Power supply with increased specific energy intensity based on hydrogen fuel cells for unmanned aerial vehicle

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Abstract. The structure of a power source based on hydrogen fuel cells for an unmanned aerial vehicle is described in this article. A functional diagram of the power plant is presented. The method for calculating the power part of a step-down voltage converter is proposed. The idea of improving the accuracy of optimization of power plants by flight time of the unmanned aerial vehicle (drone) is proposed. Design features and the operating algorithm of an experimental source with a specific energy consumption of 529.3 W * h / kg are described.

1. Introduction

The advantage of fuel cells is their low weight [1] and dimensions [2], which make it possible to create power sources for aircraft that can stay aloft for a long time [3]. Compared to UAV with lithium-ion batteries, the flight duration increases by 2–3 times. The use of power plants with hydrogen fuel cells on aircraft imposes severe restrictions on them in terms of mass and specific energy consumption. In this paper, the design and study of a power source with the parameters given in table 1 are considered.

Table 1. Power technical requirements.

| Name of parameter                      | Value                              |
|----------------------------------------|------------------------------------|
| Rated output voltage, V                | 36 ±10%                            |
| Range of output voltage variation, V   | 39.6 - 32.4                        |
| Rated output power, W                  | 1300                               |
| Maximum output power, W                | 2000 (5 times in 2 minutes)        |
| Operating time in the nominal mode, hour | 3                                 |
| Start-up time, min                     | No more than 15                    |
| Environment temperature, °C            | 0...+35                            |
| Mass., kg                              | No more than 7                     |
2. Power supply design

In accordance with the technical requirements, a structural and functional diagram of the power supply was proposed. As noted above, the main part of the source is a step-down converter. To improve the thermal regime of the converter, a synchronous circuit is used (figure 1). To control the converter, a synchronous PWM controller LTC7801 was used, its additional advantage is the ability to work with 100% duty cycle. To reduce energy losses, current feedback was organized using the active resistance of the inductor as a current sensor. The output voltage of the converter was controlled by changing the voltage at LTC7801 soft start terminal using a digital-to-analog converter. The output of the converter is connected to the load through the circuit of an "ideal diode" implemented on Q3 transistor. This decision was made due to the features of LTC7801 chip and the safe operation of the converter keys. The battery is connected to the load through the key on Q4 transistor. This solution allows cutting it off when discharged below the minimum voltage.

The digital control system is based on STM32F103 microcontroller and provides voltage and current control in three nodes of the power circuit: at the output of the fuel cell stack (at the converter input), at the battery, at the load (at the output of the power source). Based on the data on currents and voltages, the microcontroller program generates voltage on the load by setting the required level at the output of DAC. Additionally, the control system monitors the temperature inside the stack, controls the moisture and exhaust gas vent valve and, if necessary, turns off the battery. To control the parameters of the stack and the converter, as well as their settings, the control system includes a telemetry module over the wireless link (Bluetooth). The analog and digital parts of the control system are powered through diode isolation from the fuel cell and the battery. This solution allows, if necessary, to work only from the stack of fuel cells without using a battery. Stack fans are connected via a separate voltage converter to the output of the power source.

![Figure 1. Power supply functional diagram.](image)

For a preliminary selection of power circuit elements, a methodology for calculating a buck converter was developed. Since the principle of operation of the step-down converter is similar to the principle of the output stage of a bridge converter with hard switching, the calculated ratios were derived similarly to those given in [4–7]. The difference lies in the fact that in this circuit there is no
pulse transformer and, accordingly, the magnitude of its scattered inductance is excluded in the formulas. Parameters obtained in general terms as a result of the calculation are given below.

1. Output voltage:

\[ U_{\text{out}_{-\text{over}_{-\text{stab}}}} = f \left( U_2, U_{vd}, U_{vt}, L, R_{\text{load}}, \gamma_f, T_f, I_{\text{over}}, I_{\text{out}_{-\text{avg}}}, U_{\text{out}_{-\text{avg}}}, \right) \]

where \( U_2 \) is the input voltage of the lowering stabilizer,
\( U_{vd} \) is a voltage drop on the reverse diode,
\( U_{vt} \) is a voltage drop on the power key,
\( L \) is a throttle inductance,
\( R_{\text{load}} \) is load resistance,
\( \gamma_f \) is a PWM duty cycle,
\( T_f \) is PWM period,
\( I_{\text{over}} \) is setting of loop current limiting,
\( I_{\text{out}_{-\text{avg}}} \) is a set point stabilization by the average output current,
\( U_{\text{out}_{-\text{avg}}} \) is setting for the average output voltage.

2. Load current:

\[ I_{\text{out}_{-\text{over}_{-\text{stab}}}} = f \left( U_2, U_{vd}, U_{vt}, L, R_{\text{load}}, \gamma_f, T_f, I_{\text{over}}, I_{\text{out}_{-\text{avg}}}, U_{\text{out}_{-\text{avg}}}, \right) \]

3. Load power:

\[ P_{\text{out}_{-\text{over}_{-\text{stab}}}} = f \left( U_2, U_{vd}, U_{vt}, L, R_{\text{load}}, \gamma_f, T_f, I_{\text{over}}, I_{\text{out}_{-\text{avg}}}, U_{\text{out}_{-\text{avg}}}, \right) \]

4. The amplitude of the throttle:

\[ I_{\text{max}_{-\text{over}_{-\text{stab}}}} = f \left( U_2, U_{vd}, U_{vt}, L, R_{\text{load}}, \gamma_f, T_f, I_{\text{over}}, I_{\text{out}_{-\text{avg}}}, U_{\text{out}_{-\text{avg}}}, \right) \]

5. Throttle current swing:

\[ \Delta I_{L_{-\text{over}_{-\text{stab}}}} = f \left( U_2, U_{vd}, U_{vt}, L, R_{\text{load}}, \gamma_f, T_f, I_{\text{over}}, I_{\text{out}_{-\text{avg}}}, U_{\text{out}_{-\text{avg}}}, \right) \]

6. Real PWM duty cycle:

\[ \gamma_{f_{-\text{over}_{-\text{stab}}}} = f \left( U_2, U_{vd}, U_{vt}, L, R_{\text{load}}, \gamma_f, T_f, I_{\text{over}}, I_{\text{out}_{-\text{avg}}}, U_{\text{out}_{-\text{avg}}}, \right) \]

7. The effective value of the throttle current:

\[ I_{\text{rms}_{-L_{-\text{over}_{-\text{stab}}}}} = f \left( U_2, U_{vd}, U_{vt}, L, R_{\text{load}}, \gamma_f, T_f, I_{\text{over}}, I_{\text{out}_{-\text{avg}}}, U_{\text{out}_{-\text{avg}}}, \right) \]

8. The current value of the key current:

\[ I_{\text{rms}_{-VT_{-\text{over}_{-\text{stab}}}}} = f \left( U_2, U_{vd}, U_{vt}, L, R_{\text{load}}, \gamma_f, T_f, I_{\text{over}}, I_{\text{out}_{-\text{avg}}}, U_{\text{out}_{-\text{avg}}}, \right) \]

9. The effective current value of the reverse diode:

\[ I_{\text{rms}_{-VD_{-\text{over}_{-\text{stab}}}}} = f \left( U_2, U_{vd}, U_{vt}, L, R_{\text{load}}, \gamma_f, T_f, I_{\text{over}}, I_{\text{out}_{-\text{avg}}}, U_{\text{out}_{-\text{avg}}}, \right) \]

10. Converter efficiency:
\[
\eta_{\text{over} \_ \text{stab}} = f\left(U_2, U_{\text{vd}}, U_{\text{st}}, L, R_{\text{load}}, \gamma_f, T_f, I_{\text{over}}, I_{\text{out} \_ \text{avg}}, U_{\text{out} \_ \text{avg}}, R_{\text{st}}, R_{\text{vd}}, R_L\right)
\]

where \( R_{\text{st}} \) is the active resistance of the key, \( R_{\text{vd}} \) is active resistance of the reverse diode, \( R_L \) is throttle resistance.

11. The range of throttle induction:
\[
\Delta B_{\text{over} \_ \text{stab}} = f\left(U_2, U_{\text{vd}}, U_{\text{st}}, L, R_{\text{load}}, \gamma_f, T_f, I_{\text{over}}, A_e, w, I_{\text{out} \_ \text{avg}}, U_{\text{out} \_ \text{avg}}\right)
\]

where \( A_e \) is a cross-sectional area of the magnetic circuit of the throttle, \( w \) is a number of turns of the throttle.

12. Maximum induction of the throttle:
\[
\Delta B_{\text{max} \_ \text{over} \_ \text{stab}} = f\left(U_2, U_{\text{vd}}, U_{\text{st}}, L, R_{\text{load}}, \gamma_f, T_f, I_{\text{over}}, A_e, w, I_{\text{out} \_ \text{avg}}, U_{\text{out} \_ \text{avg}}\right)
\]

The calculation formulas make it possible to obtain surfaces of interest for determining the maxima corresponding to the most intense modes of operation of the elements. To the maximum, a preliminary selection of the elements of the power part of the converter is performed. The proposed calculation method can be used as a component to optimize the flight duration of a power plant of a drone based on hydrogen fuel cells. In [8], the basic design relations for such optimization were proposed, however, the mass of the converter, \( m_{\text{converter}} \) and its efficiency, \( \eta_{\text{converter}} \) were taken constant for simplification. The mass estimation of the transducer can be performed by calculating the parameters for the most intense modes of the transducer according to the proposed technique. When calculating the efficiency of a power plant, losses in the converter can also be taken into account more accurately. As a result, the final calculation formula for optimizing the power plant by flight time will take the form:
\[
E_{\text{fuel}} \cdot \eta_{\text{STAK}} \cdot \eta_{\text{converter}}(U, n) = \frac{P_{\text{STAK}}(U, n)}{t_{\text{flight}}(U, n)}
\]

The mass of the power plant at each iteration is defined as:
\[
m_{\text{ps}} = m_{\text{STAK}}(U, n) + m_{\text{converter}}(U, n) + m_{\text{battery}} + m_{\text{balloon}}
\]

The battery at the output of the power source, in addition to the initial start-up of the system, also serves to meet the requirements for power overloads. The excess of power up to 2 kW for 2 minutes was studied. During development and testing, two power mixing schemes were investigated and compared:

1. The load was connected to the battery and the inverter output through isolation on “ideal diodes”. In this case, the battery was not charged during operation from the converter, and its capacity was chosen so that the stored energy compensated for all 5 peak overloads in accordance with the statement of work. It was planned in this way to increase the efficiency of the converter and simplify the control system.

2. The battery was connected directly to the output of the power source. Moreover, its capacity was calculated only taking into account the compensation of one peak overload. In the intervals between the peaks, it was planned to charge it from the converter.

As a result of the experimental verification, it was found that the source built according to the first scheme loses in the specific energy consumption (mass) of the second scheme. In the first case, a
battery capacity of 5000 mAh was required. At the same time, due to the decrease in capacity at high discharge currents, the battery at the fifth peak of the overload was almost completely discharged (below 32V). The battery capacity when using the second circuit was 3300 mAh. In addition, the microcircuits controlling the “ideal diodes” did not provide fast switching of transistor switches and in transient conditions there were power flows from the stack to the battery and vice versa. In this case, the charge and discharge mode in the second scheme was implemented as follows. At rated load, the voltage at the converter output was maintained at 39V (according to the terms of reference). If the current consumed from the stack of fuel elements of a given value at times of overloads is exceeded, the control system provides a decrease in the output voltage. In this case, part of the load current is provided by the battery. When the overload mode ends, the stack current decreases and the controller gradually increases the output voltage, returning the stack current to the nominal level. The load voltage in this case automatically increases, as the battery is charged, reaching a predetermined 39V.

To control the power source and display telemetry data, the program, which dialog box is shown in Figure 2, has been developed.

The program provides changing the settings of the voltage regulator, thresholds for charging and discharging the battery, the settings for voltage and current protection, turning on and off the voltage at the output of the power source. A feature of the implemented control and monitoring algorithm is that in order to save fuel during purging, it is proposed to automatically change the duration and period of operation of the valve one hour after the converter starts to compensate for the decrease in hydrogen pressure. To do this, the appropriate settings window has been added to the program.

As a result of research and testing of all modules, the design of the power source was developed (figure 3). The specific power of the source was 529.3 W·h/kg. The mass of the entire power plant together with the hydrogen cylinder was 6398 g. The tests performed showed the stable operation of the source at a rated power of 1300 W and a peak of 2000 W.

![Figure 2. Control software and parameter checkout of the power source during the flight.](image-url)
The power source was tested as part of the quadcopter power plant, provided by the organizers of the UpGreat technology contest “The First Element. Air” [9] (figure 4).

At the same time, the time for UAV to operate the power source according to the load schedule specified in the terms of reference was 2 hours 32 minutes. Currently, a set of tasks to improve the power supply modules, their elemental base and software for the power plant control system in order to increase the operating time is being carried out.
Acknowledgments
The article was prepared based on the results obtained in the implementation of Agreement No. 05.604.21.0248 on the provision of subsidies (unique identifier RFMEFI60419X0248)

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