

INVESTIGATION OF A MULTILEVEL INVERTER BASED ON IGBT TRANSISTORS FOR POWER SUPPLY OF A TETHERED UAV WITH TELEMETRY-BASED MONITORING OF POWER PARAMETERS

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Abstract. This paper presents the development and experimental investigation of a power supply system for a tethered unmanned aerial vehicle (UAV) based on a multilevel inverter using IGBT transistors. The relevance of this research is determined by the need to ensure stable and energy-efficient power supply for multicopter platforms operating in long-duration flight modes. The proposed power supply system includes a ground-based energy source, a multilevel inverter with a rated power of up to 3 kW, and an on-board power unit of the multicopter system, which provides voltage conversion to the level required for supplying the on-board systems of the UAV. The inverter converts the energy from the ground power source into AC voltage of 220 V, 50 Hz, which is transmitted through a tethered power supply cable to the quadcopter, where the voltage is further reduced to 22.2 V to power the on-board equipment. Particular attention is given to the implementation of a telemetry-based monitoring system for power parameters, which enables continuous monitoring of voltage, current, and temperature parameters of the power electronic components during UAV operation. Laboratory and field tests of the experimental prototype confirmed the stability of the inverter output parameters, high efficiency, and reliable system performance under varying tethered UAV flight heights and different load conditions. The obtained results demonstrate the potential of the developed multilevel inverter-based power supply system with telemetry monitoring for ensuring long-duration and reliable operation of tethered multicopter platforms.

Keywords: multilevel inverter, energy efficiency, IGBT, power converter, photovoltaic system, multi-stage energy conversion

BADANIE WIELOPOZIOMOWEGO FALOWNIKA OPARTEGO NA TRANZYSTORACH IGBT DO ZASILANIA BEZZAŁOGOWEGO STATKU POWIETRZNEGO NA UWIEŻI Z TELEMETRYCZNYM MONITOROWANIEM PARAMETRÓW MOCY

Streszczenie. W niniejszym artykule przedstawiono opracowanie i badania eksperymentalne systemu zasilania dla bezzałogowego statku powietrznego (UAV) na uwięzi, opartego na falowniku wielopoziomowym wykorzystującym tranzystory IGBT. Znaczenie tych badań wynika z potrzeby zapewnienia stabilnego i energooszczędnego zasilania dla platform wielowirnikowych działających w trybach lotów długotrwałych. Proponowany system zasilania obejmuje naziemne źródło energii, falownik wielopoziomowy o mocy znamionowej do 3 kW oraz pokładowy moduł zasilający system wielowirnikowy, który zapewnia konwersję napięcia do poziomu wymaganego do zasilania systemów pokładowych bezzałogowego statku powietrznego. Falownik przekształca energię z naziemnego źródła zasilania na napięcie prądu przemiennego o wartości 220 V, 50 Hz, które jest przesyłane za pomocą przycelowanego kabla zasilającego do quadkoptera, gdzie napięcie jest następnie obniżane do 22,2 V w celu zasilania wyposażenia pokładowego. Szczególną uwagę poświęcono wdrożeniu systemu monitorowania parametrów zasilania opartego na teledzielnictwie, który umożliwia ciągłe monitorowanie parametrów napięcia, prądu i temperatury elementów elektroniki mocy podczas pracy UAV. Testy laboratoryjne i terenowe eksperymentalnego prototypu potwierdziły stabilność parametrów wyjściowych falownika, wysoką sprawność oraz niezawodne działanie systemu przy zmiennych wysokościach lotu bezzałogowego statku powietrznego na uwięzi oraz w różnych warunkach obciążenia. Uzyskane wyniki wskazują na potencjał opracowanego systemu zasilania opartego na wielopoziomowym falowniku z monitorowaniem teledzielnictwem w zakresie zapewnienia długotrwałej i niezawodnej pracy platform wielowirnikowych na uwięzi.

Słowa kluczowe: falownik wielostopniowy, efektywność energetyczna, IGBT, przetwornica mocy, system fotowoltaiczny, wielostopniowa konwersja energii

Introduction

Unmanned aerial vehicles (UAVs) have experienced rapid development in recent years in both civilian and defence sectors due to their high mobility, cost-effectiveness, and ability to perform tasks in hazardous and hard-to-reach environments. The most common applications of autonomous UAVs include aerial surveillance, environmental monitoring, disaster response, precision agriculture, cargo delivery, and other mission-critical tasks. In this context, high reliability and fault tolerance of unmanned systems become essential requirements for their effective operation [4].

Unmanned aerial vehicles, widely known as drones, have increasingly become an integral component of modern technological systems and are applied in various fields of science and industry. Owing to advances in digital technologies, control systems, and power electronics, UAVs are capable of performing a wide range of tasks, including medical supply delivery to remote areas, environmental monitoring, disaster management, as well as commercial applications such as aerial photography, geodesy, infrastructure inspection, and logistics operations [6, 16].

However, the dependence of UAVs on battery energy sources remains one of the key factors limiting their practical application. Operational experience shows that even when carrying relatively small research payloads, the flight duration of UAVs often does not exceed 20 minutes. This significantly restricts the use of unmanned platforms for long-duration missions such as surveillance, monitoring, and telecommunication support.

Thus, the primary challenge of modern UAV systems is limited energy autonomy, which is mainly associated with the low energy density of on-board battery power sources.

In situations where high horizontal mobility of the platform is not critically required, an effective solution to this problem is the use of a tethered power supply system, where the UAV is connected to a ground station through a power cable. Such an architecture makes it possible to significantly increase flight endurance and ensure near-continuous operation of the unmanned platform. The use of tethered power supply systems enables long-duration surveillance, monitoring, and communication missions without the need for frequent battery replacement or recharging [8, 18].

1. Analysis of recent research on power supply systems for tethered UAVs

For the practical implementation of a power supply system for tethered UAVs, it is not sufficient to simply transmit energy from a ground station through a power cable; it is also necessary to ensure efficient power conversion, voltage stabilization, and real-time monitoring of system parameters. In this context, the use of multilevel inverters based on IGBT transistors becomes particularly relevant, as they enable the generation of high-quality output voltage, reduction of harmonic distortions, minimization of switching losses, and improvement of the overall energy efficiency of the system [15]. The integration of telemetry-based monitoring elements additionally provides continuous supervision

of voltage, current, temperature, and other operating parameters, thereby improving the reliability and operational safety of tethered UAV systems [6].

Multilevel inverters (MLIs) are widely used in modern power electronics systems due to their ability to generate output voltages with improved spectral characteristics. The main advantage of multilevel topologies lies in their capability to produce an output waveform close to a sinusoidal shape, which significantly reduces the level of Total Harmonic Distortion (THD) compared with conventional two-level inverters. Furthermore, the use of multilevel inverters contributes to the reduction of switching losses, mitigation of electromagnetic interference, and improvement of the overall efficiency of energy conversion [14].

Recent research has focused extensively on the development of new multilevel inverter topologies aimed at improving output voltage quality and reducing harmonic distortion. One promising approach is the Soft Charging Switched Capacitor Multilevel Inverter, which utilizes a soft capacitor charging scheme to reduce switching losses and improve energy conversion efficiency [10].

Currently, several major multilevel inverter topologies are widely used in power electronics, including the Neutral Point Clamped (NPC) inverter, the Flying Capacitor (FC) inverter, and the Cascaded H-Bridge (CHB) inverter. Each of these topologies has specific advantages and limitations related to circuit complexity, the number of power switches, power supply requirements, and control algorithms [1].

Inverters of the NPC type are characterized by high reliability and are widely used in medium-power systems; however, they require complex voltage balancing across intermediate levels. The Flying Capacitor topology provides good output voltage quality but requires the use of a large number of capacitors and complex algorithms for controlling their charge. Cascaded H-Bridge inverters allow a large number of output voltage levels to be generated and offer high modularity; however, they require multiple independent power sources [3].

Considering the specific requirements of a tethered UAV power supply system – such as high energy conversion efficiency, low harmonic distortion, and high operational reliability – a multilevel inverter topology based on IGBT transistors was selected. This topology provides an optimal balance between circuit complexity, energy efficiency, and output voltage quality. The use of this approach makes it possible to reduce the level of Total Harmonic Distortion (THD), decrease switching losses, and ensure stable operation of the power supply system under various load conditions.

Modern studies propose various methods for reducing harmonic distortion in multilevel inverters. The most common approaches include Pulse Width Modulation (PWM), Selective Harmonic Elimination (SHE), and various optimization algorithms for controlling switching angles. The application of these methods significantly improves the spectral characteristics of the output voltage and ensures compliance with power quality requirements [5].

Despite the significant advantages of multilevel inverters, existing solutions have several limitations. In particular, as the number of voltage levels increases, energy losses in power switches and passive components also increase. Furthermore, the complexity of control algorithms required to generate high-quality output voltage and reduce harmonic distortion leads to more complicated control systems and increased computational requirements. Another important limitation of many existing systems is the lack of telemetry-based monitoring of power parameters, which makes it difficult to control the operating conditions of the power converter and reduces system reliability in real operating environments [11].

Thus, the development of a highly efficient power supply system for tethered UAVs based on modern power converters represents an important scientific and engineering task. In this context, the capability for real-time monitoring of system operating parameters becomes particularly significant [2]. In modern unmanned systems, the use of telemetry technologies

plays an increasingly important role, enabling remote monitoring of key electrical and thermal parameters of equipment [7].

The integration of telemetry-based monitoring of power parameters enables continuous observation of voltage, current, temperature conditions of power components, and other system characteristics in real time. This allows deviations in equipment operation to be detected promptly, prevents emergency operating conditions, and increases the overall reliability of tethered UAV operation.

Therefore, the development of a tethered UAV power supply system that combines a multilevel inverter based on IGBT transistors with telemetry-based monitoring of power parameters represents significant scientific and practical interest.

2. Materials and methods

This study examines the development and analysis of a power supply system for a tethered unmanned aerial vehicle based on a multilevel inverter using IGBT transistors. The main objective of the design is to ensure stable and energy-efficient power supply for on-board UAV systems during long-duration operation.

The developed power supply with a rated power of 3 kW is intended to provide stabilized electrical power to on board loads and is built using a two-stage architecture that includes a power factor correction (PFC) stage and an LLC resonant converter.

An AC voltage of 220 V is supplied to the input of the system, which in the first stage is converted using an active Totem-Pole PFC. This stage ensures the formation of a sinusoidal input current synchronized in phase with the input voltage, making it possible to achieve a high power factor and reduce harmonic distortion. At the same time, stabilization of the intermediate DC-link voltage is performed.

The generated DC voltage is then supplied to the second stage – a high-frequency LLC DC/DC converter that provides galvanic isolation, voltage step-down, and stabilization of the output voltage [12]. The use of the resonant LLC topology enables soft-switching modes such as ZVS/ZCS, which reduces switching losses and improves the overall energy efficiency of the system.

The output voltage of the converter is 22 V DC, which meets the power supply requirements of the propulsion electric motors and on-board electronic equipment of the tethered UAV. Additionally, the system includes a telemetry-based monitoring module for power parameters, which enables real-time monitoring of voltage, current, and temperature conditions of power components.

To analyse operating modes and evaluate the energy characteristics of the system, a simulation model of the 3 kW IGBT-based multilevel inverter was developed in the MATLAB/Simulink environment. The model includes functional blocks of the active Totem-Pole PFC, the resonant LLC converter, models of power semiconductor components, passive circuit elements, and the control system.

The developed model makes it possible to investigate:

- dynamic and steady-state operating modes of the multilevel inverter;
- the power factor and the spectrum of the input current;
- power loss levels in the PFC and LLC stages;
- energy conversion efficiency under various load conditions.

The simulation results confirm the operability of the proposed architecture and its compliance with the requirements for energy efficiency, stability of output parameters, and electromagnetic compatibility. This demonstrates that the proposed solution is promising for application in power supply systems of tethered unmanned aerial vehicles.

The converter operates in two stages. The PFC AC/DC stage converts the incoming 220 V AC supplied from the ground charging station into approximately 400 V DC after rectification. Subsequently, the LLC DC/DC converter stage reduces the voltage to a stable 22 V DC required for powering the quadcopter.

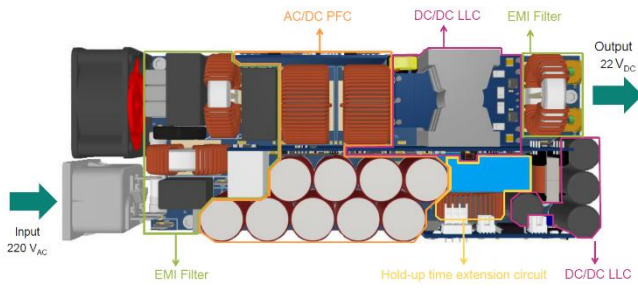


Fig. 1. Structural diagram and operating principle of a 3 kW multilevel inverter

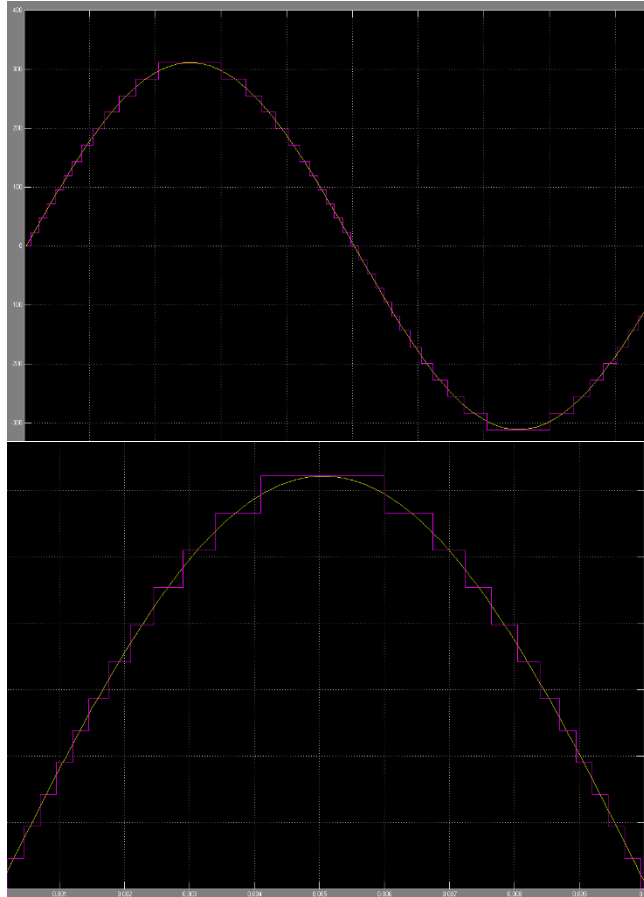


Fig. 2. Output characteristics of the IGBT-based multilevel inverter

Figure 3 presents the spectral analysis of the output voltage of the multilevel inverter. The obtained results show that the Total Harmonic Distortion (THD) is 2.65%, which indicates the high quality of the generated output voltage.

The low THD value is achieved due to the use of a multilevel inverter topology, which allows the generation of a waveform close to a sinusoidal signal. The reduction of higher-order harmonics improves power quality, decreases the load on the output filters, and increases the overall efficiency of the tethered UAV power supply system.

In order to evaluate the energy efficiency of the developed IGBT-based multilevel inverter, calculations of its main parameters were performed. The efficiency was determined based on the analysis of thermal power losses in the active and passive elements of the inverter electrical circuit. The schematic diagram of the developed device includes the main power and passive components presented in Table 1.

Additionally, the system includes a telemetry monitoring module designed to supervise power supply parameters, including voltage, current, and temperature conditions of the power components. The obtained data are transmitted to the ground station for analysis and monitoring of the operating modes of the tethered UAV power supply system [9].

Total Harmonic Distortion (THD) = 2.65%

Maximum harmonic frequency used for THD calculation = 11000.00 Hz (220th harmonic)

0 Hz (DC):	0.00	90.0°
50 Hz (Fnd):	311.78	0.0°
100 Hz (h2):	0.01	0.0°
150 Hz (h3):	1.12	224.6°
200 Hz (h4):	0.01	0.0°
250 Hz (h5):	0.47	0.0°
300 Hz (h6):	0.01	132.6°
350 Hz (h7):	1.12	149.0°
400 Hz (h8):	0.02	144.0°
450 Hz (h9):	0.19	95.1°
500 Hz (h10):	0.03	0.0°
550 Hz (h11):	0.15	138.8°
600 Hz (h12):	0.01	112.1°
650 Hz (h13):	0.49	181.8°
700 Hz (h14):	0.03	170.9°
750 Hz (h15):	0.44	0.0°
800 Hz (h16):	0.02	0.0°
850 Hz (h17):	1.10	158.3°
900 Hz (h18):	0.01	0.0°
950 Hz (h19):	1.65	0.0°
1000 Hz (h20):	0.01	19.6°
1050 Hz (h21):	1.03	160.3°
1100 Hz (h22):	0.03	126.4°
1150 Hz (h23):	0.56	0.0°
1200 Hz (h24):	0.02	157.9°
1250 Hz (h25):	0.22	259.6°
1300 Hz (h26):	0.03	0.0°
1350 Hz (h27):	1.34	158.6°

Fig. 3. Total Harmonic Distortion (THD) of the output voltage of the multilevel inverter

No	Component	Power per element (W)	Quantity	Total Power (W)
1	Microcontroller	0.5	1 pcs.	0.5
2	Optocouplers	0.1	10 pcs.	1.0
3	DC-DC Converters	0.1	3 pcs.	0.3
4	Transistors	0.05	30 pcs.	1.5
5	Bridge rectifiers	0.02	4 pcs.	0.08
6	IGBT transistors	20	2 pcs.	40 W
7	Fixed resistors	0.01	75 pcs.	0.75 W
8	Diodes	0.02	10 pcs.	0.2 W
Total Power (W)				45.33 W

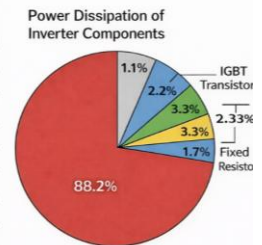


Fig. 4. List of components and active thermal power

The calculation of thermal losses was carried out at the nominal inverter power of 3 kW.

Under an active load, the output voltage waveform has the form of a multilevel sinusoidal signal with pronounced edges. In this case, dynamic power losses are relatively small and were therefore not considered [13].

Thus, the inverter efficiency is determined using the following formula:

$$\eta = \frac{P_{in} - P_{loss}}{P_{in}} = \frac{3000 - 45.33}{3000} \approx 98\% \quad (1)$$

The power supply converter operates in two stages [17]. In the first stage, the PFC AC/DC stage converts the incoming 220 V AC supplied from the ground station into DC voltage after rectification, which is approximately 400 V DC. This stage provides power factor correction and stabilization of the intermediate voltage in the DC link.

In the second stage, an LLC DC/DC converter is used, which performs voltage step-down and generates a stable output voltage of 22 V DC required to power the on-board systems of the quadcopter.

Based on the selected architecture, the main parameters of the developed IGBT-based multilevel inverter designed for powering a tethered UAV with telemetry-based monitoring of power parameters were calculated. The main characteristics of the device are as follows: output voltage – 220 V, frequency – 50 Hz, rated output power – 3 kW, output voltage waveform – multistep, device mass – 2.5 kg, dimensions – 430×220×140 mm, efficiency – up to 98%.

The integration of the telemetry monitoring system enables continuous supervision of key power parameters, including voltage, current, and temperature conditions of power components, thereby increasing the reliability and operational safety of the tethered UAV power supply system.

3. Experimental investigation of the power supply system for a tethered UAV

Laboratory tests of the experimental prototype of the IGBT-based multilevel inverter designed for powering a tethered UAV with telemetry-based monitoring of power parameters were conducted to evaluate its conversion characteristics, output voltage stability, and efficiency under various load conditions. During the testing, the operation of the switching circuit, the waveform of the output signals, and the thermal conditions of the power components were examined.

The results of the laboratory tests showed that the developed multilevel inverter provides stable output voltage and high conversion efficiency when the input voltage and switching frequency vary. Under nominal load conditions, the system efficiency reached more than 92–94%, while the deviation of the output voltage did not exceed $\pm 3\%$.

Following the successful testing of the inverter, an experimental prototype of the multicopter power supply unit was manufactured and tested. Its compatibility with the inverter and the multicopter control system was evaluated. The tests confirmed the stability of the output voltage, effective electromagnetic interference filtering, and proper operation of the protection systems.



Fig. 5. Tethered UAV power supply system with a multilevel inverter and telemetry-based monitoring of power parameters: (a) experimental field testing of the tethered UAV platform, b) structural diagram of the proposed power supply system

Additionally, field tests of the system were conducted at different tethered UAV flight altitudes. The experiments were performed at heights of 10 m, 30 m, and 50 m, while the voltage, current, and temperature parameters of the power components were monitored through the telemetry system. The results showed that changes in altitude did not significantly affect the stability of the output voltage, whose deviation remained within $\pm 4\%$.

A series of tests was also carried out under varying load conditions in the range of 30–100% of the nominal power. The obtained data demonstrated that the inverter maintains stable operation across the entire load range, while the efficiency varied within 90–94%, and the thermal conditions of the power IGBT transistors remained within permissible limits.

The testing of the experimental prototype of the multicopter power supply unit recorded positive results confirming that the device meets the technical requirements of the project and is ready for integration into a tethered dual-purpose multicopter platform.

Thus, comprehensive analytical, simulation, and experimental studies confirmed the validity of the selected UAV configuration and the effectiveness of the developed power components, which ensure reliable and energy-efficient power supply for the entire system.

4. Discussion of the research results

The results obtained from laboratory and field tests confirm the effectiveness of the developed power supply system for a tethered unmanned aerial vehicle implemented on the basis of an IGBT-based multilevel inverter. The conducted studies demonstrated that the proposed power converter architecture ensures stable electrical parameters and high energy conversion efficiency under various operating conditions.

The developed multilevel inverter performs the key function of converting energy from a ground power source (battery module or solar panels) into an AC voltage of 220 V, 50 Hz, which is transmitted through the power cable to the tethered quadcopter. On board the UAV, the voltage is converted by the multicopter power supply unit to 22.2 V, which is required to power all on-board systems, including the propulsion system, flight control system, and telemetry equipment. This architecture enables stable power supply to the UAV during long-duration flight operations.

Analysis of the test results showed that the main share of thermal losses in the system occurs in the power semiconductor components, primarily the IGBT transistors of the inverter. This is explained by the fact that these components perform the switching of power currents and operate at relatively high voltage levels and switching frequencies. Despite the significant thermal load, the temperature conditions of the power components remained within permissible limits, which confirms the correctness of the selected circuit design solutions and the effectiveness of the applied thermal management methods.

An important element of the developed system is the telemetry-based monitoring of power parameters, which provides continuous monitoring of key electrical characteristics of the system, including voltage, current, and temperature parameters of the power components. The use of telemetry enables real-time diagnostics of the power supply system and improves the operational reliability of the tethered UAV under real operating conditions.

The results of field tests conducted at different flight altitudes of the tethered quadcopter showed that the developed power supply system maintains stable output voltage and reliable operation of the entire energy subsystem. Changes in flight altitude did not significantly affect the quality of power supply to the on-board systems, which confirms the robustness of the inverter converter and the multicopter power supply unit under varying operational conditions.

Additional tests under different load conditions demonstrated that the system maintains stable operation across a wide range of operating modes. The inverter efficiency remains at a high level, while the telemetry system provides effective monitoring of power parameters and timely detection of potential deviations.

Thus, the results of the conducted research confirm the validity of the selected architecture of the tethered UAV power supply system and demonstrate the potential of multilevel inverters with telemetry-based monitoring of power parameters for ensuring long-duration and energy-efficient operation of tethered multicopter platforms.

5. Conclusion

In this work, a power supply system for a tethered unmanned aerial vehicle based on a multilevel inverter using IGBT transistors was developed and investigated. The proposed system architecture provides conversion of energy from a ground power source into an AC voltage of 220 V with subsequent transmission through a cable to the quadcopter and further conversion to 22.2 V required for powering the on-board systems.

The results of laboratory and field tests demonstrated that the developed multilevel inverter provides stable electrical parameters, high efficiency, and reliable system operation under various load conditions. The conducted studies confirmed

the stability of the power supply system when the altitude of the tethered UAV changes and under different operational conditions.

The integration of a telemetry system for monitoring power parameters enabled continuous supervision of key electrical characteristics, including voltage, current, and temperature parameters of the power components. This provides real-time diagnostics of the system state and increases the operational reliability of the unmanned aerial vehicle.

Thus, the results of the conducted research confirm the effectiveness of the developed power supply system and demonstrate the potential of using multilevel inverters with telemetry-based monitoring of power parameters to ensure long-duration and energy-efficient operation of tethered multicopter platforms.

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