On Adaptive Electro Hydrostatic Actuators

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Whenever decision makers want to follow the trend towards "all-electric" machines, but still need to maintain the major advantages of hydraulic drives, electro hydrostatic actuators (EHA) have become the technology of choice for industrial applications. In an EHA, a variable speed electric motor drives a displacement pump which is directly coupled to the actuator, namely a cylinder. After proofing the functionality of this concept in many commercial applications, current developments are targeting features and levels of efficiency that will even outperform the electro mechanical state of the art. Adaptive electro hydrostatic actuators will finally be the benchmark in terms of compactness, ease of use and energy efficiency for many application classes. This paper presents two different implementations for variable pitch EHAs and a mobile device for EHA fluid management and service.

Keywords: EHA, Adaptive Electro Hydrostatic Actuator, Hybrid Drive, Sizing Trap, Downsizing
Target audience: Industrial Hydraulics, Production Equipment, Machinery for Pressing, Cutting, Forming

1 Introduction

During the last decade, EHAs have made their way from research lab into real life industrial applications /1/. Theoretical and scientific work has given us the necessary understanding of their dynamic and thermal behaviour /2,3/. Just as important, the progress in synchronous servo motor and driver technology has enabled EHA to be not only technically satisfying but also commercially competitive. Power efficiency at the working point is just as good as that of the electro mechanical alternative. In this situation, it is our task to work on the ease of use of EHAs and also to think about further development that – in this form - is only possible for hydraulic drives.

One critical issue with EHAs is fluid quality and fluid maintenance. The amount of fluid inside an EHA is 1..2 orders of magnitude less, compared to a classical throttle control system. We may find only 2..10 litres of fluid in an EHA, whereas a comparable classical hydraulic drive would run on a tank of 200...300 litres. As a consequence, the mechanical and thermal stress is concentrated on the small amount of fluid. Because such EHAs often are closed systems and pre-pressurised, cleaning and filtering or replacing the fluid becomes a real problem in the field, if the necessary tools are not at hand. At Voith, a mobile fluid service and management device has been developed to make this task manageable and straightforward even for non-experts.

Another challenge for EHAs is the "sizing trap". What has always been part of the electro mechanic drive engineer's daily work has become a "new" challenge for hydraulic systems engineers. Designing a classical hydraulic drive, almost any system requirement can be fulfilled, provided the servo valve response is fast enough and there is enough of energy supplied by the pump station. But with EHAs, same as for electro mechanical drives, all the mechanical energy needed must be delivered on premise by the servo motor. Using pressure accumulators for peak power is not possible in EHAs. Sizing the motor becomes a critical task. If the motor is too small, the torque will not be sufficient for the requirements in maximum force. Simply choosing the next bigger motor may just move the problem into another domain, because the increased inertia of that bigger motor may prevent the system from meeting the requirements in dynamics and acceleration. This contradictionary set of requirements is called the sizing trap. It applies to EHAs in the same way as for electro mechanical drives. But with EHAs, there is a way out that does not exist for electro mechanical drives.

2 EHAs with non-constant Pitch

2.1 The Sizing Trap

For purpose of comparison, the following figure 1 shows a basic EHA structure and figure 2 shows the equivalent electro mechanical drive, employing a screw drive. We further assume volumetric efficiency η_{VOL} and mechanical efficiency η_{VOL} of the pump to be 1, same as we assume the mechanical efficiency of the screw η_{MEC} to be 1.

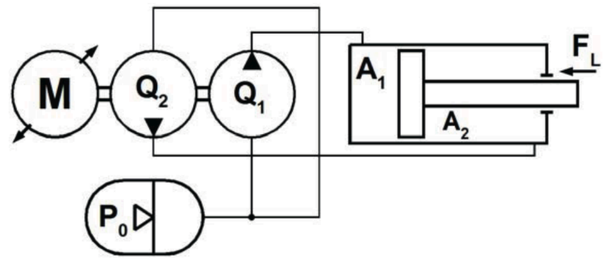


Figure 1: basic schematic of EHA with constant gear

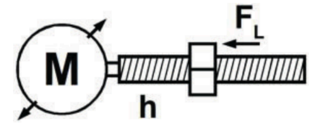


Figure 2: electro mechanical screw drive

For the mechanical screw drive, basic mechanics let us calculate linear speed V_{LIN} and force F_{LIN}:

$$V_{LIN} = \frac{\omega_{MOT}}{2 * \pi} * h_{MEC} \tag{1}$$

$$F_{LIN} = \frac{M_{MOT}}{h_{MEC}} * 2 * \pi \tag{2}$$

For an EHA we can define the hydrostatic pitch h_{EHA}. For a balanced EHA with pump displacement ration Q_1/Q_2 equal the surface ratio A_1/A_2, we get a uniform hydrostatic pitch for both directions of movement:

$$h_{EHA} = \frac{Q_1}{A_1} = \frac{Q_2}{A_2} \tag{3}$$

Replacing the mechanical pitch h_{MEC} by the hydrostatic pitch (3), we can now use (1) and (2) to calculate the relations between linear speed and force in relation to rotational speed and torque of the driving motor in an EHA.

Many industrial applications are mainly characterized by the maximum speed V_{MAX} and the maximum force F_{MAX}. It is obvious that these requirements from the linear domain will define the requirements for the driving motor. As a function of V_{MAX} and F_{MAX} we would get the maximum power P_{MAX}.

$$P_{MAX} = F_{MAX} * V_{MAX} \tag{4}$$

But in industrial equipment, F_{MAX} and V_{MAX} are not always seen at the same time. Instead, F_{MAX} is related to a low process speed V_{FMAX} and V_{MAX} is often related to a low load force F_{VMAX}. Thus, we get the relations for two operating points and their relative operating power P_{FMAX} and P_{VMAX}.

$$P_{FMAX} = F_{MAX} * V_{FMAX} \tag{5}$$

$$P_{VMAX} = F_{VMAX} * V_{MAX} \tag{6}$$

In production machinery, the ratio $P_{\mathrm{MAX}}/P_{\mathrm{FMAX}}$ and $P_{\mathrm{MAX}}/P_{\mathrm{VMAX}}$ can often be found in the range of 2..10. But because we always have to choose one single type and size of motor, it must be sized closer to P_{MAX}. This is the sizing trap: we may only need 10 kW at either maximum speed or maximum force, but we may end up with a motor of 30 kW so it can deliver the data at any speed / torque.

The following figure shows a stroke vs time diagram and a power chart for the parameters of (5,6). P_{FMAX} and P_{VMAX} are shown to be equal, which is just an example for simplification.

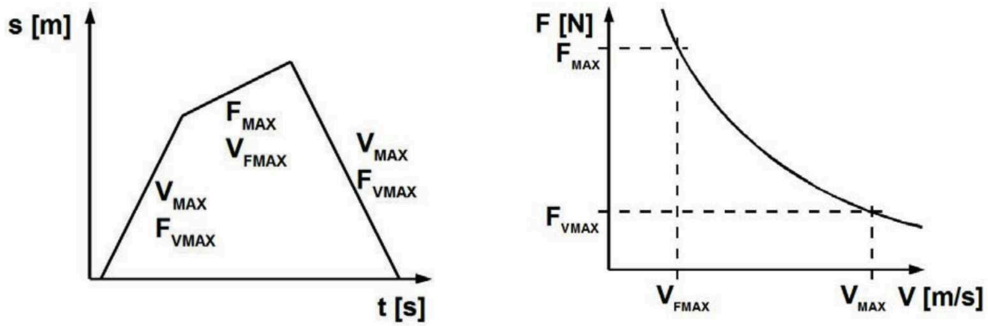


Figure 3: drive power chart

Taking advantage of over loading to get high peak torque and using field weakening to get high speed is not really an escape from this trap. It is just a method of optimally using the motor's iron, copper and magnets.

But if we were able to use two different pitches h_{FMAX} and h_{VMAX}, we would be able to choose a smaller motor and utilize this motor's performance in a better match to the application requirement. Whereas this is hardly a practical approach for electro mechanical drives, EHAs have several options at hand.

2.2 Choosing Topology for Adaptive Pitch

With respect to figure 1 and (3), we identify the pump displacement and cylinder effective surface as key parameters. If we want the effective pitch to be adaptive, we must vary at least one of these parameters under live operating conditions. To avoid the cost, noise and complexity of variable displacement pumps, we focus on constant displacement internal gear pumps. Driven by specific project requirements, several such topologies have been implemented and brought to work. These topologies cover only a small fraction of the possible solution space. And they do not claim to be the theoretically best solution to a given problem. They were created to solve a given industrial drive problem in mind, with a good compromise on equipment cost, complexity and resulting drive performance.

2.2.1 CLSP: Differential Cylinder with 4Q Pump

The following figure shows the simplified schematic of a CLSP drive /4/. The combination of a differential cylinder and a 4Q pump comes with complexity. Many of the components deal with balancing the symmetric fluid input / output of the 4Q pump with the non-symmetric fluid flow for a differential cylinder. Automatically adapting the active cylinder surfaces according to the load situation also needs dedicated components.

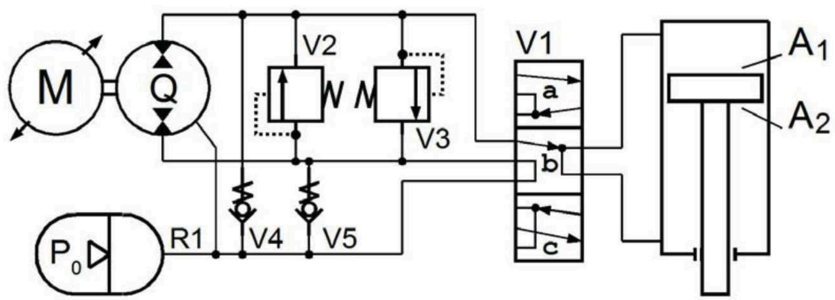


Figure 4: CLSP principal schematic

Before explaining the function, we will consider the sizing trap for this case. The following table shows the target parameters of a real project for positive full load, positive empty stroke and negative empty stroke. Note that full load is only required in positive direction (compare figure 3a). This is typical for many production processes like metal forming, metal bending or special sheet metal connection processes like riveting or clinching. Note F_2 and F_3 are very small because the actuator has only to move its own (piston) weight and a very light weight tool.

Mode	Force	Speed	Power
Positive full load	F_1 = 85.0 kN	V_1 = 0.090 m/s	P_1 = 7.650 kW
Negative empty load	F_2 = -1.0 kN	V_2 = -0.335 m/s	P_2 = 0.335 kW
Positive empty load	F_3 = 1.0 kN	V_3 = 0.375 m/s	P_3 = 0.375 kW

Table 1: CLSP target parameters

For first overview, we outline the sizing of a motor for a suitable spindle drive. Spindle pitch h_{3A} is derived from the highest linear speed V_3 and the motor's maximum speed ω_3 (here: 3.800 min^{-1}):

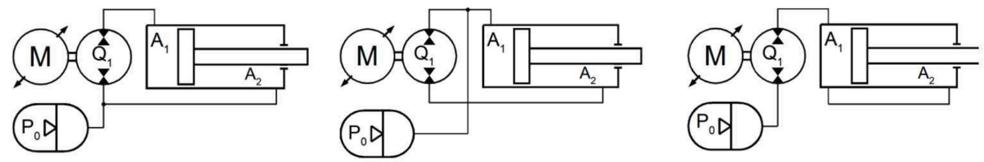
$$h_{3A} = \frac{V_3}{\omega_3} * 2 * \pi = 0.0059\ m \qquad (7)$$

With h_{3A} given, we now calculate the torque M_1 for full load F_1:

$$M_{1A} = F_1 * h_{3A} * \frac{1}{2 * \pi} = 80.1\ Nm \qquad (8)$$

Assuming a reasonable torque overload factor, we choose a catalogue motor with a rated torque of 26 Nm, a rated power of 8.2 kW and a weight of 31.5 kg (T7-4000, /6/).

The design target for an EHA with adaptive pitch is to reduce size and rated power of the motor. For this, we implement an EHA with two distinct hydraulic pitches, h_F for high force and h_V for high speed. The following figure shows the three configurations, to meet the load cases of full force, positive empty stroke and negative empty stroke. The differential cylinder is used with piston surface for high force and annular rod side surface or differential surface for high speed on low force. Note that the EHA according to figure 4 automatically adapts itself into one of the configurations of figure 5. The 5-3 valve V1 is implemented by a plurality of logic elements and pressure valves. Table 2 shows implementation parameters for the project.



5a: full force *5b: pos. empty load* *5c: neg. empty load*

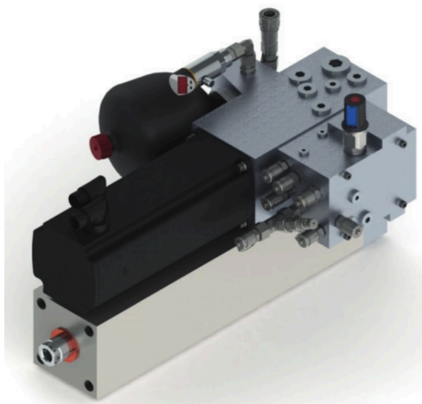
Figure 5: CLSP modes of operation

Parameter	Value	Unit	Comment
Q_1	0.0000083	m³	Pump displacement (8.3 cm³)
D_1	0.058	m	Piston diameter
D_2	0.040	m	Rod diameter
A_1	0.00264	m²	Piston surface

A_2	0.00139	m²	Annular rod side surface
A_3	0.00125	m²	Differential surface $A_1 - A_2$
h_{1B}	0.00314	m	Pitch for full load (figure 5a)
h_{2B}	0.00599	m	Pitch for neg. empty load (figure 5b)
h_{3B}	0.00664	m	Pitch for pos. empty load (figure 5c)

Table 2: CLSP chosen dimensions

Figure 6 shows a possible implementaion for this example of CLDP. Because of the benefits in size and weight through downsizing the motor and pump, the system is well suited for "mobile" applications, like robot based production and assembly machinery.



6a: CLSP compact version

6b: robot based CLSP application

Figure 6: CLSP example

We can calculate the maximum speed and torque required from the motor, with respect to each load case.

$$\omega_{1B} = \frac{V_1}{h_{1B}} = 180\, rads^{-1} = 1.719\, min^{-1} \quad \text{Positive full load} \tag{9}$$

$$M_{1B} = F_1 * h_{1B} * \frac{1}{2*\pi} = 42.5\, Nm \quad \text{Positive full load} \tag{10}$$

$$\omega_{2B} = \frac{V_2}{h_{2B}} = 319\, rads^{-1} = 3.045\, min^{-1} \quad \text{Negative empty load} \tag{11}$$

$$M_{2B} = F_2 * h_{2B} * \frac{1}{2*\pi} = 0.63\, Nm \quad \text{Negative empty load} \tag{12}$$

$$\omega_{3B} = \frac{V_3}{h_{3B}} = 393\, rads^{-1} = 3.756\, min^{-1} \quad \text{Positive empty load} \tag{13}$$

$$M_{3B} = F_3 * h_{3B} * \frac{1}{2*\pi} = 0.67\, Nm \quad \text{Positive empty load} \tag{14}$$

Note that M_{1B} for the EHA with dual pitch is only 50% of M_{1A} for the screw drive with constant pitch. Maximum speed is at the same 3.800 rpm.

For the highest torque of M_{1B}, we find a catalogue motor with a rated torque of 14.5 Nm, a rated power of 4.6 kW and a weight of 13.7 kg (T5-1700, /6/). This motor will also deliver the highest speed ω_3 in field weakening.

This example shows how the size (rated power) of the driving servo motor could be cut by a factor of almost two by using an adaptive EHA. The weight of the adaptive EHA's smaller motor is less than half of the weight for a constant pitch screw drive or for a constant pitch EHA.

Downsizing the motor for this adaptive EHA was key to meet the limit of 60 kg for the weight of the complete system, including motor, pump and valves assembly and the actuating cylinder. The weight limitation is motivated by the EHA being mounted on a robot arm as part of a flexible assembly cell.

Another design goal for this project was to avoid any actively commanded switching valves for changing the configuration. Therefore, all such functions are implemented by pressure sensitive hydro mechanical switching of the respective valves. This makes the system robust and independent from correct software implementation of mode selection.

It must be noted that the particular topology of CLSP has its drawbacks. It is only applicable for applications where the moving mass is relatively small and where the negative stroke (retracting the rod) is always in low force mode.

2.2.2 PDSC: Multi Surface Cylinder for high moving Masses

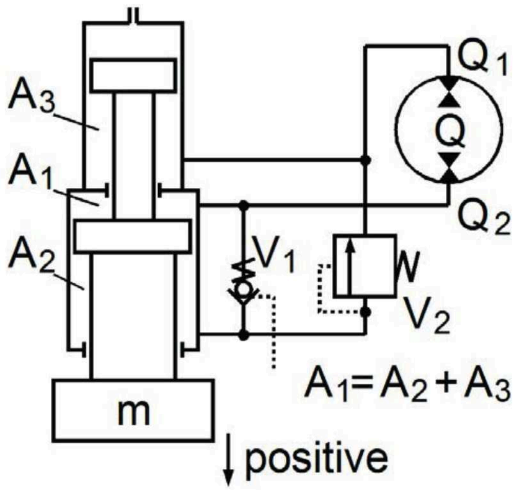
A different project required a solution for a heavy vertical press, with a tool weight of several tons. Table 3 shows the parameters summary:

Parameter	Value	Unit	Comment
F_{MAX}	4,000,000	N	Max. force for load stroke
V_{FMAX}	0.030	m/s	Max. speed for load stroke
F_{VMAX}	400,000	N	Max. force for empty stroke (pos. and neg.)
V_{MAX}	0.270	m/s	Max. speed for empty stroke
h_{FMAX}	0.00088	m	Pitch for load stroke
h_{VMAX}	0.00784	m	Pitch for empty stroke
Q_1	0.000125	m³	Pump displacement (125 cm³)

Table 3: PDSC parameter summary

The power requirement for full load (F_{MAX} * V_{FMAX}) is 120 kW, the power requirement for no load (F_{VMAX} * V_{MAX}) is 108 kW. Because of the sizing trap, if implemented with a fixed pitch configuration, the theoretical peak dimensioning power (F_{MAX} * V_{MAX}) would be 1.08 MW. Obviously, this project will benefit from any downsizing that can be achieved. The previously described CLSP was not a solution, because it cannot manage relatively high masses. The additional requirement here is the ability to hold a relatively high moving mass under all operating modes. In a typical punch or forming application it may also be a requirement to decelerate the drive in a controlled way after the process force collapses following the cutting or punching process.

The following functional description refers to the simplified schematic of PDSC /5/ in figure 7. In the "no load" configurations, the 4Q pump works on the relatively small surfaces A_3 and A_1-A_2, because valve V1 effectively connects the surfaces A_1 and A_2. In the "full load" configuration, V1 separates surfaces A_1 and A_2 and V2 connects A2 to A3, but the pressure in A2 is always maintained at the pressure set value of pressure valve V2. This feature implements the moving mass management and also the controlled deceleration for cutting or punching processes. V1 may be controlled automatically by sensing the operating pressure or under control of an electrically commanded switching valve.



Mode	V1	V2	Q1	Q2
No load positive			A_3	$A_1 - A_2$
No load negative			A_3	$A_1 - A_2$
Full load positive			$A_2 + A_3$	A_1

Figure 7: PDSC principal schematic and modes of operation

In this project, the surfaces A_1, A_2, A_3 have been chosen to result in a relatively high switching ratio of 1:8,9 between h_{FMAX} for "full load" and h_{VMAX} for "empty load". This ratio was chosen to be similar as the ratio between the operating speeds under full load and empty load. As a result, the driving motor will operate approximately at the same speed in both modes.

The following figure shows PDSC implementation for requirements of table 3. Note the relatively small motor with a rated power of 88 kW driving the relatively big cylinder delivering a maximum force of 4,000 kN. To simplify mechanical handling and installation, the motor and pump combination is connected to the cylinder unit with flexible hoses.

Figure 8: PDSC implementation

3 Mobile Device for Fluid Management and Service

One attractive key feature of modern EHAs is that they are fully self-contained. No external hoses or pipes are used to connect a pump station. Only a small "tank" exists in the form of a pre-pressurized compensation volume. Even though the pressure level in this tank ranges between 2..10 bar, this has a crucial consequence: as soon as a single hydraulic element of the EHA needs to be serviced or replaced, the system must first be de-pressurized in a controlled way. After the service work has been done, the system must be re-pressurized to the correct level again. For re-pressurizing, it is vital that no air will be injected into the fluid. The same conditions must be met when the operating fluid itself shall be serviced, filtered or even replaced. For this purpose, Voith designed a mobile device for fluid management and service of EHAs.

For connecting the service unit, each EHA is equipped with two leakage free quick connection ports, one for fluid input from the service unit and another for fluid return to the service unit. By means of a manual three way valve, the unit supports three modes of operation:

Internal filtering: in this mode, the EHA's fluid is continuously circled between the EHA and the service unit, with filter cartridges in both connection lines between the service unit and the EHA. Because the EHA's pre-pressurization is not affected by this process, it can be conducted in-place. The EHA may remain in the application machine. This mode of fluid filtering may even be carried out while the EHA is fully operational in the machine.

Fluid change: in this mode, the EHA's fluid is drained into the reservoir canister connected to the service unit.

Filling / external filtering: in this mode, fluid from the fresh fluid canister is pumped to the EHA, while the pre-pressurizing level for the EHA can be set on a pressure valve on the service unit.

The following figures shows the hydraulic structure of this unit.

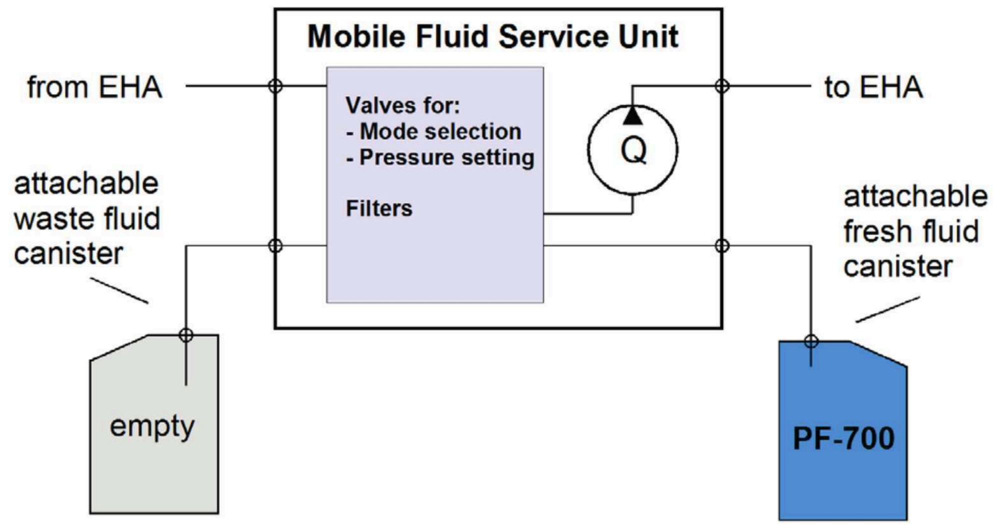


Figure 9: simplified schematic of mobile device for fluid management and service

It was an important design goal to create a small mobile device which can easily be transported to a customer's or end user's site. A trolley like handle and wheels supports transportation. Necessary hoses and power cords are encapsulated during transportation. The following figures show the design.

10a: transport configuration

10b: use configuration

Figure 10: mobile device for fluid management and service

4 Summary and Conclusion

EHAs are widely applied to satisfy customers' requests for easy to use and energy efficient hydraulic drive solutions. Adding the feature of adaptive hydrostatic pitch allows such EHAs to outperform electromechanical drives in terms of reliability, compactness, hardware investment cost and energy efficiency. Experience shows that there is no single topology for adaptive EHAs which may be applied to all application requirement profiles. Parameters such as moving mass and external process force distribution over stroke cause different topologies to be applied.

Fluid management is one of the less-sexy aspects of hydraulics. Compared to classical hydraulic drives, fluid volume is significantly reduced in modern EHAs. A dedicated mobile device simplies the on site fluid management even for non-experts, which is another contribution for better user acceptance.

Nomenclature

Variable	*Description*	*Unit*
V_{LIN}	Linear Speed	[m]
F_{LIN}	Linear Force	[N]
ω_{MOT}	Rotational Speed	[rad/s]
h_{MEC}	Mechanical Pitch	[m]
M_{MOT}	Motor Torque	[Nm]
h_{EHA}	Hydrostatic Pitch of EHA	[m]
Q_{n}	Hydrostatic Displacement of Pump	[m³]
A_{n}	Cylinder Effective working Surface	[m²]
P_{n}	Power	[W]

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