up to 3 hours. The market requires at least twice as much. The main limiting factor is the specific energy of the used batteries. Their development perspectives do not indicate any significant changes in the next 5 years.

Possibilities for hybrid-electric propulsion of UAVs using hydrogen and hydrocarbons.

In the statement below will be considered the technical parameters of electrically powered UAVs(multicopers and fixed wing) with a maximum take-off weight of up to 20 kg, which are powered by a power source up to 2000 W having a total weight of up to 10 kg.

Hybrid drives convert the energy of a particular fuel into electricity - directly or indirectly. The technology is based on the high energy density of hydrogen and liquid hydrocarbons.

The calorific value of hydrogen - C_pF is 39400 Wh/kg; of liquid hydrocarbons: alcohol – 3830 Wh/kg, kerosene – 12020 Wh/kg, gasoline 12220 Wh/kg.

C_pF is a chemical energy that should be converted into electrical energy. For the scale of the UAVs under consideration, this can be done:

- Directly, in fuel cells working on hydrogen. Cells with small sizes and weights are available on the market with efficiency up to 65 %. A serious technical problem in their use for the purpose is the low hydrogen density ρ – 0.0899 kg/m^3. To place the required amount of fuel on the UAVs board, it must be compressed to a high pressure. The existing technology applications use 35 Mpa, which puts high demands on bottles, pressure pumps and other hydrogen fueling equipment.

- Indirectly, by combustion of fuel in internal combustion engines (ICE), generating mechanical energy and transforming it in electric - into driven by the ICE electric generators.

For the needs of the hybrid electric drives for UAVs, mainly ICE can be used, because on the indicators: power density and power-to-weight ratio they are superior to the other representatives of the small heat engines. The disadvantage of the considered ICE is their low efficiency and high specific fuel consumption (bcfc).

For the considered power(2000 W), the two-stroke petrol engines are the most suitable. Their specific weight, fully completed (with ignition system, exhaust and cooling system), is (1,10 1,80) kg/kW, specific power (80–110) kW/dm^3, efficiency η_{th} - (11.0 - 15.0)%, bcfc - (750.0–550.0) g/kWh.

In hybrid power plants, ICE drive power generators.

The electric generators are brushless, AC, with permanent magnets and efficiency in the range (88–92) %. Rectifier blocks consist of active, pulse rectifiers, which are developed on the most up-to-date electronic schemes, with the latest generation of semiconductor components. Their efficiency is over 90 %. Maintaining a constant voltage at the output of the motogenerator is accomplished by high-efficiency (with over – 90 %) buck/step-down DC-DC converters.

Propulsion drives in moto-electric generators can be with toothed belts or gears. The efficiency is above 95 %.

All hybrid propulsion systems include buffer batteries. They are LiPo. The energy that they provide is 80–100 Wh.

Comparison of the parameters of the UAVs electric power sources.

A comparison will be made of commercially available sources for electric propulsion of multicopters and airplanes:

- **A** - LiPo battery with: maximum C_pE_c – 300 Wh/kg; Actual specific energy taking into account the charge - discharge limits – 150 Wh/kg; weight - 10 kg. With such a battery, an electric powered multicopter with a total weight of 20 kg and a payload of 2 kg has a flight duration of 45 minutes. Fitted on an airplane, with the same total take-off weight and payload, it provides a flight duration of up to 3 hours.

- **B** - Hybrid fuel cell power plant with a rated power of 1800 W and total weight, together with a hydrogen bottle and a buffer battery (100 Wh) – 9.2 kg. It drives a multirotor with total weight of 19 kg, and a payload of 2 kg. The flight duration is 4 hours.

- **C** - Hybrid motogenerator propulsion system with two-stroke internal combustion engine with a rated output of 1800 W and a total weight including fuel and a buffer battery (80 Wh) - 8.8 kg. By it is powered a multicopter with maximum take-off weight of 19.5 kg and a payload of 2 kg. A flight duration of 4 hours is achieved.

The described hybrid drives are not mounted on flying platforms with fixed wings. By analogy with power source - **A**, they would provide a flight duration of over 8 hours.

- Comparison of the specific energy parameter - SpEc (Wh/kg)**:**

- The actual CpEc of the compared LiPo battery is 150 Wh/kg.

- The specific energy of different hybrid power plants can be determined by the following formula:

$$C_pE_c = \frac{P_n \text{ x } T_{flight}}{\Sigma\, m_f + \Sigma\, m_v} \tag{1}$$

T_{flight} - flight duration;

P_n - total rated power of the drive;

$\Sigma\, m_f$ - the sum of the permanent masses in the installation - of the ICE and its systems, of the tank - empty, of the electric generator and its systems, of the supporting frame, etc .;

$\Sigma\, m_v$ - the sum of the variable masses in the set - the fuel, the buffer battery (if the number of cells is changed) and so on.

- If calculate the C_pE_c of the hydrogen fuel cell hybrid plant (Pn – 1800 W; Tflight – 4 hr; Σ mf + Σ mv = 9.2 kg), based on the above formula, the result will be – 782 Wh/kg.

- For the motogenerator hybrid drive (Pn –1800 W; Tflight – 4 hr; Σ mf + Σ mv = 8.8 kg), the C_pE_c is 818 Wh/kg.

The comparison of the actual energy density data of the various UAV electric drives: with a LiPo battery – **A**, a hybrid fuel cell set – **B** and an ICE – **C**, proves that the relationship between C_pE_c and flight duration is linear. For a LiPo battery only, at an optimum mass ratio for a particular multicopter and a practical C_pE_c of 150 Wh/kg, the maximum flight duration is 45 minutes. If the same multirotor is powered by a hybrid power plant with a fuel cell that has 5.2 times higher energy density, the flight duration should be 234 min. The manufacturer declares such up to 240 min. In the case of the motogenerator, which has – 5.4 times higher energy density, T_{flight} should be 243 min. In real conditions, the flight duration was 240 min.

By the specific energy indicator, leading, with almost identical data are the hybrid drives with the internal combustion engine and the hydrogen fuel cell. They have more than 5 times higher C_pE_c than the best LiPo batteries. Even with the most optimistic development of lithium batteries, over the next few years this competitive advantage of hybrid power plants is likely to remain.

- Comparison of specific volume parameter - C_pE_v (Wh/dm^3)**:**

- For the compared LiPo battery, the maximum C_pE_v is around 450 Wh/dm^3(Wh/l). Taking into account its charge-discharge limits, C_pE_v should be corrected to 225 Wh/dm^3.
- The C_pE_v of the hybrid power plants can be determined by the formula:

$$(2) \qquad C_pE_v = \frac{P_n \text{ x } T_{flight}}{V_{hd}}$$

T_{flight} - duration of flight(h);
P_n - total rated power of the drive(W);
V_{hp} - total volume of the hybrid drive (dm^3).

- The fuel cell has a total volume of 19.2 dm^3 (the cell – 7.8 dm^3 and the bottle for the compressed hydrogen - 11.4 dm^3). For P_n – 1800 W and T_{flight} – 4 h, its C_pE_v is 375 Wh/dm^3.

- The total volume of the motogenerator with the gas tank is 26 dm^3. For P_n – 1800 W and T_{flight} – 4 h, its C_pE_v is 277 Wh/dm^3.

By the specific volume indicator, the difference between the compared electric drives for UAV is not large. Hybrid power plants have a better C_pE_v, with fuel cell leading.

- Comparison of the parameter – relative price – C_pP (EUR/Wh)**:**

- For 12S LiPo batteries, with a capacity of more than 22000 mAh, C_pP averages 1.14 EUR/Wh. If we take into account that in order to avoid overheating, they actually work at half their maximum capacity, the relative price should be adjusted to C_pP - 2.28 EUR/Wh.
- For hybrid power plants, the relative price is determined by the formula:

$$(3) \qquad C_pP = \frac{P_{hd}}{P_n \text{ x } T_{flight}}$$

P_{hd} - delivery price of the propulsion system in EUR.

- The price of the compared hydrogen fuel cell – P_{hd} is 36080 EUR, its nominal power P_n – 1800 W, and T_{flight} – 4 h. Its relative price is C_pP – 4.92 EUR/Wh.

- The motogenerator unit is available from the manufacturer for 4100 EUR. For P_n - 1800 W and T_{flight} – 4 h, its relative price is C_pP – 0.57 EUR/Wh.

The relative cost of the hybrid drive with ICE is many times lower than that of competing power sources – 9 times compared to fuel cell and 4 times the LiPo battery.

- Comparison of the parameter overal efficiency – η_o (%):

The overal efficiency of the electric power source to drive UAVs – η_o in % is the ratio:

(4) $$\eta_o = \frac{E_{ex}}{E_{in}} 100\ (\%)$$

E_{in} – the energy at the source input:

- for batteries represents the electrical energy when charging;
- for hybrid power plants – the sum of fuel energy - E_f + the energy of buffer batteries - E_{bb};
- fuel energy = C_pF (fuel specific energy) x fuel quantity - W_f (kg) required to ensure T_{flight};

E_{ex} - the electrical energy at the source output;

(5) $$E_{ex} = P_n \times T_{flight}$$

- The efficiency of LiPo batteries is very high (96-98)%.

- In hybrid drives, the overall efficiency depends on: the chemical energy of the fuel and the efficiency when transforming it into electrical power to the output of the equipment.

- In the fuel cell bottle, the hydrogen is compressed to 35 MPa. The fuel density, after compression, can be determined using the Kleiperon-Mendeleev equation:

(6) $$PV = RT\ ;\ V = \frac{RT}{P}\ ;\ \rho = \frac{m}{V}\ ;\ \rho = \frac{mP}{RT}$$

ρ - hydrogen density (kg/m^3);
P - gas pressure – 35000000 Pa;
V - volume of the gas(m^3);
R - universal gas constant – 8314 J/kg^{0}K;
T - absolute temperature – 273;
m - molar mass of hydrogen – 2 g/mol.

After compression, the density of hydrogen is 30.8 kg/m^3. With a cylinder volume of 0.011 m^3, the weight of the fuel in it - W^f is 0.338 kg. The calorific value of hydrogen - C_pF is 39400 Wh/kg, E_f = 13317 Wh. Besides this energy, the energy of the buffer battery - E_{bb}, which is 100 Wh, is also supplied at the input of the hybrid drive. E_{in} = 13417 Wh. At the output of the fuel cell, the power is 1800 W. At the maximum flight duration of the multicopter of 4 hours, it will consume energy E_{ex} - 7200 Wh. Calculated on this basis, the overal efficiency of the hybrid hydrogen cell propulsion is η_o - 54%.

Fuel cells of the type of comparison have maximal efficiency up to 65%.

- With the motogenerator hybrid unit, the UAV has a 4-hour flight with 2 kg payload, consuming 4.7 kg of gasoline (6.5 dm^3). W_f – 4.7 kg, and C_pF – 12220 Wh/kg. The energy supplied by the fuel - E_f is 57434 Wh. The buffer battery energy should be added – 80 Wh. E_{in} = 57514 Wh. Efficiency, calculated on these data – η_o is 12.5 %.

The overall efficiency of motogenerator hybrid power plant - η_{mhd}, can be represented by the expression:

(7) $$\eta_{mhd} = \eta_{he}\ \eta_{dg}\ \eta_{eg}$$

η_{he} - the ICE efficiency;
η_{dg} - drive efficiency(where fitted) – 95 %;
η_{eg} - the electric generator efficiency + the rectifying and control unit efficiency – a total of 90%.

For the compared motogenerator hybrid system, the efficiency of the internal combustion engine is 14.6 %.

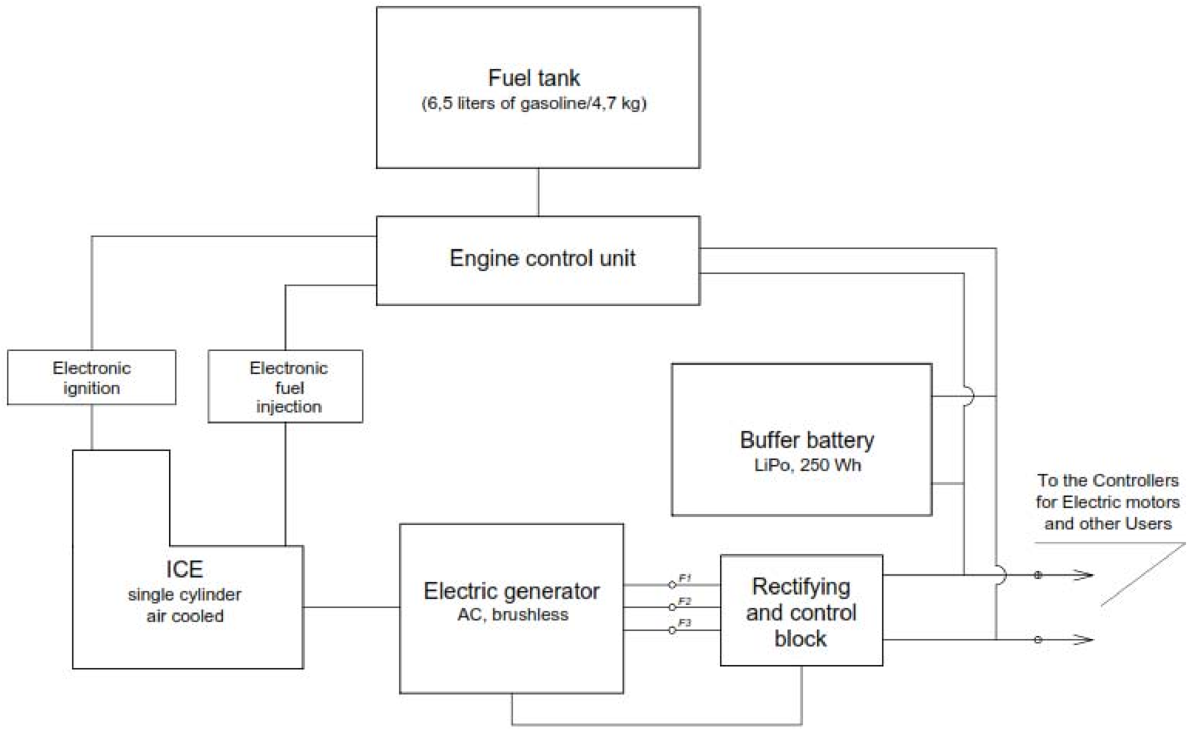
There is technical information about several similar hybrid propulsion systems. For each of them, a single-cylinder or twin-cylinder, aero-model or auto-model two-stroke petrol gasoline ICE is used. They have a standard electronic ignition and are supplied by a carburetor or electronic gasoline injection system. Start up manually or by the generator that switches to starter mode. Their efficiency is in the range (8.5–15.0) %.

The comparative analysis of the parameters of the LiPo battery, the hybrid hydrogen fuel cell propulsion and the motogenerator power plant give decisive advantage to the motogenerator. Obviously, the limiting factor in the development of this type of hybrid drives is the efficiency of the used internal combustion engines.

- Hybrid Motogenerator System (HMGS), driven by specially designed ICE for power supply of UAV.

The HMGS is built according to the following technological scheme - Fig. 1:

Fig. 1



- Two-stroke, single-cylinder, air cooled gasoline ICE. Its displacement is 50 cm^3, and its nominal power - 2.5 kW at 8000 rpm. Various technical solutions have been implemented in the engine to increase its efficiency:

- fuel injection in the crankcase of the engine;
- reed valve for air supply;
- stratified resonance scavenging;
- electronic plasma ignition with 3 spark plugs, controlled by the speed and the load of the ICE, ambient temperature and atmospheric pressure;
- resonance exhaust system.

The engine systems are controlled by an electronic block.

The engine crankcase and its head are made of aluminum alloy and are maximally lightweight. The piston is made of aluminum alloy with low coefficient of friction and thermal expansion. The cylinder is coated with a high-wear-resistant, low friction coefficient and high oil-holding properties coating. Crankshaft bearings are ceramic. The engine is designed based on the specific operating conditions of the HMGS.

The engine efficiency at nominal power of 2.5 kW is 21.5 % and its fuel consumption bcfc - below 380 g/kWh.

- Fuel tank. Made of composite material. Its capacity is 6.5 liters/4.7 kg.
- Electric generator - AC, three-phase, brushless with permanent magnets. Directly drived. Its housing is incorporate with the ICE crankcase. The bearings are ceramic. Its nominal power is 2.2 kW. When the ICE starts up, it runs as a starter.
- Rectifying and control unit. Includes: active, pulse rectifier; buck DC-DC converter down to adjust the output voltage. Switching blocks for controlling: the starter - generator modes, the voltage to the individual users on the board, charging the buffer battery.
- Buffer battery. It is 12S LiPo with a capacity of 12000 mAh. It provides energy of 250 Wh.

The total weight of the HMGS is 10 kg.

The HMGS is designed to power UAVs from the class considered above. When driving a multicopter with a maximum take-off weight of 20 kg and a payload of 2 kg, its operating parameters are:

- bcfc – 350 g/kWh;
- flight duration – T_{flight} - 6 hours
- C_pE_c – 1200 Wh/kg;
- C_pE_v – 400 Wh/dm^3;
- overall efficiency – 20.8 %;
- The battery of the unit allows an independent start up of the engine on the ground and in the air, as well as a flight for 6–10 minutes with switched off ICE.

Mounted on the board of a fixed wing wing UAV it will provide a flight duration of more than 15 hours.

Conclusion

The motogenerator hybrid system for UAVs solves the problem of their limited flight duration when are powered by batteries. Generally, it outperforms the other existing alternative for hybrid propulsion - with hydrogen fuel cells, because it has higher specific energy and is much cheaper. The parameters of the HMGS can be improved mainly by increasing the efficiency of the ICE. Researches and actual practical results in other ICE applications close to the compared allow the engine efficiency to be increased up to 25–28 %. This will make possible the C_pE_c of HMGS to exceed 2000 Wh/kg. None of the pespective battery designs have even theoretically such specific energy.

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