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CHOOSING THE TYPE OF CELLS FOR A MULTI-COMPONENT ENERGY STORAGE SYSTEM FOR AN ELECTRIC BUS THAT IS CHARGED AT A DEPOT

Abstract. *The paper develops a methodology for determining the optimal parameters of a combined energy storage system for an electric bus based on solving a conditional minimization problem taking into account the driving mode, route parameters, and weight and size restrictions when charging the storage system at a depot. The practical significance of the work lies in determining the parameters of combined energy storage systems for an electric bus using the example of a plug-in hybrid power plant. Analysis of the results of the study on solving the optimization problem proved that when using charging systems at a depot, energy consumption is a significant indicator for storage systems, but the power of optimal energy storage systems is excessive and exceeds the minimum requirements by 2,05–3,29 times, which can be used to improve the dynamic performance of an electric bus.*

Keywords: *traction drive, energy storage, electric bus, trolleybus, parameter optimization, objective function.*

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ВИБІР ТИПУ КОМІРОК БАГАТОКОМПОНЕНТНОГО НАКОПИЧУВАЧА ЕНЕРГІЇ ДЛЯ ЕЛЕКТРОБУСУ, ЯКИЙ ЗАРЯДЖАЄТЬСЯ У ДЕПО

Анотація. *В роботі розроблено методологію визначення оптимальних параметрів комбінованого накопичувача енергії для електробуса на основі вирішення задачі умовної мінімізації з урахуванням режиму руху, параметрів маршруту, та обмежень за вагою та розмірами при заряджанні накопичувача в депо. Практичне значення роботи полягає у визначенні параметрів комбінованих накопичувачів енергії для електробуса на прикладі plug-in гібридної енергетичної установки. Аналіз результатів дослідження щодо вирішення задачі оптимізації довів, що при використанні систем заряджання в депо енергоємність є значущим показником для накопичувачів, проте потужність оптимальних систем накопичення енергії є надмірною та перевищує мінімальні вимоги у 2,05–3,29 рази, що можливо використати для покращення динамічних показників електробусу.*

Ключові слова: *тяговий привод, накопичувач енергії, електробус, тролейбус, оптимізація параметрів, цільова функція.*

Introduction. Trolleybuses and electric buses are the main type of trackless passenger transport, making up a significant share of the fleets of most large cities in Ukraine. Their widespread introduction, which began in the second half of the 20th century and continues today, is largely due to several advantages they have over conventional buses. First, trolleybuses are more environmentally friendly, as they do not produce direct harmful emissions during operation, except for the indirect environmental impact associated with the production of electricity at power plants. Second, they are able to recover kinetic energy during braking. In modern models, up to 70 % of the braking energy can be recovered and fed back into the contact power grid. Third, trolleybuses, as a rule, have a longer service life than buses, which is explained by the lower vibration load on the structural elements, since they do not have internal combustion engines.

Analysis of previous research. The combination of the above advantages, as well as the elimination of the disadvantages characteristic of trolleybuses, can be achieved by using electric buses as public transport. In addition to a high level of environmental and energy efficiency, electric buses have excellent maneuverability, which allows them to operate flexibly along specific routes with certain permissible deviations. The only limiting factors in this case are the capacity of on-board energy storage systems and the availability of appropriate charging infrastructure.

To analyze energy consumption by trackless passenger transport, the following types of vehicles were considered:

Electric bus with large-capacity energy storage systems, providing an autonomous range of 150 to 250 km, which are charged mainly at the depot;

An electric bus with a medium-capacity storage battery, offering an autonomous range of up to 50 km, charged at terminal stops using fast charging methods (10–30 minutes);

An electric bus with a minimum storage capacity, providing a range of up to 10 km, is charged through short-term charging sessions at regular passenger stops, with charging times comparable to boarding and alighting times [1, 2].

When assessing energy efficiency, it is important to ensure that the calculated results closely match the actual operational parameters recorded during the operation of public transport in a dense urban environment. To do this, it is necessary to develop a representative calculation cycle of traffic that accurately reflects the real conditions of movement of trackless passenger vehicles in cities.

The initial stage of defining such a cycle included the selection of a typical urban public transport route in the city. In this study, the selection was based on bus routes operating in the Ukrainian city of Ivano-Frankovsk, which is characterized by high traffic intensity and frequent congestion at the time of the study. [3, 4, 5]

In order to determine the route that most accurately reflects the operating conditions of urban public transport, several selection criteria were established. First, only bus routes were considered, since the main goal was to study technical solutions to improve the environmental performance of existing trackless public transport by switching to electric traction. Secondly, all intermediate stops along the selected route had to be located strictly within the city limits. Thirdly, the spatial distribution of these stops was carefully analyzed, with special attention paid to routes passing through the central and historical districts of the city. Based on these considerations, routes 4 and 10 were determined as the most representative [5].

The efficiency of electric transport depends not only on the technical characteristics of vehicles, but also on their operating modes. Significant energy savings can be achieved by optimizing the speed regimes of vehicles on urban roads. This issue has become particularly relevant, given that electricity costs have increased significantly [7]. Since trams and trolleybuses are not equipped with on-board electricity meters, drivers cannot choose the most energy-efficient driving mode. Energy consumption is recorded only at the enterprise level, which makes it difficult, if not impossible, to determine specific goals and the amount of electricity used. In this study, mathematical modeling methods were used to analyze electricity consumption and propose energy saving measures.

Research on improving the efficiency of electric transport through traffic control is based on vehicle dynamics, which is a central topic in the theory of electric traction [8, 9,10]. These issues can be approached more broadly, namely from the perspective of automated electric drives for special technological applications. A distinctive feature of this approach is that the equation of motion is reduced to the wheel rim, not the motor shaft, and the distance traveled is taken as the independent variable. Since trams and trolleybuses do not have gearboxes, the gear ratio from the motor shaft to the wheel rim remains constant, which makes the first difference insignificant. The second difference arises because time cannot be considered as an independent variable, since speed and motion vary in real operating conditions.

In [11], hybrid systems incorporating different lithium cell types were analyzed. The study demonstrated an increase in energy density of 5,56 % and specific energy of 28,21 % compared to batteries consisting of homogeneous lithium cells. Similarly, a study presented in [12] showed that hybrid configurations combining NMC cells (with high specific energy) and LTO cells (with high specific power) prevent weight reductions of up to 33,5 % or damage costs of up to 30 % of the same type of batteries. In [13], which focused on the optimization of hybrid batteries with lithium cells of different chemistries, it was found that hybrid energy storage systems can significantly reduce the overall cost at the expense of single-cell systems.

Therefore, research on the determination of parameters and methods for optimizing hybrid energy storage devices for electric rolling stock is very relevant, since they make it possible to significantly increase the efficiency of energy storage technologies in modern rolling stock. Based on the calculations given in [11, 13], the performance of single-cell storage devices using only LTO cells, LFP cells and supercapacitors was determined. As an example, LTO cells YINLONG 66160H 2.3v 40ah [14], LFP cells ENERpower 26650 LiFePO4 3,2V 3000mAh (10C) [15] and supercapacitors Maxwell 3000 FARAD Capacitor Boostcap 3000f 2,7 volt BCAP3000 [16], taking into account the elements of technical cost parameters based on information from [13].

According to the comparative analysis presented in [12, 13], LFP-based storage systems exhibit the highest mass and size parameters. Conversely, the supercapacitor-based storage system exhibits the lowest total mass, while the LTO-based configuration requires the smallest installation volume. The lowest total component cost is also observed for the LTO-based storage system. The total energy density of a single-cell supercapacitor storage system is almost equal to its nominal energy density. In contrast, the energy density exceeds the required value by a factor of about 5,5 for LTO cells and by a factor of 14,7 for LFP cells. Although the ability to recharge the storage system after several trips is a positive feature, the significant underutilization of the available energy density leads to increased costs in terms of mass, volume, and capital costs. Among the analyzed options, the single-cell LTO-based storage system provides the lowest total cost, while the LFP-based system offers the lowest cost per kilowatt-hour [12, 13].

When evaluated according to the criteria of mass, volume, total cost and cost per kilowatt-hour, none of the single-cell energy storage systems simultaneously achieves optimal performance in all aspects. Therefore, a rational solution involves the implementation of a hybrid (combined) energy storage system that combines the advantages of the cell types discussed above.

Problem statement. The aim of the work is to determine the parameters of cells for a multi-component energy storage system for an electric bus that is charged at a depot using the example of electric buses for routes № 4 and 10 in Ivano-Frankivsk, Ukraine.

Research results. The main element of the solution to the analysis problem represented by expression (2) is the determination of losses in the electrical part of the traction drive. Losses consist of losses in the semiconductor converter and losses in the traction motor.

The energy consumption of the on-board storage device is determined depending on the storage device operating mode.

$$\mathrm{W_n} = \mathrm{W_{1km}}\, L_m\,, \tag{1}$$

L_m – vehicle mileage using an energy storage device, which is determined according to the storage device usage mode when charging at a depot

The general energy consumption indicators of accumulators for electric buses are given in Table 1.

The capacity of the on-board storage must ensure the operation of electrical equipment during the operation of the traction drive and auxiliary systems.

The power at the wheels of an electric bus is determined by the force of resistance to movement according to the expression

$$P_1 = \frac{W_0 V}{3600} = \frac{(12+0{,}004\ \ V^2)\, gm\, V}{3600} \quad . \tag{2}$$

Table 1 – Energy capacities of storage devices for electric buses

Electric bus driving mode	Vehicle route	Energy capacity of the storage device, kWh
Economical	4	265
Fast	4	329
Intermediate	4	485
Behind obstacles	4	592
Economical	10	218
Fast	10	272
Intermediate	10	400
Behind obstacles	10	487

The storage capacity is determined taking into account the efficiency of the traction drive determined for the traction drive of the electric bus according to the dependencies given in [17] and the efficiency of the mechanical transmission, which is $\eta_m = 0.17$ [9] and taking into account additional own needs (for heated trolleybuses it is $P_d = 18$ kW)

$$P_{nak} = P_1(\eta - \eta_m) + P_d \quad . \tag{3}$$

The results of determining the capacity of the energy storage device for the operating modes are given in Table 2.

For further research, we will use elements that are characterized by the following technical parameters.

Table 2 – Capacity of storage devices for electric buses

Electric bus driving mode	V	w_0	W_0	P_2	η	η_m	η_{sum}	P_1	P_{nak}
-	kWh	H/kH	H	kW	r.u.	r.u.	r.u.	kW	kW
Economical	50	12,78	2257	113,7	0,78	0,17	0,61	186	205
Fast	56,2	12,97	2290	128,7	0,82	0,17	0,65	197	216
Intermediate	61,2	13,15	2323	142,2	0,87	0,17	0,.70	203	221
Behind obstacles	61,2	13,15	2323	142,2	0,87	0,17	0,70	203	221

The number of series-connected elements is determined

$$N_s = \frac{U_{dc}}{U_{ch}} , \tag{4}$$

U_{dc} – intermediate circuit voltage; U_{ch}– the voltage at the end of charging the cell. The resulting value N_s is rounded up.

$$x_i = \max(N_1, N_2), \tag{5}$$

N_1 – the number of parallel branches, determined from the condition of ensuring the required level of energy storage;

N_2 – the number of parallel branches, determined from the condition of ensuring the required level of storage capacity.

The number of parallel branches, determined from the condition of ensuring the required level of energy storage (W_n), is determined by the expression

$$N_1 = \frac{W_n}{N_S E_{cell} k_{ch}}, \tag{6}$$

where E_{cell}– capacity of one element, expressed in kWh, k_{ch}– a coefficient that takes into account the reduction in energy that an energy storage element can store when charged with a current exceeding the optimal value. According to the recommendations [12], we take it equal to 0.9. The resulting value N_1 is rounded up.

The number of parallel branches, determined from the condition of ensuring the required level of storage capacity, is determined by the expression

$$N_2 = \frac{P_n}{N_S U_{dis} I_{cell}} , \tag{7}$$

where P_n– nominal capacity of the storage device; $\mathrm{U_{dis}}$– discharge voltage of the cell; $\mathrm{I_{cell}}$– the smaller of the charge and discharge current of the cell $\mathrm{I_{cell}} = \min(\mathrm{I_{ch}}, \mathrm{I_{dis}})$. Here $\mathrm{I_{ch}}$– permissible charging current, $\mathrm{I_{dis}}$– permissible discharging current.

The resulting value N_2 is rounded up.

Number of elements

$$\mathrm{N_{cell}} = x_i \mathrm{N_s}. \tag{8}$$

Total mass of elements

$$m = \mathrm{N_{cell}} \mathrm{m_{cell}} \ , \tag{9}$$

where $\mathrm{m_{cell}}$ is the mass of one element.

We will determine the volume required to accommodate the elements of the on-board storage device

$$\mathrm{V} = \mathrm{N_{cell}} \mathrm{a_{cell}} \mathrm{b_{cell}} \mathrm{h_{cell}}, \tag{10}$$

where $\mathrm{a_{cell}}$, $\mathrm{b_{cell}}$, $\mathrm{h_{cell}}$ are the geometric dimensions of the element, respectively: length, width and height.

Cost of storage elements

$$C = \mathrm{N_{cell}} \mathrm{c_{cell}}. \tag{11}$$

The total capacity of the storage elements is equal to

$$E = \mathrm{N_{cell}} \mathrm{E_{cell}}. \tag{12}$$

General results of calculations of basic single-cell storage devices are given in [12, 13].

The calculations did not take into account the volumes and masses of the cooling system components, as well as the dimensions of the battery management system (BMS).

The optimization of the parameters of a hybrid energy storage system belongs to the class of constrained parameter minimization problems. Based on previous studies [12, 13] and considering the uncertainty of operating and disposal costs, the total cost of the storage system components was chosen as the optimization criterion that needs to be minimized.

The objective function has the following form

$$\mathrm{C} = \mathrm{C_{LTO}} + \mathrm{C_{LFP}} + \mathrm{C_{SC}} \rightarrow \mathrm{MIN} \ , \tag{13}$$

where $\mathrm{C_{LTO}}$,– is the cost of LTO cells, $\mathrm{C_{LFP}}$, – is the cost of LFP cells and $\mathrm{C_{SC}}$ – is the cost of supercapacitors. Table 1 shows the technical parameters of the cells.

Due to the fact that the energy storage device consists of parallel branches of connected elements, it is rational to choose the number of branches of each type of storage device as parameters for the combined storage device: x_1– number of branches with LTO elements, x_2– number of branches with LFP elements , x_3– number of branches with supercapacitors.

Thus, the total cost of the elements can be determined by the expression

$$C = x_1C_1 + x_2C_2 + x_3C_3 \rightarrow MIN, \quad (14)$$

where C_1– the cost of the LTO cell branch, C_2– the cost of the LFP cell branch, C_3 –the cost of the supercapacitors branch.

Let us consider the constraints imposed on the storage parameters and used in the conditional minimization problem.

Constraints in the form of equalities. This group of constraints includes constraints that set the required nominal power (P_n) and nominal energy capacity of the storage device (W_n)

$$P = P_{LTO} + P_{LFP} + P_{SC} = P_n, \quad (15)$$

where P_{LTO}, – the nominal power of LTO cells, P_{LFP}, – the nominal power of LFP cells and P_{SC}– the nominal power of supercapacitors.

$$W = W_{LTO} + W_{LFP} + W_{SC} = W_n, \quad (16)$$

where W_{LTO},– the operating energy capacity of LTO cells, W_{LFP}, – the operating energy capacity of LFP cells, and W_{SC} – the operating energy capacity of supercapacitors.

According to the approaches, to set the constraints in the minimization problem in the form of equalities, we transform them into inequalities in the form

$$P \geq P_n , \quad (4.28)$$

where P_n. – the specified storage capacity.

$$W \geq W_n, \quad (17)$$

where W_n– the specified energy capacity of the storage device.

Taking into account the parameters of the storage device, we transform the dependencies (12)-(17) to the form necessary for solving the problem

$$x_1P_1 + x_2P_2 + x_3P_3 \geq P_n \ , \quad (18)$$

where P_1 is the power of branches with LTO elements, P_2 is the power of branches with LFP elements, P_3 is the power of branches with supercapacitors.

$$x_1 W_1 + x_2 W_2 + x_3 W_3 \geq W_n , \tag{19}$$

where W_1 – the energy density of branches with LTO cells, W_2 – the energy density of branches with LFP cells, W_3 – the energy density of branches with supercapacitors.

Let's consider restrictions in the form of inequalities. This group includes restrictions that are set for the storage device according to mass-dimensional indicators (m_n maximum mass of storage device elements, V_n maximum volume of storage device elements), i.e.

$$m = m_{LTO} + m_{LFP} + m_{SC} \leq m_n , \tag{20}$$

where m_{LTO}, – the mass of LTO cells, m_{LFP}, –the mass of LFP cells and m_{SC} – the mass of supercapacitors.

$$V = V_{LTO} + V_{LFP} + V_{SC} \leq V_n , \tag{21}$$

where V_{LTO}, – the volume of LTO cells, V_{LFP}, – the volume of energy capacity of LFP cells and V_{SC} – the volume of supercapacitors.

Taking into account the parameters of the components of the combined storage device, we transform the dependencies (19), (20) to the form necessary for solving the problem

$$x_1 m_1 + x_2 m_2 + x_3 m_3 \leq m_n , \tag{22}$$

where m_2 – the mass of the LTO cell branch, m_2 – the mass of the LFP cell branch, m_3 is the mass of the supercapacitors branch.

$$x_1 V_1 + x_2 V_2 + x_3 V_3 \leq V_n , \tag{23}$$

where V_1 – the volume of the LTO cell branch, V_2 – the volume of the LFP cell branch, V_3 – the volume of the supercapacitors branch.

In addition to constraints in the form of equalities and inequalities according to the approaches [10-12], we set constraints on the parameters of the optimization problem

$$\begin{gathered} x_{1min} \leq x_1 \leq x_{1max}, \\ x_{2min} \leq x_2 \leq x_{2max}, \\ x_{3min} \leq x_3 \leq x_{3max}, \end{gathered} \tag{24}$$

where x_{1min}– the minimum number of branches of LTO elements, x_{1max}– the maximum number of branches of LTO elements, x_{2min}– the minimum number $x_{3min}$of branches of LFP elements, – the maximum number of branches of LFP elements, x_{2max}– the minimum number of branches of supercapacitors, x_{3max}– the maximum number of branches of supercapacitors .

To solve the conditional minimization problem, we use the MATLAB software environment (USA) with the optlab optimization complex (Ukraine), which allows us to choose a large number of methods for solving the problem. With a low number of test solutions, the best result was obtained when using the Weyl method at different initial search points [18, 19, 20, 21].

Let us solve the problem of finding optimal configurations of combined energy storage for different capacities, which are determined by the driving modes, the profile and track plans and the rolling stock load on plug- in hybrid power plants of rail rolling stock of a quarry locomotive, which are given in the works [18, 19, 20, 21]. The course of solving the problems of finding optimal configurations of a combined energy storage is given in Fig. 1. on which the starting point is marked as a round point, the end point as a rhombus.

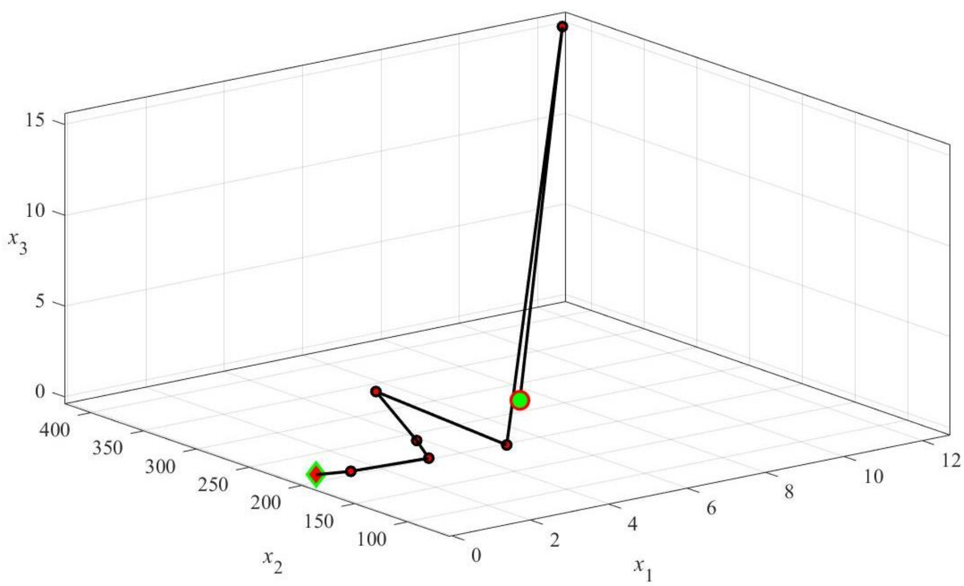

Figure 1 – The progress of solving the problem of optimizing the parameters of the energy storage system with a given maximum energy capacity of 329 kWh and power of 216 kW

The overall results are presented in Table 3.

Table 3 – Results of solving the problem of finding the optimal parameters of the energy storage device when charging an electric bus at a depot.

Route	W_n	P_{sum}	x_1	x_2	x_3	P	W	m	V	C
-	kWh	kW	-	-	-	kW	kWh	tons	m^3	thousand euros
4	265	205	0	147	1	452	267	2,52	1,32	115
4	329	216	0	199	0	561	359	3,25	1,64	142,1
4	485	221	0	281	0	792	507	4,59	2,32	200,1
4	592	221	1	316	0	981	592	5,47	2,78	245,8
10	218	205	0	131	0	369	236	2,14	1,08	93,52
10	272	216	0	159	1	486	288	2,74	1,42	123,5
10	400	221	0	225	1	672	407	3,79	1,97	170,7
10	487	221	0	281	0	830	509	4,71	2,43	210,6

The assessment of specific indicators of storage devices is given in Table 4.

Table 4 – Results determination specific indicators of energy storage devices when charging an electric bus at a depot

Route	Electric bus driving mode	x_1	x_2	x_3	P_u	W_u	m_u	V_u
-	-	-	-	-	thousand euros /kW	thousand euros / kWh	thousand euros / tons	thousand euros /m^3
4	Economical	0	147	1	0,254	0,431	45,635	87,121
4	Intermediate	0	199	0	0,253	0,396	43,723	86,646
4	Fast	0	281	0	0,253	0,395	43,595	86,250
4	Behind obstacles	1	316	0	0,251	0,415	44,936	88,417
10	Economical	0	131	0	0,253	0,396	43,701	86,593
10	Intermediate	0	159	1	0,254	0,429	45,073	86,972
10	Fast	0	225	1	0,254	0,419	45,040	86,650
10	Behind obstacles	0	281	0	0,254	0,414	44,713	86,667

The analysis of the obtained general results proves the following. When using an energy storage device for an electric bus when charging an electric bus at a depot on routes 4 and 10, it is optimal to use a single- or two -component type of storage device. It is not optimal to use a three-component storage device. So, in the economical mode of use for route 4, it is optimal to use a two-component storage device based on 147 branches with LFP elements and 1 branch with supercapacitors , and on route 10, a mono-storage device based on 131 branches with LFP elements is optimal.

This mode of movement can be applied when applying organizational requirements for the movement of electric buses and rational requirements for the speed of passenger transportation. The mass of the optimal storage devices for routes 4 and 10 is 2,52 tons. and 2,14 tons., and the cost is 115 thousand euros and 93,52 thousand euros, respectively. When using electric buses in “obstacle” modes, the weight and cost of accumulators on routes 4 and 10 increase significantly to 5,47 tons, 4,71 tons (2,17 times and 2,2 times) and 245,8 thousand euros, 210,6 thousand euros, (2,13 times and 2,25 times) respectively, which is due to a significant 2,31 times increase in the requirements for the energy consumption of storage devices. The type of storage device also changes when switching to the mode with obstacles. So, for route 4, the optimal is a two-component storage device with 1 branch with LTO elements and 316 branches with LFP elements, and for route 10 – a mono-component 281 branch with LFP elements.

Conclusions.

1. For the first time, a methodology has been developed for determining the optimal parameters of a combined energy storage system for an electric bus based on solving a conditional minimization problem taking into account the driving mode, route parameters, and weight and size restrictions when charging the storage system at a depot.

2. The practical significance of the work lies in determining the parameters of combined energy storage systems for an electric bus using the example of a plug-in hybrid power plant.

3. Analysis of the results of the study on solving the optimization problem proved that when using charging systems in a depot, energy consumption is a significant indicator for storage systems, but the power of optimal energy storage systems is excessive and exceeds

the minimum requirements by 2,05–3,29 times, which can be used to improve the dynamic performance of an electric bus.

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