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Tethered Drone Power Supply System with High-Voltage Intermediate Link

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***Abstract*— Existing tethered drones operate at low voltages of up to 43.2 V, which significantly reduces the length of the power cable and reduces the weight of the payload. The purpose of the work is is to calculate the power supply system of a tethered drone with an intermediate high-voltage link, based on which it is possible to provide a power cable weight close to the minimum, at a giv-en maximum flight altitude and a given motor thrust. A methodology for calculating the power supply system of a tethered drone with an intermediate high-voltage link is developed. Based on the analysis of the disadvantages and advantages of alternating and direct current electricity transmission, the principles of conductor insulation depending on the voltage level, and the determination of the current density through the conductor depending on the heat dissipation conditions, a mathematical model of the power supply system was developed, which allows to determine the operating voltage of the cable, which, at a given drone power, provides close to the minimum cable weight for powering the tethered drone. Based on the developed mathematical model, the parameters of the power cable for low-, medium- and high-power drones are calculated and the calculation results are compared with a power supply voltage of 43.2 V.**

Keywords — tethered drone; XPLE cross-linked polyethylene-based insulation; power supply system with an intermediate high-voltage link.

I. INTRODUCTION

Drones are becoming an integral part of life, they are actively used in agriculture, terrain patrolling, cartography, aerial photography, in the military, industry, construction, logistics, and in the fight against natural disasters [1]. The main advantages of drones in these areas of use are mobility, high positioning accuracy, and barrier-free operation [2].

Today, traditional quadcopters are powered by electric batteries installed on board the device, and the maximum flight time is 30-60 minutes depending on the model, payload, and weather conditions [3]. This time is critically short for many possible tasks, for which the use of quadcopters have a significant advantage.

An alternative for tasks with long-term execution of tasks and conditional 24/7 operation is a docking station. This is the device to which the drone returns for recharging. This station also analyzes the environment: wind speed, humidity, air purity, etc. and does not allow the drone to take off if the conditions are too dangerous. In this case, time is lost for the drone to return for recharging. Such stations are presented by the leading manufacturers of DJI quadcopters, namely DJI Dock, Dock 2 [4], Autel — Autel EVO Nest [5] and Atlas — AtlasNest [6]. The mentioned docking stations are heavy and large, which makes them not very mobile, the drone charging time is from 30 minutes to one hour. The range of such docking stations is limited by the battery capacity and allows you to perform tasks in a short and medium range.

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In conclusion, among the disadvantages of docking stations, we can highlight:

- bulkyness;
- large weight;
- waiting for the drone to charge for up to 1 hour;
- limited range.

For a number of tasks, a drone operating 24/7 does not does not fly far from the the docking station, and therefore can be connected to it by a power cable and (if necessary) a wired communication channel. These drones belong to a separate class known as tethered drones [7]. The structural diagram of the tethered drone is shown in Fig. 1.

According to Fig. 1, such drones have a power supply not only in the docking station, but also on the drone, which is necessary to compensate for the voltage drop on the wires and regulate it by level. Tethered drones have the following advantages [8]:

- long-duration flights: Tethered drones can remain airborne for long periods of time, making them ideal for applications that require long-term monitoring and surveillance;
- uninterrupted power supply: Tethered drones have a constant power supply via a cable without the need to replace or charge the battery;
- real-time data transmission via wired communication; tethered drones provide high bandwidth via a secure wired communication channel.

The use of tethered drones is quite extensive:

- patrol of areas, events, large crowds;
- agriculture;
- security of industrial facilities;
- firefighting;
- retransmission of acoustic and radio signals.

Existing solutions offer a station with a cable length of up to 100 m and a continuous flight time of 50 hours. The leader in this field is ElistAir company [9]. Their products include the Khronos and Orion drones, as well as Safe-T and Light-T universal drone power stations.

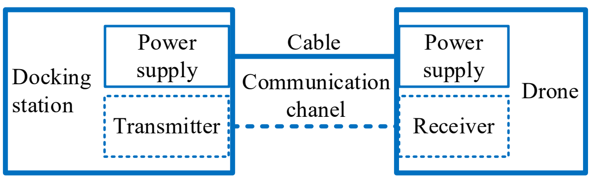


Fig. 1. The structural diagram of the tethered drone

Another technology company, Volarious from Singapore, offers a ground power station for DJI and Autel drones: V-line, V-line Pro and V-scout [10]. These stations permit reaching heights up to 100 meters and are compatible with the flagship models of DJI and Autel. Table 1 shows the technical features of the ground stations of the described drones.

According to the data in Table 1, the maximum height of tethered drones is 100 m with an output voltage range from 21.6 to 43.2 V.

Thus, we can conclude that because of the low operating voltage, the flight altitude of the drone is significantly limited. With higher altitude, the weight of the power cable exceeds the weight of the tethered drone's payload.

II. *Analysis of General Requirements for Designing Power Supply Systems for Tethered Drones*

To design a tethered drone power supply system that provides the minimum weight of the power cable, it is necessary to develop a methodology for designing a tethered drone power supply system at a given maximum flight altitude of the tethered drone $h_{\max}$ and the total motor thrust $T_{dr(\max)}$.

For methodology developing, it is necessary to analyze the following issues:

1. The voltage form for energy transmitting through wires in order to ensure the minimum weight of the wire and the power supply system a whole with the same energy losses.
2. Topology of power converters for the docking station and drone, allowing to convert the cable voltage level U_c into the drone input voltage level U_{out}.
3. Dependence of the weight of copper per unit length of cable $m_{c(1)}$ on the output power P_{out} and the operating voltage of the cable U_c.
4. Dependence of the thickness and weight of wire insulation on the operating voltage of the cable U_c.
5. Creating a mathematical model of the total weight of the tethered drone, including the power cable, from the voltage U_c and the power P_{out} transmitted by the power cable.

Table 1 Comparison table of tethered drone ground stations

Drone brand	Altitude, m	Voltage, V
ElistAir Safe-T 2	100	21,6 / 43,2
ElistAir Ligh-T 4	70	21,6 / 43,2
Volarious V- line	60	25 - 26,1
Volarious V- line PRO	100	25 - 26,1

Based on the analysis performed, it is possible to develop a clear and consistent procedure for designing a power supply system based on the following input data:

- the maximum flight altitude of the tethered drone h_{max} that directly determines the length of the power cable l_c, $h_{max} \approx l_c$.
- transmitted power by cable P_{out};
- payload weight m_{ld};
- drone weight $m_{dr(net)}$ without equipment, excluding the weight of the wire and power supply system.

A. Voltage form for power transmission over a power cable

For efficient power transmission over wires, the following voltage forms should be considered:

- single-phase alternating rectangular;
- single-phase sinusoidal;
- three-phase sinusoidal;
- constant.

The variable voltage waveform of rectangular and sinusoidal forms makes it possible to reduce the weight of the power supply system due to the absence of an input voltage inverting link in the drone's power supply unit. However, at the same time, it has significant disadvantages associated with the generation of reactive power in the power wires:

- difficulties with increasing the operating frequency
  of the f_{sw} converter to reduce the transformer weight and the output filter of the drone power supply, since the amount of reactive power also increases in proportion to the frequency and length of the cable l_c;
- a decrease in the cable capacity inversely proportional to its length l_c and the operating frequency f_{sw};
- the dependence of the specific capacitance and inductance of the cable and, as a result, the amount of generated reactive power on the winding of the cable on the reel.

Therefore, despite the greater complexity of the power supply system, transmitting electricity via direct current is more expedient, as evidenced by the experience showing that DC lines have greater capacity and energy efficiency compared to AC transmission lines. [11].

B. Topology of power converters for the docking station and drone

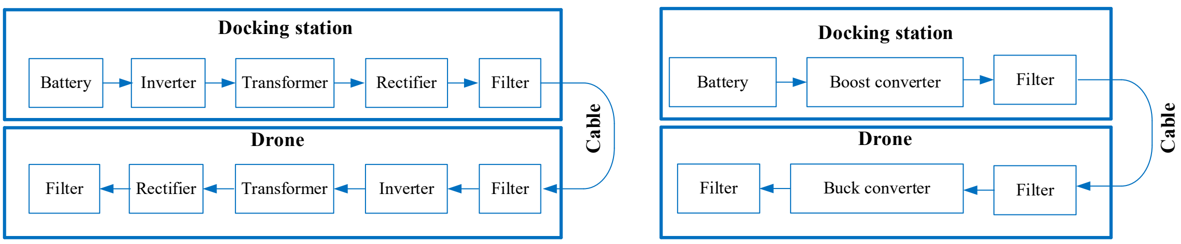
The structure of the drone power supply system with direct current energy transfer is shown in Fig. 2, *a* — for a converter with galvanic isolation, in Fig. 2, *b* — without it.

As a result of comparing the structure of the power supply system, it can be concluded that it is significantly simplified in the absence of galvanic isolation. However, the use of such a system is possible for a voltage gain factor of no more than 3 and a voltage decrease of no more than 5, otherwise the use of converter transistors in non-isolated power converters becomes extremely inefficient [12].

C. Dependence of the weight of copper per unit length of cable on the output power

According to the IEC 60364-5-52 standard, a two-core cable with a cross-sectional area of each core 1.5 mm^2 max. with XPLE insulation placed in air can have a current density of j = 15 A/mm^2 [13]. Since in operating mode part of the wire is in the air, the other is wound on a spool, the current density is selected depending on the heat dissipation from the cable wound on the spool. If the heat dissipation is insignificant, it is necessary to focus on the current density used in transformers, j_c = 3 A/mm^2, if at the operating altitude the cable is wound in only a few rows with good heat dissipation, it is advisable to set the current density, j_c = 10 A/mm^2.

Let us calculate the dependence of the cross-sectional area S_c and the weight of the copper wire for a unit of cable length $m_{c(1)}$ on the power P_{out} and the operating



a) *b*)

Fig. 2. The structure of the drone power supply system with direct current energy transmission: a) with galvanic isolation; b) without galvanic isolation

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voltage of the cable U_c. The current I_c flowing through the cable is calculated by the formula:

$$I_C = \frac{P_{out}}{\eta_b U_c}, \quad (1)$$

where η_b is the efficiency of the buck converter (together with the wire) installed on the drone.

Let us express the cable current I_c in terms of the current density j_c and the cable cross-sectional area S_c:

$$I_C = j_c S_c. \quad (2)$$

After substituting expression (2) into (1) and expressing the cross-sectional area S_c we obtain:

$$S_c = \frac{P_{out}}{\eta_b U_c j_c}. \quad (3)$$

The copper weight of a cable with two cylindrical conductors m_c is calculated by the formula:

$$m_c = 2\rho l_c S_c, \quad (4)$$

where ρ is the density of copper, ρ = 8900 kg/m^3, and l_c is the cable length.

Substituting expression (3) into (4), we have

$$m_c = \frac{2\rho l P_{out}}{\eta_b U_c j_c}. \quad (5)$$

The dependences of the cross-sectional area of the copper cable S_c and its weight $m_{c(1)}$ at the length l = 1 m on the voltage U_c and efficiency η_b = 0.95 for a set of power values P_{out} = 100 W, 300 W, 1 kW, 3 kW, 10 kW are shown in Fig. 3. To reduce the requirements for the safety of using a tethered drone, it is advisable to use cable voltage U_c up to 1500 V that according to the IEC60038 standard belongs to low voltage range.

From Fig. 3 we can conclude that if transmitted power through the cable is lower than 10 kW and voltage belongs to range 0-1500 V, it is possible to obtain a cable copper weight not exceeding 30 g/m, which potentially allows for obtaining a cable length l_c that exceeds 100 m.

D. Analysis of the weight of cable insulation

Cable insulation is divided into conductor insulation (internal insulation) and sheath (external insulation). Conductor insulation protects the conductors from contact with each other and must be designed for the operating voltage of the cable. External insulation or sheath holds the cable conductors together and serves to protect against thermal, mechanical and chemical influences.

A cable for a tethered drone must have increased tensile strength as the weight of the cable in the air creates significant loads on its attachment point on the drone. To improve the mechanical strength of the cable, the external insulation can be covered with armor (galvanized steel tape), Fig. 4, *a*. However, this significantly increases the weight of the cable and reduces its flexibility when wound on a reel. Therefore, to ensure mechanical stability in this case, it is advisable to use a steel string as the third uninsulated wire in the cable, as shown in Fig. 4, *b*.

The following are most often used as insulating materials:

Polyvinyl chloride (PVC) - this material is the most common for insulating cables and wires mounted indoors. Polyvinyl chloride has high flexibility and wear resistance. The material is non-flammable and resistant to aggressive chemical compounds. It has high indicators of permissible current load. The disadvantages of the material are the acceleration of the aging process under the influence of ultraviolet rays and the lack of resistance to high temperatures.

Rubber is a natural material based on natural rubber that features elasticity, waterproofness, and electrical insulating properties. The advantages of rubber insulation include resistance to many aggressive substances. Products with rubber insulation withstand harsh operating conditions and retain their flexibility and elasticity even at low temperatures. However, rubber insulation is not considered durable. After a certain time, the outer rubber shell loses its elasticity and protective properties. Rubber ages, undergoes changes in chemical properties

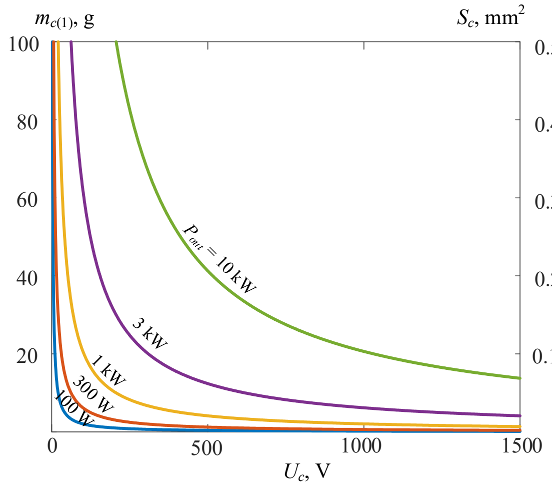
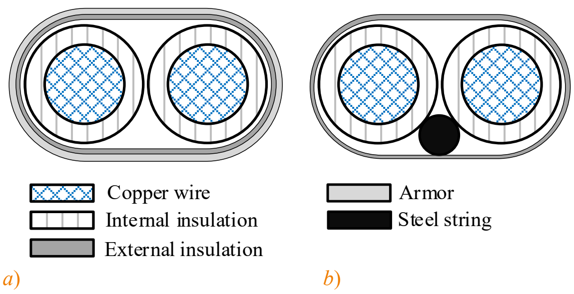


Fig. 3. The dependence of the cross-sectional area of the copper cable S_c and its weight $m_{c(1)}$ on the cable voltage U_c



and cracks under the influence of low or high temperatures.

Cross-linked polyethylene (XPLE) has fairly high dielectric properties, good electrical strength and low weight. It has good mechanical characteristics and relative flexibility. It is resistant to fire, sunlight, moisture, alkalis and acids. It can withstand temperature changes and is used in various temperature ranges.

Given the conditions of operation outdoors in a wide range of temperatures and significant mechanical loads, it is advisable to use XPLE material for electrical insulation.

The insulation thickness of cables with a voltage of 1 kV is regulated by the DSTU IEC 60502-1 standard [15]. For a conductor with a nominal core cross-sectional area S_c = 1.5-2.5 mm^2 or less the insulation thickness of the XPLE material is $d_{ins(1000)}$ = 0.7 mm. For other operating voltages, the insulation thickness d_{ins} can be calculated using the formula:

$$d_{ins} = d_{ins(1000)} \frac{U_c}{1000}. \tag{6}$$

The steel string as a load-bearing element must have a tensile force P_{st} exceeding the total weight of the cable. For steel, this indicator can be approximately considered equal to 500 MPa [16]. Then, knowing the total weight of the cable m_{cab}, we can determine the cross-sectional area of the string S_{str}:

$$S_{str} = \frac{m_{cab} g}{P_{st}}, \tag{7}$$

where g is the acceleration of gravity, g = 9.81 m/s^2, and the weight of one meter of the string $m_{str(1)}$:

$$m_{str(1)} = \rho_{st} S_{str}, \tag{8}$$

where ρ_{st} is the density of steel, ρ_{st} = 7800 kg/m^3.

The outer shell can also be made of XPLE material and have a thickness of d_{ins_sh} = 0.2 mm.

Given that the radius of copper conductors r_c, calculated based on formula (3):

$$r_c = \sqrt{\frac{P_{out}}{\pi \eta_b U_c j_c}}, \tag{9}$$

is equal to the inner radius of the conductor insulation, r_c = $r_{ins(in)}$. Considering the insulation thickness (6), the outer insulation radius $r_{ins(out)}$ is calculated as follows:

$$r_{ins(out)} = \sqrt{\frac{P_{out}}{\pi \eta U_c j_c}} + d_{ins} \frac{U_c}{1000}. \tag{10}$$

The weight of the inner insulation $m_{ins(in)(1)}$ of two copper conductors $m_{ins(in)}$ with a length of one meter, corresponding to the inner $R_{in(in)}$ and outer $R_{in(out)}$ radii, is equal to:

$$m_{ins(in)(1)} = 2\rho_{XPLE} (\pi r_{ins(out)}^2 - \pi r_c^2), \tag{11}$$

where ρ_{XPLE} is the density of the insulation material, ρ_{XPLE} = 950 kg/m^3.

To calculate the weight of the external insulation $m_{ins(out)}$, we calculate its inner radius $r_{ins\_sh(in)}$ according to Fig. 4, *b*:

$$r_{ins\_sh(in)} \approx \frac{6 r_{ins(out)}}{\pi}. \tag{12}$$

Considering that the thickness of the external insulation is d_{ins_sh} = 0.2 mm and it is made of XPLE material, the weight of a meter of external insulation $m_{ins(out)(1)}$ is:

$$m_{ins(out)(1)} = \rho_{XPLE} \times (\pi (r_{ins\_sh(in)} + d_{ins\_sh})^2 - \pi r_{ins\_sh(in)}^2). \tag{13}$$

The weight of a steel string one meter long $m_{str(1)}$ is calculated using formulas (7) and (8). Given this, the total weight of the cable m_{cab} is:

$$m_{cab} = (m_{c(1)} + m_{ins(in)(1)} + m_{ins(out)(1)} + m_{str(1)}) l_c. \tag{14}$$

From equation (14), the cable length l_c is determined for a given cable weight m_{cab}, output power P_{out} and cable operating voltage U_c.

$$l_c = \frac{m_{cab}}{m_{c(1)} + m_{ins(in)(1)} + m_{ins(out)(1)} + m_{str(1)}}. \tag{15}$$

Taking into account the above considerations, Fig. 5 shows the function of the cable length l_c on the operating voltage U_c and power P_{out}, $l_c = f(U_c, P_{out})$ at a cable weight m_{cab} = 1 kg in the form of contour lines. Fig. 5 *a* for current density j_c = 3 A/mm^2, Fig. 5,*b* for current density j_c = 10 A/mm^2.

From the analysis of Fig. 5, *a* and Fig. 5, *b* we can conclude that for a given cable weight m_{cab} its length l_c significantly depends on the power P_{out} transmitted by it and the voltage U_c. Moreover, for a given cable length l_c there is a certain voltage valueU_c at which the maximum transmitted power P_{out} (red curve in the graphs) is achieved. Therefore, to increase the drone's payload, it is advisable to choose the mode with maximum power P_{out}. At current density j_c = 10 A/mm^2, Fig. 5,*b*, the maximum power curve covers the entire analyzed power range up to 10 kW, whereas for a current density j_c = 3 A/mm^2 the power range is covered only partially. This indicates that with the current density j_c = 3 A/mm^2 in the given voltage range up to 1.5 kV, it is possible to effectively transmit power only up to the value $P_{lim} \approx$ 4.8 kW.

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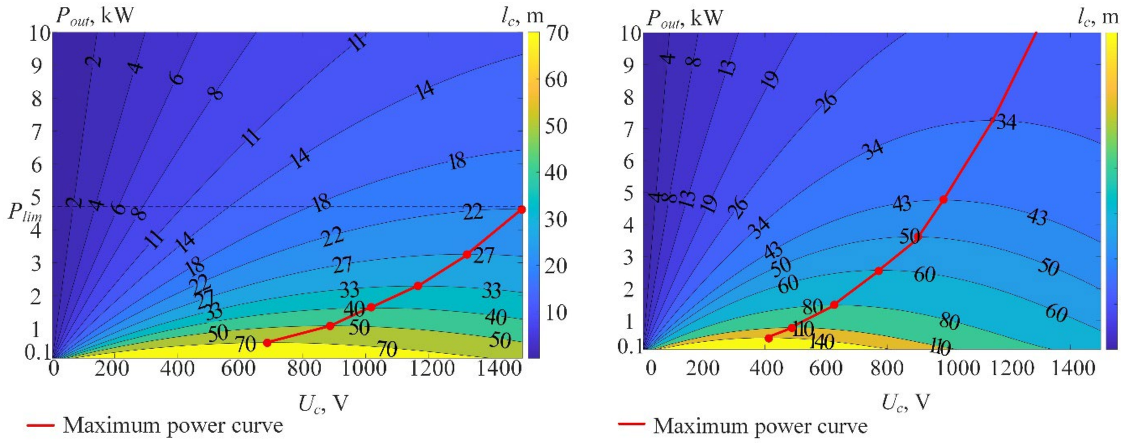

a) b)

Fig. 5 Function of cable length l_c on operating voltage U_c and power P_{out}, $l_c = f(U_c, P_{out})$ with cable weight m_{cab} = 1 kg: a) for current density j_c = 3 A/mm^2; b) for current density j_c = 10 A/mm^2

III. Assessment of the Operating Voltage of the Power Supply System of Tethered Drones of Different Classes

To determine the power of the supply system of tethered drones, it is necessary to take into account the net weight of the drone $m_{dr(net)}$, cable m_{cab}, battery $m_{bat(nom)}$ and payload m_{ld}, as well as the traction characteristics of the drone motors T_{dr} and their total power P_{mot} that determine the ratio of the weight of the equipped drone and the power required to lift it.

Let us consider the technical characteristics of drones, representatives of small (~ 1 kg), medium (~ 15 kg) and large (~ 50 kg) payload capacities, namely, DJI Mavic 3 [17], DJI Matrice 600 [18], and DJI Agras T20 [19], Table 2.

From the analysis of the data presented in Table 2, the nominal thrust of the motors allows for an additional lifting of the payload, which is approximately equal to the net weight of the drone, and the maximum thrust exceeds the weight of the drone by 3-3.5 times. At the same time, the nominal power of the traction system for light drones is up to 100 W, medium – 1-3 kW, heavy – up to 10 kW. The maximum power values are 2-3 times higher, but peak consumption is observed during relatively short time intervals, i.e. during high-speed takeoff and maneuvers. As a rule, modes with significant accelerations when piloting tethered drones are not used and may not be analyzed.

Table 2 Technical characteristics of drones of different payload capacities

Model	Net drone weight $m_{dr(net)}$, kg	Battery cell weight $m_{bat(nom)}$, kg	Engines	
			Thrust T_{dr} nom/max, kg	*Power P_{mot} nom/ max, W*
DJI Mavic 3	0.895	0.34	2.0 /3,6	0.09 / 0.2
DJI Matrice 600	9.1	3.6	15.1 / 30,6	1.7 / 5.0
DJI Agras T20	27.5	6.4	47.5 / 81	6.2 / 14.4

When designing the power supply system for tethered drones, it is also necessary to take into account that their battery is designed only for an emergency landing when power is no longer supplied through the cable. Therefore, the weight of the battery m_{bat} is assumed to be 10% of the nominal value:

$$m_{bat} = 0.1 m_{bat(nom)}. \tag{16}$$

However, in this case, an additional power converter is installed on the drone. Its weight m_{con} depends on the power P_{out}. Let's assume that other drone components consume 5% of the nominal power of the drone's engines and another 5% is used to recharge the battery, which discharge during short-term peak loads. Then the power P_{out} consumed by the drone is calculated by the formula:

$$P_{out} = \frac{0.1 P_{mot(nom)} + P_{mot(nom)}}{\eta_b}, \tag{17}$$

where $P_{mot(nom)}$ is the nominal power of the drone for the nominal thrust $T_{dr(nom)}$ shown in Table 2, P_{mot} is the power of the drone engines for defined thrust T_{dr}, which is less than the nominal $T_{dr(nom)} < T_{dr}$ and is determined by the weight of the equipped drone $m_{dr(br)}$:

$$m_{dr(br)} = m_{dr(net)} - 0.9 m_{bat} + m_{con} + \\ + m_{cab} + m_{ld} \le T_{dr(nom)}. \tag{18}$$

When estimating the weight according to formula (18), typical power density p_d = 1 kW/kg is taking to account:

$$m_{con} = \frac{P_{out}}{p_d}. \tag{19}$$

In turn, the weight of the cable depends on the input power of the tethered drone P_{out}, formula (17). Considering the static mode of operation of the tethered drone without significant accelerations, it can be assumed that the drone thrust T_{dr} is equal to the gross weight of the drone $m_{dr(br)} \approx T_{dr}$ and provided by consumption the power P_{out} (17). The motors total power consumption of the P_{mot} depends on the performance of the drone propulsion system η_T, its structural, electrical and aerodynamic characteristics. Theoretically, without taking into account losses, P_{mot} depends on the thrust T_{dr} according to the power law of 3/2 [20]:

$$P_{mot} = \frac{T_{dr}^{3/2}}{\sqrt{2\rho_a S_d}}, \qquad (20)$$

where ρ_a is the air density, S_d is the area of the propeller disk.

Taking into account, on the one hand, the optimization of motor operation mode for a specific speed, and on the other hand, the electrical losses in the propulsion system and air resistance, certain areas, usually with low thrust, may have certain deviations from the law of 3/2.

Unfortunately, not all manufacturers provide full specifications for their motors and limit them to only specific values of thrust and power consumption in nominal mode. Open sources only provide the performance η_T of the propulsion system of the drone DJI Matrice 600 based on the engine E2000 [18]. This data, together with the theoretical curve obtained based on law (20), allow to define the approximation formula for the power P_{mot}:

$$P_{mot} = k_{app} T_{dr}^{3/2}, \qquad (21)$$

where k_{app} is the approximation coefficient, k_{app} = 29.5, and the formula for calculating productivity η_T for a given quantity:

$$\eta_T = \frac{n_{mot} T_{dr}}{P_{mot}}, \qquad (22)$$

which are shown in Fig. 6.

As we can see from Fig. 6, in the operating range of thrust, highlighted in blue, the real and theoretical performance almost coincide, while at lower thrust the real performance of the propulsion system is significantly less than the theoretical one, which indicates the possibility of using the theoretical dependence (20) to estimate the power consumption of motors from thrust. Therefore, input power P_{out} estimation is based thrust range T_{dr}, which theoretically can be within:

$$m_{dr(net)} - 0.9 m_{bat} + m_{con} \le T_{dr} \le T_{dr(nom)}. \qquad (23)$$

To estimate the minimum thrust $T_{dr(\min)}$, we express the weight of the converter m_{con} in terms of thrust, using formulas (19), (17) and (21):

$$m_{con} = \frac{29.5(0.1 T_{dr(nom)}^{3/2} + T_{dr}^{3/2})}{p_d \eta_b}. \qquad (24)$$

Substituting expression (24) into inequality (23), for the minimum thrust $T_{dr(\min)}$, we obtain the equation:

$$T_{dr(\min)} = m_{dr(net)} - 0.9 m_{bat} + \\ + \frac{29.5(0.1 T_{dr(nom)}^{3/2} + T_{dr(\min)}^{3/2})}{p_d \eta_b}, \qquad (25)$$

which can only be solved numerically, $T_{dr(\min)}$ = 6.6 kg, which corresponds to the power $P_{out(\min)}$ = 704 W. At nominal thrust $T_{dr(nom)}$ = 15.1 kg, the power consumption is $P_{out(nom)}$ = 2004 W.

For the given power range $P_{out} \in [P_{out(\min)}; P_{out(nom)}]$ the weight of the voltage converter m_{con}, (24) shall be calculated. After that, knowing the cable length l_c and the payload weight m_{ld}:

- the operating voltage U_c is calculated, which provides the minimum cable weight m_{cab}, formula (14);
- the weight of the equipped drone $m_{dr(br)}$ is calculated according to formula (18);
- the following condition is checked: $m_{dr(br)} \le T_{dr(nom)}$.

In general, the procedure for calculating a power supply system with a minimum weight of power cable can be described by the algorithm shown in Fig. 7.

To estimate the cable length l_c and the operating voltage of the wire U_c for drones in Table 2, the functions of the cable length l_c and the operating voltage U_c from the weight of the equipped drone $m_{dr(br)}$ and the weight of the payload m_{ld}, $l_c = f(m_{dr(br)}, m_{ld})$, $U_c = f(m_{dr(br)})$ are derived. The function are shown in Fig. 8, *a* – Fig. 10, *a* – for current density j_c = 3 A/mm^2, in Fig. 8, *b* – Fig. 10, *b* –

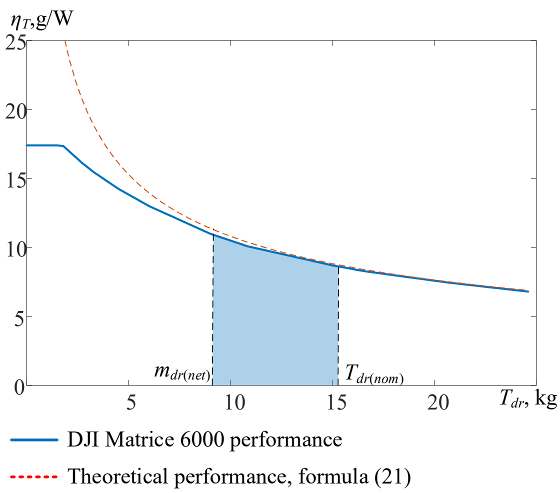

Fig. 6 The DJI Matrice 600 drone propulsion system performance η_T and the theoretical performance curve

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for j_c = 10 A/mm^2. For quantitative comparison with conventional tethered drones, additionally, in Fig. 8, c – Fig. 10, c, the function $l_c = f(m_{dr(br)}, m_{ld})$ is derived for the supply voltage U_c = 43.2 V and the current density j_c = 10 A/mm^2, which is the maximum value of the supply voltage given in Table 1.

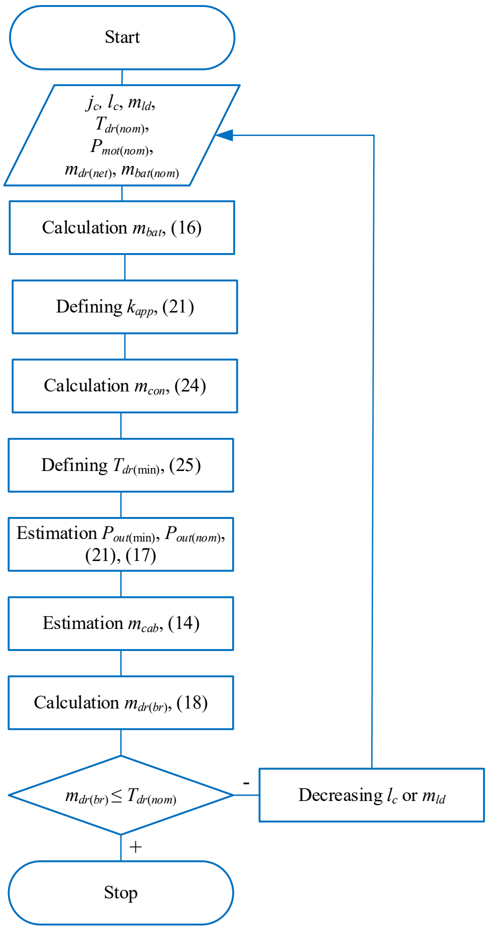

Fig. 7 Algorithm for calculating a power supply system with minimum power cable weight

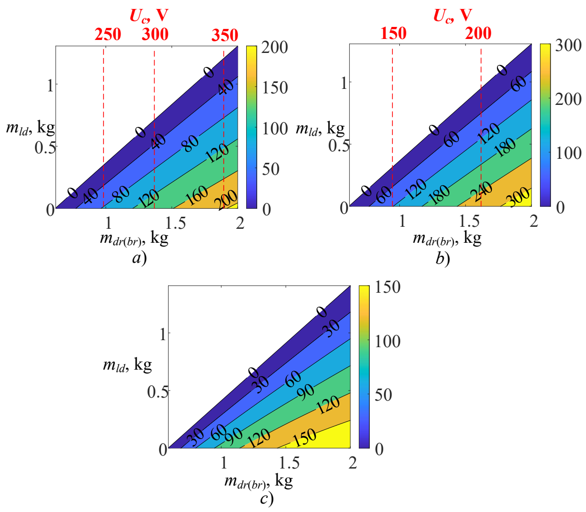

Fig. 8 Function of cable length l_c and wire operating voltage U_c for the DJI Mavic 3 drone: a) for current density j_c = 3 A/mm^2; b) for current density j_c = 10 A/mm^2; c) for fixed operating voltage U_c = 43.2 V and current density j_c = 10 A/mm^2

Generalized information about the maximum wire length $l_{c(max)}$, operating voltage $U_{c(max)}$ and power $P_{out(max)}$ for the maximum drone weight $m_{dr(br)}$ is given in Table 3.

According to the results of the analysis of the data presented in Table 3, it can be concluded that for the DJI

TABLE 3 TECHNICAL FEATURES OF DRONES OF DIFFERENT PAYLOAD CAPACITIES

Model	j_c = 3 A/mm^2/ 10 A/mm^2 / U_c = 43.2 V		
	$l_{c(max)}$, m	$U_{c(max)}$, V	$P_{out(max)}$, W
DJI Mavic 3	207 / 336 / 180	362 / 225 / 43.2	104
DJI Matrice 600	249 / 465 / 87	1109 / 710 / 43.2	2004
DJI Agras T20	303 / 583 / 71	1756 / 1138 /43.2	7164

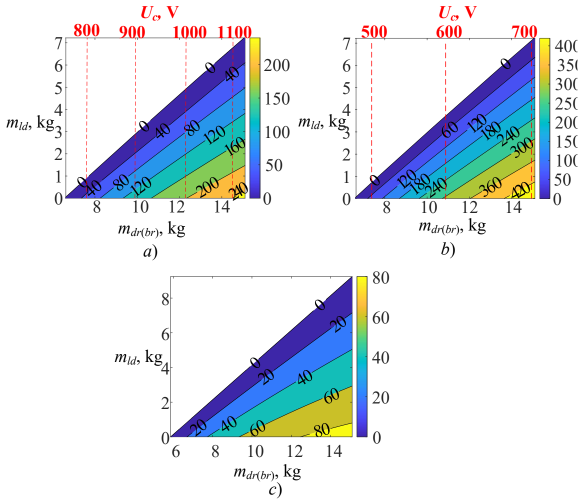

Fig. 9 Function of cable length l_c and wire operating voltage U_c for the DJI Matrice 600 drone: a) for current density j_c = 3 A/mm^2; b) for current density j_c = 10 A/mm^2; c) for fixed operating voltage U_c = 43.2 V and current density j_c = 10 A/mm^2

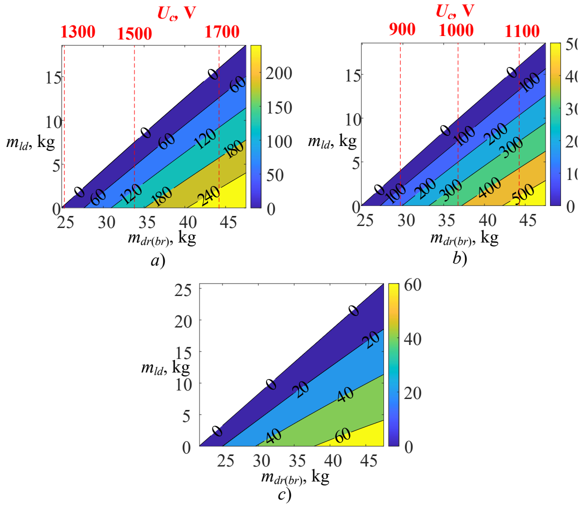

Fig. 10 Function of cable length l_c and wire operating voltage U_c for the DJI Agras T20 drone: a) for current density j_c = 3 A/mm^2; b) for current density j_c = 10 A/mm^2; c) for fixed operating voltage U_c = 43.2 V and current density j_c = 10 A/mm^2

Mavic 3 drone with a power of 100 W, the cable length can be increased by 85% by increasing the supply voltage to 225 V, for the DJI Matrice 600 drone with a power of 2 kW - by 434% at a supply voltage of 710 V, for the DJI Agras T20 drone with a power of 7.2 kW - by 721% at a supply voltage of 1138 V, which indicates a significant advantage of the power supply system with an intermediate high-voltage link.

Conclusion

The paper provides a calculation of the power supply system of a tethered drone with an intermediate high-voltage link, which allows for a significant reduction of the weight of the power cable at the same length. The created mathematical model of the power supply system was used to calculate the parameters of the cable and voltage converter of drones of low (up to 100 W), medium (1-3 kW), and high (up to 10 kW) power. The calculation results confirmed a significant reduction in the weight of the power cable compared to existing analogues operating at low voltage (43.2 V) - for the DJI Mavic 3 drone with a power of 100 W, the cable length can be increased by 85% when the power voltage is a power of 2 kW - by 434% at a power voltage of 710 V, for the DJI Agras T20 drone with a power of 7.2 kW – by 721% at a power voltage of 1138 V.

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Система електроживлення прив’язного дрона з проміжною ланкою підвищеної напруги

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***Анотація*— Існуючі прив’язні дрони працюють на низькій напрузі до 43.2 В, що суттєво зменшує довжину живлячого кабеля та зменшує масу корисного навантаження. Метою роботи є розрахунок системи електроживлення прив’язного дрона з проміжною ланкою підвищеної напруги, спираючись на який можливо забезпечити близьку до мінімальної масу живлячого кабелю, при заданій максимальній висоті польоту та заданій тязі двигунів. У статті розроблено методику розрахунку системи електроживлення прив’язного дрона з проміжною ланкою підвищеної напруги. На основі аналізу недоліків і переваг передачі електроенергії змінним та постійним струмом, принципів ізоляції провідників залежно від рівня напруги, визначення щільності струму через провідник залежно від умов тепловідведення створено математичну модель системи електроживлення, що дозволяє визначити робочу напругу кабелю, що при заданій потужності дрона забезпечує близьку до мінімальної масу кабелю для живлення прив’язного дрона. Показано, що для кабелю з фіксованою масою, розрахованого на задану потужність, існує робоча напруга, при якій він має найбільшу довжину. За допомогою розробленої математичної моделі розраховано параметри живлячого кабелю для прив’язних дронів малої, середньої та високої потужності. Сумарну масу цих дронів порівняно з дронами без ланки підвищеної напруги, що живляться напругою 43.2 В. Результати порівняння засвідчили, що для дронів з низькою потужністю довжину кабелю можна збільшити на 85 % при збільшенні напруги живлення до 225 В, для дронів з середньою потужністю – на 434 % при напрузі живлення 710 В, для дронів з високою потужністю – на 721 % при напрузі живлення 1138 В.**

Ключові слова* — *прив’язний дрон; ізоляція на основі зшитого поліетилену XPLE; система електроживлення з проміжною ланкою підвищеної напруги.